Abstract. A one-dimensional model is being considered where a fully ionized plasma is separated from a neutral gas by a homogeneous magnetic field directed along the plasma boundary. The plasma and the neutral gas consist of two different types of ions and neutral particles. In a stationary state the outflux of plasma by diffusion across the magnetic field is compensated by an influx of neutrals which are ionized in a partially ionized boundary region.

It is found that the ratio between the ion densities in the fully ionized region will in general differ from the density ratio of the two types of neutrals being present in the gas region. This provides a separation mechanism with applications both to cosmical and laboratory plasmas, such as in the following cases:

(i) The abundance anomalies in magnetic variable stars and in the solar wind.
(ii) Separation processes of non-identical ions and neutral atoms in gas blanket systems.

1. Introduction

Effects which produce a separation of non-identical ions in an ionized gas are important both to cosmical problems, such as to the distribution of elements in stellar atmospheres, and to experiments with plasmas in the laboratory. Such mechanisms, being caused by diffusion across a magnetic field, have earlier been treated by a number of authors in the case of a fully ionized multicomponent plasma (Spitzer, 1952, 1962; Longmire and Rosenbluth, 1956; Post, 1959, 1960; Taylor, 1961; Bonnevier, 1966).

This paper extends an earlier investigation on the balance of a plasma confined by a magnetic field and surrounded by neutral gas (Lehnert, 1968, 1969). The ion density of the fully ionized central parts of the plasma and the thickness of the partially ionized boundary region situated between the plasma and the neutral gas were found to be functions of the collision cross sections, the particle masses, and the ionization rate. This suggests that separation of elements should take place in a corresponding multicomponent system, in the sense that the relative concentrations of different neutral atoms in the surrounding neutral gas should differ from the concentrations of non-identical ions in the fully ionized plasma region. In the present paper the balance in the boundary region will be discussed in terms of a simple model for two ion species, and it will be shown that such a separation process becomes possible.
2. Outline of Theoretical Analysis

A one-dimensional model is adopted where an impermeable plasma of two ion species is immersed in a homogeneous magnetic field $B$ directed along $z$ of a frame $xyz$. All density and pressure gradients are along $x$. The plasma is kept in a fully ionized state by energy sources far inside the region $x > 0$, whereas matter in a "gas blanket" region $x < 0$ is kept at a low ionization degree. The plasma is separated from the neutral gas by a partially ionized boundary region defined by $0 < x < x_b$. The steady-state balance of matter is established by plasma diffusion in the negative $x$ direction, being compensated by a counter-diffusion of neutral gas in the positive $x$ direction. Thus, the densities $n_1$ and $n_2$ of the two ion species drop from their full values $n_{1b}$ and $n_{2b}$ at the inner edge $x = x_b$ of the boundary region to values $n_{10} \ll n_{1b}$ and $n_{20} \ll n_{2b}$ at its outer edge $x = 0$. Further, the corresponding densities $n_3$ and $n_4$ of the neutral gas drop from their full values $n_{30}$ and $n_{40}$ at $x = 0$ to $n_{3b} \ll n_{30}$ and $n_{4b} \ll n_{40}$ at $x = x_b$. The temperature and ionization rate in the boundary region are low enough for the plasma balance to be mainly determined by diffusion. In the region $x > x_b$ the neutral densities have on the other hand become small enough for the available plasma heat flow across the magnetic field to ionize the incoming neutral gas.

The balance equations of charged and neutral constituents in the boundary region can be normalized as follows (Lehnert, 1968, 1969). With subscripts 1, 2 for ions and 3, 4 for neutrals we introduce the coefficients $\sigma_{\mu \nu} = m_{\mu \nu} \langle \sigma_{\mu \nu} w_{\mu \nu} \rangle$, where $m_{\mu \nu}$ is the reduced mass of ion-neutral collisions and collisions between non-identical neutrals, with the cross section $\sigma_{\mu \nu}$ and relative velocity $w_{\mu \nu}$. We further introduce the dimensionless coefficients $c_{\mu \nu} = \sigma_{\mu \nu} / \alpha$, where $\alpha$ is some characteristic value of $\sigma_{\mu \nu}$, the coefficients $\alpha_e = m_e \langle \sigma_{el} w_{el} \rangle$ and $\alpha_{12} = m_{12} \langle \sigma_{12} w_{12} \rangle$ for electron-ion collisions and collisions between non-identical ions, $c_e = \alpha / \alpha_e$, $c_{12} = 1 + \alpha_{12} / \alpha_e$, the normalized plasma density $n_p = eB/(\alpha_{tot} \langle \sigma_{el} \rangle)^{1/2}$, the normalized densities $N_v = n_v / n_p$, where $v = 1, 2, 3, 4$, as well as the dimensionless coordinate $s = (G/kT)x$. Here $G = n_3 v_3 = -n_1 v_1 = \text{const}$ and $\gamma G = -n_4 v_4 = -n_2 v_2 = \text{const}$ are the ion and neutral fluxes by diffusion across the boundary region, taking place at the fluid velocities $v_{ex}$. The momentum balance equations then reduce to a system of the form

$$\frac{dN_v}{ds} = f_v(N_p), \quad v, \mu = 1, 2, 3, 4,$$  \hspace{1cm} (1)

where $f_v$ are functions of $N_p$ containing dimensionless coefficients which are combinations of $c_{\mu \nu}$, $c_{12}$, $c_e$ and $\gamma$.

The solution of Equations (1) represents an eigenvalue problem for $\gamma$ which is determined by the condition that $N_3$ and $N_4$ should both have zeros close to the plane $x = x_b$. For a given ratio $N_{30}/N_{40}$ of the neutral atom densities this yields a ratio $N_{1b}/N_{2b}$ of the corresponding ion densities which is a function of the dimensionless coefficients $c_{\mu \nu}$, $c_{12}$ and $c_e$ representing the collision processes between the particle types involved. Since these coefficients differ by a factor of the order of 2 and more for