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## ABSTRACT

A model has earlier been proposed for a boundary layer which separates a cloud of matter from one of antimatter in a magnetized ambiplasma. In this model steady pressure equilibrium ceases to exist when a certain beta limit is exceeded. The latter is defined as the ratio between the ambiplasma and magnetic field pressures which balance each other in the boundary layer. Thus, at an increasing density, the high-energy particles created by annihilation within the layer are "pumped up" to a pressure which cannot be balanced by a given magnetic field. The boundary layer then "disrupts". The critical beta limit thus obtained falls within the observed parameter range of galaxies and other large cosmical objects. Provided that the considered matter-antimatter balance holds true, this limit is thus expected to impose certain existence conditions on matter-antimatter boundary layers. Such a limitation may apply to certain cosmical objects and cosmological models. The maximum time scale for the corresponding disruption development has been estimated to be in a range from about $10^{-4}$ to $10^{2}$ seconds for boundary layers at ambiplasma particle densities in the range from $10^{4}$ to $10^{-2}$ $m^{-3}$, respectively.

## 1. Introduction

In their theory on the metagalaxy, Alfvén and Klein (1962) and Alfvén (1965) suggested that there exist regions of matter and antimatter which are separated by boundary layers with a very low rate of annihilation reactions. Simplified models of such layers have been established (Lehnert 1977, 1978) in which the matter-antimatter "ambiplasma" is immersed in a magnetic field being parallel to the layer surfaces. In the deductions of the models, the steady particle, momentum and heat balance equations have been used to estimate the relation between the high- and low-energy component densities, the high-energy component temperature, and the layer thickness.

This paper extends the layer analysis to the existence condition of a steady equilibrium state. Thus, it will be shown that, with the constraints of the earlier considered transport and radiation phenomena, limitation in the beta value (ratio between ambiplasma and magnetic field pressures) leads to a corresponding limitation in the high- and low-energy particle densities at a given characteristic magnetic field strength. The disruption of the matter-antimatter boundary layers at the critical beta value may have an application to a cosmological model of the plasma universe being proposed by Alfvén (1981,1986). According to this model there is a "Bigger Big Bang" turning point between contraction and expansion of the universe at which large amounts of annihilation energy are released.

## 2. Starting Points

In a first approach we recall the results of an earlier treated low-beta model including a unidirectional magnetic field as outlined in Fig.1 (Lehnert 1977). In principle the present deductions can be extended to a magnetic neutral sheet configuration (Lehnert 1978), but this case will not be discussed in detail here. As starting-points we thus introduce the following earlier derived relations between the layer parameters (see Lehnert 1977).

The particle balance (continuity) equation yields

$$\hat{n}_e^{+-} = -\frac{1}{2}(n_e^{+-} + N) + \left[\frac{1}{4}(n_e^{+-} + N)^2 + 2n_i^+ n_i^- (n_e^{+-} + N)\alpha_i/\alpha_e (n_e^{-+} + N)\right]^{1/2} \qquad (1)$$

where $n_i^+$, $n_i^-$, $n_e^-$ and $n_e^+$ denote the densities of low-energy protons, antiprotons, electrons and positrons, respectively, $\hat{n}_e^-$ and $\hat{n}_e^+$ stand for high-energy electrons and positrons, $\alpha_i \cong \alpha_e \cong 10^{-20} m^3/s$ are the rates of the proton-antiproton and electron-positron reactions, and $N = (n_e^+ + n_e^-)\hat{\rho}/\alpha_e$ with $\hat{\rho}$ being the rate of Coulomb collisions between the high-energy particles. The particle distributions $n_m(x) = n_i^+ \cong n_e^-$ and $n_a(x) = n_i^- \cong n_e^+$ of matter and antimatter in Fig.1 are assumed to be each other's images in the plane x=0, i.e. $n_m(-x) = n_a(x)$, and to have the characteristic value $n_\infty = n_m(-\infty) = n_a(+\infty)$ far away from x=0.

Further, the heat balance equation results in the expression

$$\hat{T}_o \cong \tau_o/\left[1 + c_o(B_o^2/n_o)\right] \qquad (2)$$

for the equivalent temperature of the high-energy electrons and positrons at the centre x=0. In this equation $\tau_o \cong 5\times10^{11}K$, $c_o = 10^{19} m/V^2 s^2$, $B_o$ is the characterisic magnetic field strength within the layer, $n_o \equiv n_m(0) = n_a(0)$ stands for the characteristic density of the low-energy components at the centre x=0 of the layer, and SI units are used throughout this paper.

Eq. (2) is mainly due to a balance between the released annihilation energy and the energy losses due to particle losses, bremsstrahlung and synchrotron radiation.

Finally, combination of the particle and momentum balance equations of the low-energy components leads to a relation for diffusion across the magnetic field, from which a layer thickness of the order of

$$x_o = (12kk_\eta/\alpha_i B_o^2\sqrt{T_o})^{1/2} \tag{3}$$

has been deduced in the low-beta case. Here $T_o$ is the characteristic temperature of the low-energy components within the boundary layer, and $k_\eta = 129\ (\ell n\Lambda)$ with $\Lambda$ standing for the ratio between the Debye distance and the Coulomb impact parameter. Thus, in this simplified model a tail of matter plasma diffuses into the antimatter plasma and vice versa, the corresponding tail thickness being of the order of $x_o$.

## 3. The Beta Limit

### 3.1. The Partial Pressure of the High-Energy Component

According to Eq.(2),the equivalent temperature $\hat{T}$ of the high-energy components should be of the order of some $10^{11}$K,which is much higher than the expected temperature $T$ of the low-energy components. We then have $\hat{\rho}/\alpha_e << 1$ and Eq. (1) yields $\hat{n}_e^{+-} \cong n_o$ at $x=0$. Further, in the present model the low-energy matter and antimatter densities $n_m(x)$ and $n_a(x)$ will nowhere exceed $n_o$ by orders of magnitude, i.e. the characteristic density $n_\infty$ far away from $x=0$ will become comparable to $n_o$, $\hat{n}_e^+(x=0)$ and $\hat{n}_e^-(x=0)$ as far as orders of magnitude are concerned.

Since $\hat{T}_o >> T_o$, the low-energy partial pressure $p = (n_m+n_a)kT$ becomes much smaller than the high-energy partial pressure $\hat{p} = (\hat{n}_e^+ + \hat{n}_e^-)k\hat{T}$. When discussing the pressure effects on the immersed magnetic field, $p$ can therefore be neglected as compared to $\hat{p}$.

### 3.2. The Existence Condition of Steady Equilibrium

In a simple one-dimensional model of a high-energy component plasma of pressure $\hat{p}(x)$ immersed in a field $\underline{B} = [0,0,B(x)]$ directed along $z$, the pressure balance is expressed by

$$\hat{p}(0) = \hat{p}(x) + [B^2(x) - B^2(0)]/2\mu_o \tag{4}$$

With $\hat{p} = 0$ and $B = B_\infty$ far away from the plane $x=0$, the highest possible pressure $\hat{p}(0)$ at the centre $x=0$ is given by $B(0)=0$, with a corresponding beta value $\beta = 2\mu_o\hat{p}(0)/B_\infty^2 = 1$. Thus $\beta$ is defined as the ratio between the ambiplasma and magnetic field pressures of the boundary layer.

When approaching the limit $\beta = 1$, part of the relations given in Section 2 become modified in two ways. First, the magnetic field strength $B_o$ within the layer then decreases much enough for the contribution from synchrotron radiation to become reduced in Eq.(2). Consequently we replace $c_o$ by $fc_o$ in Eq.(2) where $f$ is a dimensionless factor being smaller than unity. Second, the rate of low-energy particle diffusion is enhanced in regions close to the plane $x=0$. As in the case of a magnetic neutral sheet, however, the derived layer thickness $x_o$ should largely remain unaffected for $\beta$ close to unity (compare Lehnert 1978). This implies that in the present case we only have to replace $B_o$ by $B_\infty$ in Eq. (3) when making a first estimate of the layer thickness $x_o$.

Under these circumstances combination of Eqs. (2) and (4) results in an existence condition for equilibrium

$$\theta \equiv n_\infty / B_\infty^2 \leq \theta_c = (1/8\mu_o k T_o) + [(1/8\mu_o k T_o)^2 + (f c_o / 4\mu_o k T_o)]^{1/2} \quad (5)$$

where the critical beta limit corresponds to $\theta_c$. An illustration of relation (5) is given in Fig.2, as well as the corresponding layer thickness $x_o$ as a function of the field strength $B_\infty$ far away from the boundary layer. In the example of Fig.2 we have put f=0.25, say, which yields $\theta_c \simeq 5x10^{17}\sqrt{f}$ $m/V^2s^2$, and have introduced $T_o$=K in the expression for $x_o$.

### 3.3. The Time Scale of Disruption Development

When the critical value given by eq. (5) is exceeded, the boundary layer is expected to disrupt. As a consequence, the matter and antimatter low-energy regions then become mixed. The time scale of this process can be crudely estimated from the layer thickness of eq. (3), in combination with the Alfvén velocity $V_A = B_o/(\mu_o n_o m_i)^{1/2}$ in the low-energy proton and antiproton gases. With $n_o \simeq n$ and $B_o \simeq B_\infty$ as far as orders of magnitude are concerned, the time scale $t_c$ of disruptions can then be estimated from

$$t_c \simeq (12\mu_o k k_\eta m_i \theta_c^2 / \alpha_i n_\infty \sqrt{T_o})^{1/2} \quad (6)$$

at the critical beta limit given by condition (5). It has to be observed that $t_c$ represents the time scale of the initial phase of a disruption, being determined by the magnetohydrodynamic unbalance of the low-energy components. As soon as the matter and antimatter layers become mixed, the disruption rate is enhanced by the annihilation reactions. Consequently, Eq.(6) represents an upper limit of the time scale of the disruption development.

## 4. Discussion

The physical mechanisms behind the present beta limit can be summarized as follows. The released annihilation energy is shared by the light (high-energy) components and radiation only. Since the heat transfer by Coulomb collisions in a hot ambiplasma is comparatively inefficient, the low-energy particle temperature $T_o$ becomes many orders of magnitude smaller than the high-energy component temperature $\hat{T}_o$. Further, as a result of the particle balance, the high-energy component density $\hat{n}_o \equiv \hat{n}_e^+(0) = \hat{n}_e^-(0)$ at the layer centre x=0 does not differ by orders of magnitude from the low-energy component densities $n_o$ and $n_\infty$. Consequently, since $\hat{T}_o >> T_o$ and $n_o$ is not much larger than $\hat{n}_o$, the high-energy pressure $\hat{p}_o = \hat{n}_o k\hat{T}_o$ becomes much higher than the low-energy pressure $p = (n_m+n_a)kT$, for all values of x. In other words, at any chosen values of the low-energy matter and antimatter densities, a large high-energy pressure $\hat{p}_o$ is "pumped up" at the layer centre x=0. Finally, for a given magnetic field strength $B_\infty$, there is a beta limit $\theta_c$ above which no equilibrium becomes possible. Thus, when $\theta = n_\infty/B_\infty^2$ is made to exceed $\theta_c$ there does not exist a steady equilibrium state. The boundary layer then disrupts and the matter and antimatter regions become mixed.

Possibly there are also instability phenomena, not being discussed in this paper, due to which the layer balance becomes destroyed even before the equilibrium condition (5) is violated. This question has to be further examined.

Provided that the considered matter-antimatter balance holds true, the obtained beta limit would thus lead to certain existence conditions for matter-antimatter boundary layers. Concerning specific applications, the following points should be made:

(i) According to Alfvén and Fälthammar (1963), galactic magnetic field strengths $B_\infty$ of the order of $10^{-10}$ to $10^{-9}$ tesla are imaginable, but the estimates of such fields are as yet very uncertain. Presumably larger values of $B_\infty$, of the order of $10^{-8}$ tesla and more, become possible. Further, the observed galaxies, groups of galaxies, clusters, superclusters, and the metagalaxy, cover the ranges $10^{42}$ to $10^{48}$ kg in mass and $10^{20}$ to $10^{26}$ m in radius (Alfvén 1982). This corresponds to a characteristic particle density ranging from about $10^{-5}$ to $10^{7}$ $m^{-3}$.

These data are within the ranges outlined in Fig.2. They also correspond to an estimated layer thickness $x_o$ being much smaller than the characteristic dimensions of the considered cosmical objects, and being larger than the characteristic ion Larmor radius $a_i \cong 3\times10^{-7}\sqrt{A}T_o^{3/4}x_o$ (Lehnert 1977). Within the applicability of the present model, we thus expect beta limitation to occur in cases where matter-antimatter boundary layers exist for such objects.

(ii) The present results are not changed even by a considerable increase in the assumed low-energy component temperature $T_o$, provided that $T_o$ remains much smaller than $\hat{T}_o \cong 5\times10^{11}$K.

(iii) When the beta limit of condition (5) is exceeded, the matter-antimatter system is expected to become subject to a catastrophic event at which large quantities of annihilation energy are released.

(iv) In the diagram given by Alfvén (1982) for the mass-radius distribution of cosmical objects, there is a gap between galaxies and stars i.e. there are hardly any galaxies with a mass $M \lesssim 10^{42}$kg and a radius $R \lesssim 10^{21}$m. This limit corresponds to a maximum particle density of about $10^4 m^{-3}$. Applying this value to the beta limit of $n_\infty$ given by condition (5) and Fig.2, the resulting magnetic field strength becomes $B_\infty \simeq 3\times10^{-7}$ tesla. This corresponds to a layer thickness $x_o = 10^6$m at $T_o = 10^4$K.
To establish matter-antimatter boundary layer equilibrium in galaxies having larger particle densities, and presumably smaller mass and radius, unrealistically strong magnetic fields, of some $10^{-6}$ tesla, would thus have to be required. Further investigations are necessary to examine whether this high-density limit of galaxies becomes related to the beta limit discussed here. Also applications to other cosmical objects have to be discussed.

(v) In the "Bigger Big Bang" model proposed by Alfvén (1981,1986) a contracting universe can consist of regions of koinomatter and antimatter which are separated by matter-antimatter boundary layers. When the universe contracts, its characteristic particle density $n_\infty$ increases. Provided that characteristic value of $B_\infty^2$ increases less rapidly than $n_\infty$ during the contraction, the boundary layers would then disrupt at the critical beta value of equation (5). Large amounts of annihilation energy are then released at the turning point between contraction and expansion. This scenario has, however, to be further analysed with respect to the variations of the magnetic field strength during the contraction, and to possible normal or anomalous dissipation mechanisms which may affect the corresponding electric currents in the ambiplasma.

(vi) With $n_\infty$ ranging from $10^{-2}$ to $10^4 m^{-3}$ and $T_o$ from $10^4$ to $10^6$ K the magnetohydrodynamic time scale $t_c$ of the disruptions would range from about 300 s to $10^{-4}$ s. The visible onset of a corresponding matter-antimatter "explosion" could, of course, appear at a shorter time scale than $t_c$, because the corresponding mixing process and the resulting annihilation reactions may increase in an avalanche-like and nonlinear manner. In this connection it should be noticed that bursts of gamma rays have been observed on a time scale of microseconds to seconds (Alfvén 1986).

All these estimates have, of course, to be taken with care, because of the uncertainties of the involved parameters.

## 5. Acknowledgements

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## Figure Captions

Fig.1. Crude outline of a boundary layer separating matter from antimatter in the case of a fully ionized ambiplasma situated in a magnetic field $\underline{B}$ (Lehnert 1977). Matter and antimatter diffuse towards the central plane x=0, to compensate for the loss of particles due to annihilation.

Fig.2. Parameter values at the beta limit for f=0.25. The figure shows the characteristic density $n_\infty=n_m(-\infty)=n_a(+\infty)$ of low-energy matter and antimatter far away from the plane x=0, and the characteristic layer thickness $x_o$, as functions of the strength $B_\infty$ of the undisturbed magnetic field at $x = \pm\infty$. The values of $x_o$ correspond to a characteristic temperature $T_o=10^4$ of the low-energy components within the boundary layer.

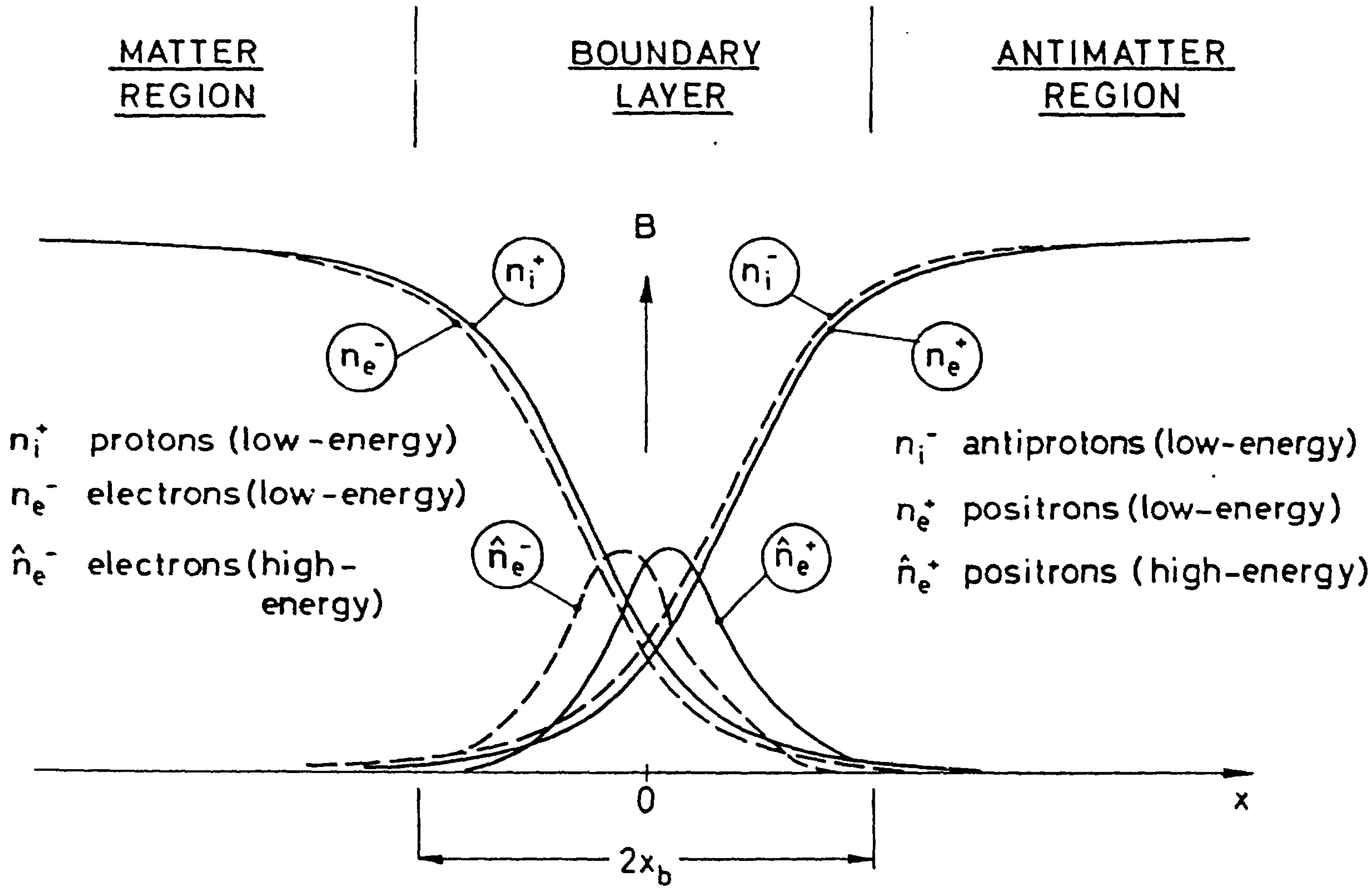
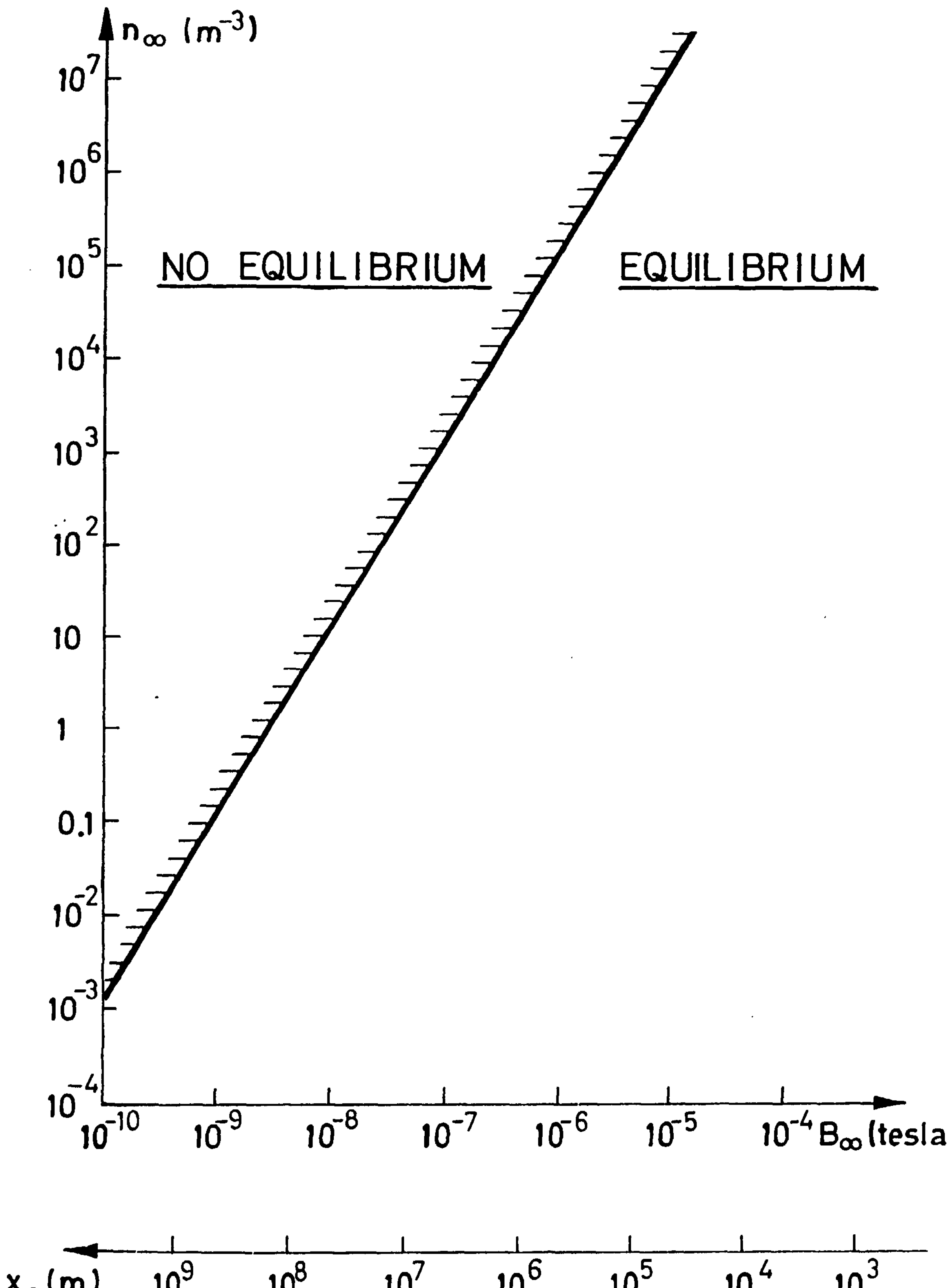

MATTER REGION
BOUNDARY LAYER
ANTIMATTER REGION
B
$n_i^+$
$n_e^-$
$n_i^-$
$n_e^+$
$\hat{n}_e^-$
$\hat{n}_e^+$
$n_i^+$ protons (low-energy)
$n_e^-$ electrons (low-energy)
$\hat{n}_e^-$ electrons (high-energy)
$n_i^-$ antiprotons (low-energy)
$n_e^+$ positrons (low-energy)
$\hat{n}_e^+$ positrons (high-energy)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

Fig. 1

Fig. 2



n∞ (m⁻³)
10^7
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^-2
10^-3
10^-4
NO EQUILIBRIUM
EQUILIBRIUM
10^-10
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4
B∞ (tesla)
x0 (m)
10^9
10^8
10^7
10^6
10^5
10^4
10^3

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A model has earlier been proposed for a boundary layer which separates a cloud of matter from one of antimatter in a magnetized ambiplasma. In this model steady pressure equilibrium ceases to exist when a certain beta limit is exceeded. The latter is defined as the ratio between the ambiplasma and magnetic field pressures which balance each other in the boundary layer. Thus, at an increasing density, the high-energy particles created by annihilation within the layer are "pumped up" to a pressure which cannot be balanced by a given magnetic field. The boundary layer then "disrupts". The critical beta limit thus obtained falls within the observed parameter ranges of galaxies and other large cosmical objects. Provided that the considered matter-antimatter balance holds true, this limit is thus expected to impose certain existence conditions on matter-antimatter boundary layers. Such a limitation may apply to certain cosmical objects and cosmological models. The maximum time scale for the corresponding disruption development has been estimated to be in a range from about $10^{-4}$ to $10^{2}$ seconds for boundary layers at ambiplasma particle densities in the range from $10^{4}$ to $10^{-2}$ $m^{-3}$, respectively.

**Key words: Magnetized ambiplasma, boundary layers.**