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PROBLEMS OF MATTER-ANTIMATTER BOUNDARY LAYERS

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ABSTRACT

This paper outlines the problems of the quasi-steady matter-antimatter boundary layers discussed in Klein-Alfvén's cosmological theory, and a crude model of the corresponding ambiplasma balance is presented:

(i) At interstellar particle densities, no well-defined boundary layer can exist in presence of neutral gas, nor can such a layer be sustained in an unmagnetized fully ionized ambiplasma.

(ii) Within the limits of applicability of the present model, sharply defined boundary layers are under certain conditions found to exist in a magnetized ambiplasma. Thus, at beta values less than unity, a steep pressure drop of the low-energy components of matter and antimatter can be balanced by a magnetic field and the electric currents in the ambiplasma.

(iii) The boundary layer thickness is of the order of $2x_o \approx 10/BT_o^{1/4}$ meters, where B is the magnetic field strength in MKS units and T_o the characteristic temperature of the low-energy components in the layer.

1. Introduction

Some twenty years ago Klein [1-4] put forward a theory on the development of the metagalaxy, being symmetric with respect to the contents of matter and antimatter. This approach was further developed by Alfvén and Klein [5] and Alfvén [6] who stressed that, during the present state of the metagalaxy, there must exist regions containing matter or antimatter being separated by thin sheaths. Consequently, such sheaths become a crucial part of the theory. It was suggested that they should have the form of "Leidenfrost" layers containing energetic particles being created by annihilation reactions.

An "ambiplasma", i.e. a mixture of ionized matter and antimatter, is a system with many degrees of freedom containing light and heavy particles of both polarities. The detailed ambiplasma balance in a boundary layer separating matter from antimatter therefore becomes a more complex question than similar problems in an ordinary plasma. The purpose of the present paper is merely to outline this balance, as well as to give crude estimates of the data of matter-antimatter sheath models.

2. Basic Concepts

2.1. Basic Parameter Data

In the analys of a hydrogen ambiplasma, six types of particles have in principle to be specified, namely four low-energy components consisting of protons, antiprotons, positrons and electrons, as well as two high-energy components consisting of positrons and electrons. In this paper we use subscripts ($_i$) and ($_e$) for heavy and light particles, superscripts ($^+$) and ($^-$) for polarity, and a circumflex ($\hat{\ }$) on top of a letter for the high-energy components. We also introduce subscript ($_\nu$) as a common symbol for all these notations.

When an electron and a positron annihilate each other, there are usually emitted two photons with an energy of about 0.5 MeV each. The annihilation of a proton by an antiproton yields, on the average, two electrons and two positrons which share an energy of about 100 MeV, whereas the rest of the released energy is radiated away. Consequently, the part $Q \approx 2 \times 10^{-11}$ joules of the released energy remains with charged particles, i.e. with the high-energy components, and the rest of this energy leaves the ambiplasma. The cross sections of the annihilation reactions just mentioned are nearly equal, and the corresponding reaction rate becomes $\alpha \approx 10^{-20}$ m^3/s in the first approximation.

Concerning the low-energy components in interstellar space, we follow Alfvén [6] and assume a particle density of the order of $n_\nu \approx 10^6$ m^{-3}.

2.2. Basic Equations

The macroscopic fluid equations of a steady, fully ionized and magnetized ambiplasma will be adopted here, their applicability being discussed to some extent in Section 3. The balance of particles is expressed by

$$\mathrm{div}(n_\nu \underline{v}_\nu) = S_\nu \qquad (1)$$

where $\underline{v}_\nu$ is the fluid velocity of the ν-th type of particle and S_ν stands for the rate of loss of particles by annihilation, as well as for the rate of change of high-energy into low-energy particles by Coulomb collisions.

Further, the balance of momentum is determined by

$$n_\nu m_\nu (\underline{v}_\nu \cdot \underline{\nabla}) \underline{v}_\nu = q_\nu n_\nu (\underline{E} + \underline{v}_\nu \times \underline{B}) - \underline{\nabla} p_\nu + \underline{F}_\nu \qquad (2)$$

where m_ν and q_ν are the mass and charge of the ν-th particle type, $p_\nu = n_\nu k T_\nu$ with T_ν as the corresponding temperature, $\underline{E}$ and $\underline{B}$ are the electric and magnetic fields, and $\underline{F}_\nu$ stands for the effects of momentum exchange and loss produced by Coulomb collisions including the Nernst effect, as well as by annihilation reactions.

Finally, the heat balance is expressed by

$$\frac{3}{2} \operatorname{div} (p_\nu \underline{v}_\nu) + p_\nu \operatorname{div} \underline{v}_\nu - \operatorname{div}(\lambda_\nu \underline{\nabla} T_\nu) - R_\nu =$$

$$= Q_\nu + C_\nu + J_\nu \qquad (3)$$

where λ_ν stands for the effective heat conductivity, R_ν for the radiation losses, Q_ν for the heat production by annihilation, C_ν for heat transfer by Coulomb collisions, and J_ν for Ohmic heating.

In addition, the condition $\Sigma q_\nu n_\nu = 0$ of quasi-neutrality has to be satisfied.

The detailed forms of S_ν, λ_ν, R_ν, Q_ν, C_ν, and J_ν for the various particle types will not be given here, but we shall return to part of the set of equations (1)-(3) later in this paper. Here we only specify the rate

$$\rho = \langle\sigma_{\mu\nu} w_{\mu\nu}\rangle = c_\rho / T^{3/2} \qquad c_\rho = \kappa_\rho(\ln\Lambda) \tag{4}$$

of Coulomb collisions between light ·ticles at the temperature T, where $k_\rho \approx 10^{-6} m^3 K^{3/2}/s$ and Λ is the ratio between the Debye distance and the impact parameter. Further, for positrons and electrons the radiation losses are mainly given by [7]

$$R_e^{+-} = k_b Z^2 (n_i^+ + n_i^-) n_e^{+-} (T_e^{+-})^{1/2} + k_c n_e^{+-} B^2 T_e^{+-} \tag{5}$$

where superscript $(^{+-})$ indicates the two alternatives $(^+)$ or $(^-)$ henceforth, Z is the charge number, $k_b \approx 1.7\ 10^{-40}\ Wm^3/K^{1/2}$ represents Bremsstrahlung, and $k_c \approx 5.3\times10^{-24}\ Am^2/Vs^2K$ stands for cyclotron radiation.

3. General Conditions for Boundary Layer Formation

Before attempting special models of matter-antimatter boundary layers, we have to examine the general conditions for such an approach. Thus, the boundary layers have to become sufficiently narrow, such as not to release excessive amounts of annihilation energy within large volumes. Also the conditions of particle, momentum, and heat balance of the layers should be satisfied, preferably under quasi-steady conditions.

3.1. The State of Ionization

The first of the basic questions concerns the presence of neutral gas. This question is also related to the pressure balance problem treated later in Section 3.2.1. The penetration length of fast neutrals into a plasma of average density n and temperature in the range $3 \times 10^4 < T < 10^6$K becomes [8]

$$L_{nf} \simeq 1/\sigma_{cf}\, n$$ ([illegible])

where $1/\sigma_{cf} \simeq 3 \times 10^{18}$ m^{-2} for hydrogen and helium. Adopting the density value $n \simeq 10^6$ m^{-3} of interstellar space mentioned in Section 2.1, the penetration length thus becomes $L_{nf} \simeq 3 \times 10^{12}$ m. This length increases rapidly as T decreases below 3×10^4 K.

Consequently, in cases where large clouds of neutral matter and antimatter should be prevented from penetrating each other, two adjacent regions of ionized matter and antimatter have to satisfy the following conditions:

(i) The depth of each region should be substantially larger than L_{nf} .

(ii) The plasma temperature within the regions should be kept high enough for a fully ionized state to be sustained.

3.2. The Pressure Balance

For thin boundary layers to exist, it is necessary that large and opposite partial pressure gradients of matter and antimatter are established in the layers. It is not obvious that such a situation can or has to be provided by a constant total pressure Σp_ν within the boundary region.

3.2.1. Balance in Absence of a Magnetic Field

In absence of a magnetic field we consider the simple case of two species $(_1)$ and $(_2)$ moving at the mutual velocity $\underline{v}_{12}$ and exchanging momentum at the rate $\rho_{12} = \langle \sigma_{12} w_{12} \rangle$, where σ_{12} and w_{12} are the corresponding cross section and thermal velocity. A pressure gradient

$$\underline{\nabla} p_1 = - m_1 m_2 (m_1 + m_2)^{-1} n_1 n_2 \rho_{12} \underline{v}_{12} \tag{7}$$

can then be sustained in the fluid of species $(_1)$ and vice versa. To make the characteristic distance $p_1/|\underline{\nabla} p_1|$ of the pressure comparable to a given dimension L_b, like that of the boundary layer thickness, it is then required that

$$v_{12}/w_{12} \approx 1/n_2 \sigma_{12} L_b \tag{8}$$

for two species with nearly the same particle masses and temperatures. Supersonic flow is of minor interest in this connection. Consequently, eq. (8) indicates that substantial pressure drops can only be sustained by subsonic flow across the distance L_b when the mean free path $1/n_2\sigma_{12}$ is much smaller than the layer thickness L_b. This result has the following consequences:

(i) In the case of a purely neutral or partially ionized interstellar gas, account has to be taken both of the neutral penetration process described in Section 3.1 and of the fact that the collision cross sections between neutral particles are of the order of $10^{-19}\ m^{-2}$. It is evident that well-defined and narrow boundary layers with large partial pressure drops cannot exist under such circumstances at densities of the order of $10^{6}\ m^{-3}$.

(ii) In the case of a fully ionized ambiplasma, the Coulomb cross sections of encounters between light particles are of the order of $2 \times 10^{-9}/T^2\ m^2$. With $T \times 10^5$ and 10^{12} K of the low- and high-energy components, respectively, sharp boundary layers cannot be formed at such densities in fully ionized non-magnetized plasmas either.

3.2.2. Balance in Presence of a Magnetic Field

From the discussions of the previous section it is clear that the mean free paths in the interstellar gas are too long for a pressure balance to be sustained in narrow boundary layers merely by collisional drag forces. However, in presence of a magnetic field being parallel with the layer surfaces, such a balance becomes possible in a fully ionized plasma. Then, large partial pressure gradients can be balanced by the magnetic field, and need not cancel each other through the condition $\Sigma p_\nu = const.$ In the case of a strong magnetic field $\underline{B}$ the macroscopic approach of eqs. (1)-(3) should also be valid with respect to the directions perpendicular to $\underline{B}$. For a well-expressed quasi-steady pressure balance of this type, two conditions have at least to be satisfied:

(i) The beta values $\beta_\nu = 2\mu_o p_\nu/B^2$ should be less than unity.

(ii) The Larmor radii a_ν should be small compared to the characteristic macroscopic dimensions L_b.

3.3. Radiation Losses and General Heat Balance

It was concluded in Sections 3.1 and 3.2 that the plasma has to be fully ionized within regions of sufficiently large dimensions to prevent neutral gas from reaching the boundary layers where annihilation takes place. To sustain such a state without external heat sources, the heat production by annihilation has at least to cover the radiation losses of the fully ionized plasma. We now define L_b as the thickness of the boundary layer (the annihilation region) and L_c as the average thickness of the adjacent fully ionized matter and antimatter regions. Then the total heat production exceeds the total radiation loss when

$$\theta = L_c \Sigma R_\nu / L_b \Sigma Q_\nu < 1 \tag{9}$$

This condition is necessary but not sufficient for sustaining fully ionized regions, because the heat produced by annihilation also has to be transferred by Coulomb collisions from the high-energy to the low-energy electrons and positrons. This transfer has the efficiency

$$f_b = 3k\hat{T}\hat{\rho}(n_e^+ + n_e^-)(\hat{n}_e^+ + \hat{n}_e^-)/2Q\alpha n_i^+ n_i^- \tag{10}$$

where $\hat{\rho} = \hat{\rho}(\hat{T})$ in eq. (4), and $\hat{T}$ stands for a typical temperature of the high-energy component.

Finally, the transferred heat has to be conducted across the magnetic field, to sustain a fully ionized state in the matter and antimatter regions on both sides of the boundary layer. Alternatively, when this condition cannot be fulfilled, electric currents or other heat sources have to provide full ionization within the matter and antimatter regions.

4. Outline of a Simple Model

The magnetized fully ionized boundary layer of matter and antimatter has some similarities with the partially ionized layer separating an impermeable plasma from a neutral gas [8], in the sense that two states of matter are separated by a narrow interaction region. On the other hand, the diffusion processes as well as the sources and sinks of particles and the heat production are different in these two systems. Here attemps are made to establish a crude one-dimensional model of the matter-antimatter system. In the model all plasma quantities are assumed to be functions of x in a rectangular frame xyz, and there is a homogeneous field $\underline{B}$ along z. Further, the system is assumed to be symmetric around $x = 0$, with matter at $x = -\infty$ and antimatter at $x = +\infty$. Classical diffusion is assumed as a working hypothesis, but at least some of the possibly arising anomalous effects may be included in the theory in an empirical way.

We first point out that the purpose of this analysis is to study the spatial distributions of the main plasma bodies consisting of matter and antimatter, where these bodies are to be separated in space by the confining effects of the magnetic field, and not by the partial pressures of the high energy components. Thus, the behaviour of the low-energy components is of main interest here, whereas only a few general features of the high-energy components need to be analysed for this purpose.

4.1. The High-Energy Components

On account of the small particle mass and the temperature of the high-energy components, their diffusion rate across a strong magnetic field should become small in cases where there is no excessive increase in this rate by anomalous effects. In this section the corresponding diffusion velocity is thus neglected.

4.1.1. The Density Distributions

Combining expressions (1) for the high-energy electrons and positrons and introducing the quantity

$$N = (n_e^+ + n_e^-)\hat{\rho}/\alpha \qquad (11)$$

the high-energy component densities $\hat{n}_e^+$ and $\hat{n}_e^-$ become

$$\hat{n}_e^{+-} = -\frac{1}{2}(n_e^{+-} + N) +$$

$$+\left[\frac{1}{4}(n_e^{+-} + N)^2 + 2n_i^+ n_i^-(n_e^{+-} + N)/(n_e^{-+} + N)\right]^{1/2} \qquad (12)$$

in terms of the low-energy component densities n_i^+, n_i^-, n_e^+, n_e^-. At temperatures of the high-energy component above 10^{11} K we have $\hat{\rho}/\alpha \lesssim 0.03$ and the contribution from N in eq. (12) therefore becomes small. A qualitative outline of the density distributions is given in Fig.1 where the quasi-neutrality condition also has been included. Especially at the centre $x = 0$ it is easily seen from symmetry reasons that $n_i^+ = n_i^-$ and $n_e^+ = n_e^-$. If, in addition, n_i^+ and n_i^- are of the same order as n_e^- and n_e^+, all quantities n_i^+, n_i^-, n_e^+, n_e^-, $\hat{n}_e^+$ and $\hat{n}_e^-$ will become comparable at $x = 0$.

4.1.2. The Temperature

Neglecting ohmic heating by electric currents, as well as diffusion, heat conduction, and adiabatic expansion, the heat balance equation (3) yields

$$a\tau^3 + b\tau^2 - c\tau + d = 0 \qquad (13)$$

where $\tau = (T_e^{+-})^{1/2}$ and

$$a = \hat{n}_e^{+-} \left[\frac{3}{2} k\alpha (n_e^{-+} + \hat{n}_e^{-+}) + k_c B^2\right] \qquad (14)$$

$$b = k_b B^2 (n_i^+ + n_i^-)\hat{n}_e^{+-} \qquad (15)$$

$$c = \alpha Q n_j^+ n_j^- \qquad (16)$$

$$d = \hat{n}_e^{+-}(n_e^+ + n_e^-)kc_\rho \qquad (17)$$

Especially at the centre $x = 0$ of the boundary layer, combination with the result of Section 4.1.1 yields

$$d/c\tau = 2kc_\rho/\alpha Q\tau = 2f_b/3 \approx 10^3/\tau \qquad (18)$$

according to eq. (10). With $\hat{T}_e^{+-} = \tau^2 > 10^{10}$ K, it is then seen that $f_b \ll 1$ which implies that only a small fraction of the released annihilation energy is transferred to the low-energy component by means of Coulomb collisions. In this case it is also possible to neglect d in eq. (13), i.e.

$$(\hat{T}_e^{+-})^{1/2} \simeq -(b/2a) + \left[(b/2a)^2 + (c/a)\right]^{1/2} \qquad (19)$$

Introducing $n_\nu(x = 0) \equiv n_o$ expressions (14)-(16) yield

$$\hat{T}_e^{+-}(x = 0) = 0.5 \times 10^{12}/\left[1 + 10^{19}(B^2/n_o)\right] \text{ K} \qquad (20)$$

where the last term within the square bracket is due to cyclotron radiation. When the latter is negligible compared to the annihilation rate at $x = 0$, a central temperature of about 5×10^{11} K is reached for the high-energy components.

4.2. The Low-Energy Components

According to Fig.1 the regions $x \ll 0$ and $x \gg 0$ mainly consist of matter and antimatter low-energy components, respectively. Annihilation reactions, the formation of large density gradients of the low-energy components, and the creation of high-energy particles are mainly taking place in the boundary layer, i.e. within a distance x_b from the plane $x = 0$.

4.2.1. The Upper Temperature Limit

From eq. (3) an upper limit T_{emax} of the electron and positron temperatures can be obtained by neglecting all losses except those due to radiation and heating of matter and antimatter diffusing into the boundary layer. This loss is equated to the rate of heat transfer from the high-energy components. The latter have a temperature $\hat{T}_e = 5 \times 10^{11}$ K according to Section 4.1.2. Thus,

$$(T_{emax})^{1/2} = - T_1^{1/2} + (T_1 + T_2)^{1/2} \tag{21}$$

where

$$T_1^{1/2} = k_b Z^2 (n_i^+ + n_i^-) n_e^- / 2(k_c n_e^- B^2 + \alpha k n_i^+ n_i^-) \tag{22}$$

$$T_2 = k c_\rho (\hat{n}_e^+ + \hat{n}_e^-) n_e^- / (\hat{T}_e)^{1/2} \, (k_c n_e^- B^2 + \alpha k n_i^+ n_i^-) \tag{23}$$

4.2.2. The Pressure Balance

For the diffusion of low-energy matter into antimatter and vice versa, a crude first approach is now made as follows:

(i) The low-energy matter and antimatter densities are assumed to be $n_m \equiv n_i^+ \approx n_e^-$ and $n_a \equiv n_i^- \approx n_e^+$, i.e. we neglect the differences $n_i^+ - n_e^-$ and $n_i^- - n_e^+$ due to the presence of the high-energy components as well as those which arise in an ambiplasma due to the presence of several particle species of both polarities.

(ii) With respect to the pressure-driven diffusion of matter across the magnetic field $\underline{B}$, there are two regions, (I) and (II) , the solutions in which have to be matched at the interface $x = 0$. In region (I) defined by $x < 0$ the annihilation reactions are neglected, and a quasi-neutral matter plasma having the average temperature T_∞ is diffusing in the positive x direction to compensate for the losses of matter caused by annihilation. In region (II) defined by $x \geq 0$ also an antimatter plasma of density $n_{ao} \approx$ const. is present, and the matter plasma having the average temperature T_o diffuses here towards the positive x direction, under the simultaneous action of annihilation reactions. The pressure--driven diffusion of antimatter leads to an analogous situation with respect to the reversed x direction.

With these simplifications eqs.(1) and (2) of the low-energy matter components reduce and combine to

$$v_{mx} = -(2kk_n/B^2T^{1/2})\frac{dn_m}{dx} \tag{24}$$

$$\frac{d}{dx}\left(n_m\frac{dn_m}{dx}\right) = Cn_m \quad ; \quad C = n_{ao}\alpha B^2T^{1/2}/2kk_n \tag{25}$$

where v_{mx} is the diffusion velocity and $k_n = 129(\ell n\Lambda)$ as given by Spitzer [9]. We introduce $n_{mo} \equiv n_m(x = 0)$, match the densities n_m and particle fluxes $n_m v_{mx}$ of the solutions of eq. (25) at the interface $x = 0$, and obtain

$$n_{mo}/n_o = \left[1 - 4\frac{x}{x_o}(T_\infty/T_o)^{1/2}\right]^{1/2} \text{ in region (I)} \tag{26}$$

$$n_{mo}/n_o = \left(\frac{x}{x_o} - 1 \right)^2 \quad \text{in region (II)} \tag{27}$$

where

$$x_o = (6n_o/C)^{1/2} = (12kk_\eta n_{mo}/n_{ao}\alpha B^2\sqrt{T_o})^{1/2} \tag{28}$$

Since we expect $T_\infty << T_o$ it is seen from eqs. (26) and (27) that the matter density decreases slowly in the x direction of region (I), and then has a steep descent in region (II) within a distance x_o. In the present simplified model the boundary layer thickness thus becomes $2x_b \approx 2x_o$ as given by eq. (28). Anomalous diffusion should increase x_o, which effect can be taken into account in a semi-empirical way by increasing the equivalent value of k_η in eq. (28). It should finally be observed that x_o is a slow function of T_o and becomes nearly independent of n_o when n_{mo} and n_{ao} are of the same order of magnitude.

4.3. A Numerical Example

The present theory is now illustrated by a numerical example where a characteristic density $n_{mo} \approx n_{ao} = 10^6\ m^{-3}$ of the low-energy components is assumed, as well as a magnetic field strength $B = 10^{-8}$ tesla. Then, eq. (20) yields a temperature $\hat{T}_e \approx 5 \times 10^{11} K$ of the high-energy components. According to eqs. (21)-(23) this leads to an upper temperature limit $T_{emax} \approx 10^9 \hat{n}/n$ of the low-energy components, where $\hat{n}/n$ stands for the ratio between the high- and low-energy component densities. Further, eq. (28) yields a layer thickness $x_o \approx 5 \times 10^8/T_o^{1/4}$ m, the maximum beta value becomes $\beta_{max} \simeq 10^{-6} T_o$, and the ratio between the maximum ion Larmor radius and the layer thickness is $a_{imax}/x_o \simeq 3 \times 10^{-7} T_o^{3/4}$. In region (I), far away from the boundary layer, there is only heat input into the plasma by thermal conduction from the boundary layer, and the average temperature T_∞ is therefore expected to become several orders of magnitude smaller than T_o . Finally, the efficiency of transfer of annihilation energy to the low-energy electrons and positrons defined by eq. (10) becomes $f_b \simeq 10^{-3} \hat{n}/n$ in the boundary layer.

Consequently, from the present example the matter and antimatter densities are expected to vary slowly in the regions far away from the boundary layer, and should drop steeply within the same layer which has a characteristic thickness of the order of $x_o \simeq 10^7$ m when $10^5 < T_o < 10^8$ K. Further, with the present data $a_{imax} < x_o$. Concerning the beta value, the situation becomes somewhat critical, and a pressure balance by a magnetic field $B \simeq 10^{-8}$ tesla at a density $n_{mo} \simeq 10^6\ m^{-3}$ should only exist when $T_o \lesssim 10^6$ K. Possibly excitation radiation and bremsstrahlung from small amounts of heavier elements, as well as losses due to anomalous diffusion, may lower the temperature T_o .

5. Conclusions

The present paper rather serves the purpose of outlining the problems associated with the ambiplasma balance of quasi-steady matter-antimatter boundary layers than of presenting a rigorous theory. Thus, the present crude model has to be improved by taking into account the full quasi-neutral ambiplasma equations of the particle, momentum, and heat balance, and by discussing more in detail the possible influence of instabilities, anomalous transport phenomena, and impurities in a hydrogen ambiplasma. Provided that this does not change the essential features of the presents results, the following conclusions can be drawn about the existence of matter-antimatter boundary layers in interstellar space:

(i) The hydrogen ambiplasma has to be treated as a mixture of six species, including a high-energy component consisting of electrons and positrons as well as a low-energy component consisting of protons, antiprotons, electrons, and positrons.

(ii) At interstellar particle densities, no well-defined boundary layers are likely to exist in presence of neutral gas, nor should such layers be sustained in an unmagnetized fully ionized ambiplasma by the frictional drag between the ambiplasma species.

(iii) On the other hand, sharply defined boundary layers should under certain conditions exist in a magnetized ambiplasma. The fully ionized regions, being mainly occupied by low-energy matter and antimatter, then have to extend over distances being large compared to the penetration length of fast neutral particles. Further, the magnetic field should be strong enough for the beta value and the relative magnitude of the ion Larmor radius to be less than unity in the boundary layer. In such a case steep pressure drops of low-energy matter and antimatter can be balanced in the boundary layer by the magnetic field and the electric plasma currents, but not by the partial pressure gradients of the high-energy components.

(iv) The boundary layer thickness is of the order of $2x_o \approx 10/BT_o^{1/2}$ meters, where T_o is a characteristic temperature value of the low-energy components in the layer. Thus, x_o becomes approximately independent of the particle density and is a slow function of temperature in the range $10^5 < T < 10^8$ K. With $B = 10^{-8}$ tesla the layer thickness becomes about $2x_o \approx 10^7$ meters, which corresponds to a thin and well-defined transition region between matter and antimatter under cosmical conditions.

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Figure Caption

Fig.1. Crude outline of boundary layer separating matter from antimatter in the case of a fully ionized ambiplasma, situated in a strong magnetic field $\underline{B}$. Matter and antimatter diffuse from each of the regions $x \ll 0$ and $x \gg 0$ towards the central plane $x = 0$, to compensate for the loss of particles due to annihilation in the layer defined by $-x_b < x < x_b$.

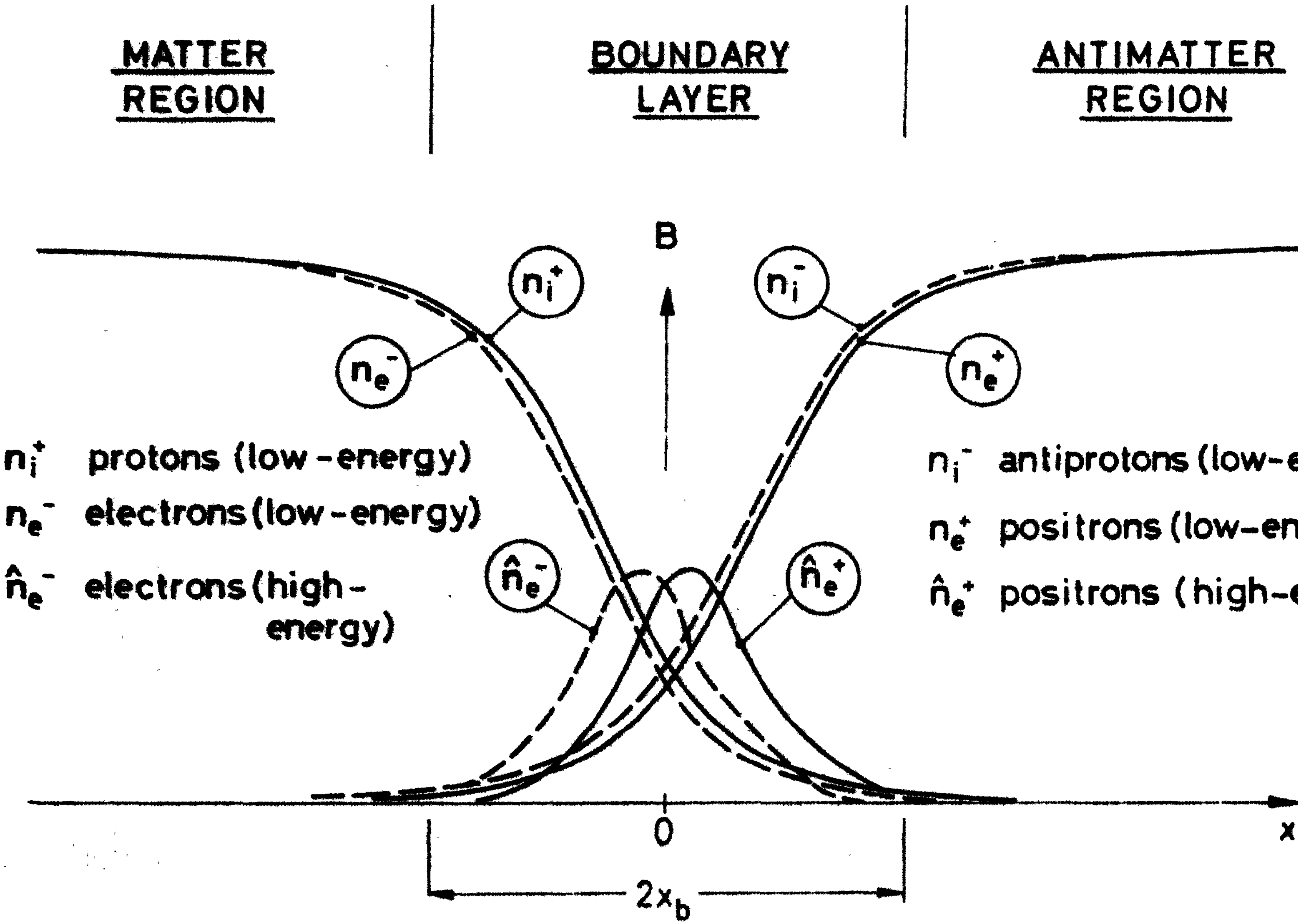
MATTER REGION
BOUNDARY LAYER
ANTIMATTER REGION
B
n_i^+
n_e^-
n_i^-
n_e^+
n_i^+ protons (low-energy)
n_e^- electrons (low-energy)
$\hat{n}_e^-$ electrons (high-energy)
$\hat{n}_e^-$
$\hat{n}_e^+$
n_i^- antiprotons (low-energy)
n_e^+ positrons (low-energy)
$\hat{n}_e^+$ positrons (high-energy)
0
x
$2x_b$

Fig. 1.

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Key words Cosmology, matter-antimatter annihilation, Leidenfrost layers, boundary layers.

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