SOCIETÀ ITALIANA DI FISICA

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SCUOLA INTERNAZIONALE DI FISICA «ENRICO FERMI»

XXIV Corso

Le ricerche spaziali e il sistema solare

ACADEMIC PRESS · NEW YORK AND LONDON

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XXIV CORSO

a cura di B. ROSSI
Direttore del Corso

VARENNA SUL LAGO DI COMO
VILLA MONASTERO
4-16 GIUGNO 1962

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ACADEMIC PRESS • NEW YORK AND LONDON

ACADEMIC PRESS INC.
111 FIFTH AVENUE
NEW YORK 3, N. Y.

United Kingdom Edition
Published by
ACADEMIC PRESS INC. (LONDON) LTD.
BERKELEY SQUARE HOUSE, LONDON W. 1

Library of Congress Catalog Card Number: 63-20571

PRINTED IN ITALY

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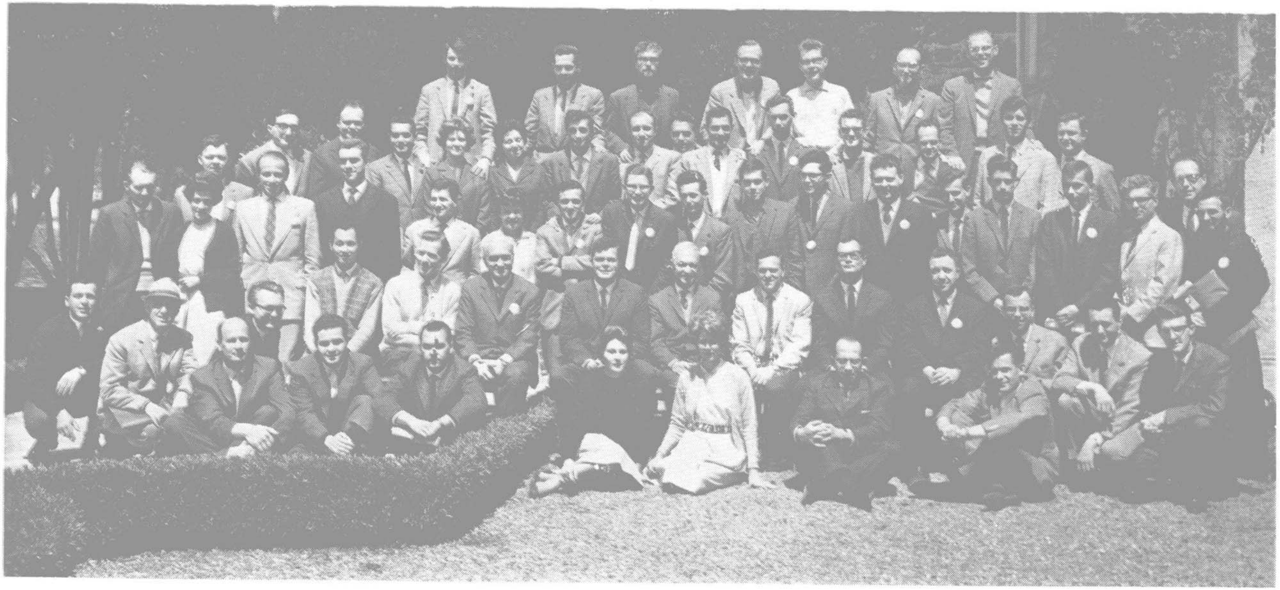

Tipografia Compositori - Bologna - Italy

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Introduction.

B. Rossi

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When, one and one-half years ago, Professor Polvani, asked me to organize a Summer School on Space Physics, I felt quite flattered, but, at the same time, rather concerned. For the scope of Space Science is almost as wide as the scope of Science itself; there are a space physics, a space geophysics, a space astronomy, a space biology. In fact one may add the prefix « space » to the name of practically any branch of Science. Obviously it was not possible to cover such a wide variety of subjects in two weeks, neither did I have the competence to plan a course of this kind. Thus, I suggested, and it was agreed, that the scope of the course should be limited to problems concerning the solar system, of which, of course, our own planet is a most important component, at least as far we are concerned. On this basis, Dr. Olbert and I set out to prepare a program and to persuade the scientists whom we thought were most competent and effective to lecture on the selected topics. I am sure you will give us credit for having been notably successful in this effort, and I would like to take this occasion to thank the lecturers for having so kindly accepted our invitation.

Let me take a few minutes of your time to outline in general terms the problems to be discussed in these two weeks.

I, for one, have been impressed by the fact that, as we learn more and more about the solar system, the boundaries between the objects of which it is formed become less and less sharp, and the whole of it appears more and more as a single unit. The space between the sun and the planets is no longer believed to be empty. Rather it is known to be filled by an ionized gas, or plasma, which presumably originates from the sum. The density of the gas is so low that one of its ions will travel distances of the order of the astronomical unit before colliding with another ion. And yet this plasma is held together by the long-range electromagnetic forces so tightly that it does not behave like an assembly of independent particles, but rather like a continuous medium. In fact, the Debye length, which is, in a way, a measure of the minimum dimensions of the cells in which we must subdivide a plasma before it ceases to appear as a continuous medium, is only of the order of meters.

There is no clear separation between the sun and the interplanetary medium; *i.e.*, without making an arbitrary decision, we cannot draw a surface and say that what lies inside of it is the sun and what lies outside is the interplanetary medium. In fact, we may well regard the interplanetary medium, in which the earth and the other planets revolve, as an extension of the solar atmosphere.

An important feature of the interplanetary medium is its magnetic field. In a vacuum or in ordinary matter, magnetic-field lines are merely a mathematical fiction; a convenient way of mapping the field, of representing graphically its strength and its direction in a given region of space. In a plasma, on the contrary, magnetic-field lines acquire a physical reality. They are « frozen » into the plasma and partake of its motions. Fast moving charged particles will spiral around them and thus will be guided by the magnetic-field lines as by invisible rails stretched through space. Presumably interplanetary plasma flows from the sun, stretching out the lines of force of the sun's magnetic field. As long as these lines remain connected with the sun's surface, they provide a path along which high-energy particles of solar origin may freely travel.

While it is difficult to define in an objective and unambiguous manner a boundary between the sun and the interplanetary medium, the separation between this medium and our own planet also poses a delicate question.

Starting from the earth's surface, we find first the *atmosphere*, which clearly belongs to the earth's environment. It is formed by gases that filter through the earth's crust, of those that originate from inorganic chemical reactions or from the metabolism of living organisms; it contains perhaps a residue of the original terrestrial atmosphere. It is held in place by the gravitational attraction of the earth.

Above the atmosphere, whose upper layers, strongly ionized by ultraviolet and X-rays from the sun, form the so-called *ionosphere*, lies a vast region, extending to several earth radii, which is often loosely described as the *magnetosphere.* This region is populated by charged particles, mainly electrons and protons with superthermal energies, which are held in the vicinity of the earth not by the gravitational, bur rather by the magnetic field of the earth. They form the great *radiation belts*, whose discovery has been the first striking accomplishment of space exploration.

Present experimental evidence seems to indicate that interplanetary plasma flows past the earth at *supersonic speed*; *i.e.*, at a speed greater that the Alfvén velocity or the modified sound velocity. The magnetic field of the earth offers an obstacle to this plasma flow; there should result the formation of a *bow* *wave*, pointing in the direction of the oncoming plasma. Beyond the wave, the plasma flows completely undisturbed by the presence of the earth and of its magnetic field; thus the space outside the wave front is certainly not part of our terrestrial environment. The flow of interplanetary plasma does not come to a stop at the front of the bow wave, but penetrates this front, undergoing more or less drastic changes in its velocity, density, temperature etc. However, it will not approach the earth beyond a certain distance. Thus, between the solid earth and the front of the bow wave there lies a surface enclosing a volume from which interplanetary plasma is excluded. This volume may be called the *geomagnetic cavity*. It clearly belongs to the terrestrial environment, while the volume between the geomagnetic cavity and the front of the bow wave may be regarded as a transition region between the earth's environment and the interplanetary medium.

An interesting question is whether the magnetosphere and the geomagnetic cavity are, in fact, one and the same thing. If we call magnetosphere the region of space where charged particles may be semipermanently trapped by the earth's magnetic field, the question reduces to the problem of the topological character of the magnetic field lines. If all magnetic field lines originating from the earth return to the earth, then the geomagnetic cavity coincides with the magnetosphere. If, however, some of the magnetic field lines of the earth's dipole connect with the field lines of interplanetary space, then the magnetosphere does not coincide exactly with the geomagnetic cavity.

* * *

Much of the material to be presented in the lectures and discussed in the seminars during the next two weeks will deal with the various problems to which I have just referred and with the contribution to the solution of these problems that space experiments have made or may be expected to make in the near future.

Dr. RIGHINI and Dr. LÜST will discuss the sun and its immediate surroundings. The sun has not yet been approached by space probes. However, rockets and artificial satellites have carried instruments beyond the opaque blanket of earth's atmosphere, and obtained preliminary but very significant results on the far ultraviolet and X-ray regions of the solar spectrum, previously entirely unknown.

Preliminary data on the interplanetary plasma were obtained with Soviet and with American space ships, notably with Explorer X, which also provided the first direct evidence for a well-defined geomagnetic cavity. These experimental results will be discussed in one of our seminars. The general problem of the interplanetary medium will form the subject of lectures by Dr. GOLD and Dr. LÜST. To lay the ground work for these lectures, Dr. LÜST will, at the beginning of the course, summarize for us the magneto-hydrodynamic theory of a dilute plasma.

As I mentioned before, an important feature of interplanetary space is its magnetic field. Space exploration has provided some preliminary information on this subject, which will be discussed at one of our seminars. Very significant information on the structure of the interplanetary magnetic field has been obtained also through the observation of energetic particles emitted from the sun and guided toward the earth by magnetic-field lines stretching out from the sun to the vicinity of our planet. This matter will be discussed by Dr. VAN ALLEN, in one of his lectures.

Dr. VAN ALLEN, of course, is the discoverer of the radiation belt and obviously no other scientist is better qualified than he to deal with this most important phenomenon. He will do so in two of his lectures and in one of the seminars, while some of the theoretical questions related to the radiation belt will be discussed Dr. HAYAKAWA. As you know, the radiation belt has been the subject of a very intensive investigation, both experimental and theoretical. As a result, we have a wealth of detailed information on the nature, the energy spectrum, and the directional distribution of the particles of which it is formed, as well as on the manner in which these properties vary with position and with time. We also have a fairly clear understanding of the dynamics of the trapped particles and of the effects responsible for the loss of these particles from the trapped orbits. However, we don't have an answer, as yet, to the problem concerning the origin of the radiation belt. As you know, decay of neutrons from the cosmic-ray albedo has been suggested as a possible injection mechanism of charged particles into trapped orbits, and it is quite likely that a substantial part of the radiation belt originates in this manner. But many of us find it difficult to believe that the whole of the radiation belt may be explained by neutron albedo. Other possible sources that have been suggested include injection into the magnetosphere of fast electrons and protons originating from the sun or local acceleration, through hydromagnetic disturbances, of electrons and protons already present in the magnetosphere.

* * *

Another substantial part of our course will deal with the solid bodies of the planets and the moon, and with the planetary atmospheres.

Through the use of space vehicles, important advances have already been made in our knowledge of the terrestrial atmosphere and ionosphere, and more are in the offing. Precise observations of the trajectories of artificial satellites have provided accurate measurements of the drag experienced by such vehicles, and these measurements in turn, have made it possible to evaluate the air density at altitudes of several hundred kilometers. One of the important results of these measurements was the discovery by JACCHIA of a variability in the air density related to the periodic changes of the solar activity due to the rotation of the sun.

Concerning the ionosphere, most of the data available until a few years ago were limited to the region below the ionization maximum (that occurs somewhat above 200 km). Most of these data had been obtained by means of ionospheric sounding based on the reflection by the ionosphere of radio signals from ground stations. Recently, direct measurements of electron and ion density above the ionization maximum have been carried out by means of probes installed aboard rockets and space vehicles. Other data have been obtained from the observation of the refraction of radio waves from transmitters carried by satellites, and from the analysis of whistler data. A most promising approach is the top-side sounding of the ionosphere, based on the observation of radio signals emitted by a satellite on a high orbit, and reflected back toward the satellite by the ionosphere below. We shall hear about these and other related matters from Dr. JASTROW, who will also deal with the atmospheres of the other planets and the ways in wyich space exploration will enable us to discover their composition and properties.

The structure of the earth, of the other planets and of the moon forms the subject of the lectures to be delivered by Dr. MCDONALD. This question, some aspects of which will be discussed by Dr. HAYAKAWA in one of his lectures, is of great scientific importance, in particular in connection with the problem of the origin of the solar system.

As you know, it was thought in the past that the planets had separed in primordial times from the incandescent mass of the sun and the moon from the incandescent mass of the earth. More recently, the « cold » origin of the solar system has gained favor, according to which the sun, the planets and the satellites have condensed separately from a primeval cold cloud of diffuse matter. These two theories, and their many variations, lead to different predictions concerning the composition and the « thermal history » of the planets and the moon. In turn the thermal conditions, both present and past, and the consequent degree of plasticity of the planetary or lunar material affect the shape of the planets and the moon, and the distribution of matter in their bodies.

Space missions have already yielded important information in this field. From the observational data on the trajectories of artificial earth's satellites it has been possible to determine accurately the equipotential surfaces of the earth's gravitational field. These results have revealed marked deviations of the shape of the earth from the theoretical spheroid to be expected in the case of a plastic body. The internal strength required to support the corresponding stresses is substantially greater than the earth was supposed to possess.

The shape of the moon is known to deviate from the equilibrium configuration even more than that of the earth. More accurate data than those now available are of vital importance. Hopefully, they may be secured by the observations of artificial satellites placed in close orbits around the moon.

Obviously a wealth of new and revealing information will become available when instruments, capable of relaying back information may be placed on the surface of the moon and the planets, and even more when man himself will be able to land on these celestial bodies and return safely upon the earth. But these achievements belong to the future and perhaps, when they have taken place, we may meet again in Varenna to discuss their results.

* * *

In addition to the lectures published in this volume of proceedings, following seminars were held:

T. Gold	*Magnetic Field in Space and Its Measurement.*
G. Righini	*Recent Experimental Results Regarding the Sun.*
G. McDonald	*Origin of the Solar System.*
B. Rossi	*Measurements of Interplanetary Plasma.*
R. Lüst	*Theory of Magnetic Storms.*
J. Van Allen	*Radiation Belts.*

Introduction to Plasma Physics.

R. Lüst

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1. – Introduction.

An ionized gas is called a plasma if it contains charged particles in such a large number that its properties are influenced in an essential way and determined by their presence.

In most cases we can regard the plasma as quasi-neutral, which means that the number of positive and negative charges are equal. The special properties of a plasma depend on the electromagnetic interaction of the particles themselves and with the external fields. The hydrodynamical properties are furthermore important, hence we have a coupling between hydrodynamical and electrodynamical phenomena.

The collective behaviour of a normal fluid is due to the short-range forces of the colliding particles. In the plasma, also the long-range Coulomb forces among the particles give rise to the collective behaviour, and these are often more important than the effect of the short-range forces.

The description of a plasma can be made in several different ways. One is the microscopic approach, based on the distribution functions of positive and negative charged particles. These distribution functions are determined by the respective Boltzmann equations. Certain effects, like for example the micro-instabilities, can be described only by this method. The description of a plasma based on this procedure is the most rigorous and complete one.

For a large number of phenomena, however, it is sufficient to represent the plasma from a macroscopic point of view, and describe it in terms of average quantities, like density, pressure, temperature and macroscopic velocity. This is equivalent to the use of the fluid theory.

We know from hydrodynamics that the fluid description holds only if a certain number of particles stays together for some time. The mechanism which provides this behaviour is the collisions among particles, and this means that the mean free path of the particles must be small compared to the characteristic length scale of the fluid.

In a number of practical cases this might not be the case, but if magnetic fields are present, the fluid model can still be used, since the charged particles are spiralling around the lines of force and are kept together at least perpendicularly to the magnetic field. The condition now which replaces the requirement of short mean free path for the validity of the fluid model is replaced by the requirement that the gyration radius of the particles be small compared to the dimensions of the system. In this case however one can no longer assume the pressure to be isotropic, but a pressure tensor has to be used.

In this introduction to plasma physics we will limit ourselves to the discussion of the macroscopic equations. In these two lectures we will assume them as given and shall analyse their structure, the importance of different terms, and certain applications of these equations. We can point out that the rigorous way of deriving these equations is to take moments of the Boltzmann equations for ions and electrons and performing averages on them. First, the so called one-fluid theory will be investigated, which is also known as magnetohydrodynamic approximation. In this approximation ions and electrons are not taken explicitly into account. Secondly we will consider the two-fluid theory and some of its complications. Thirdly we will discuss a model where the collisions are very infrequent and the pressure consequently is no longer isotropic.

2. – Magnetohydrodynamics.

2·1. – As already pointed out we may describe the plasma by combining the equations of electrodynamics and of hydrodynamics. In the following we will use Gaussian units and will not distinguish between $\boldsymbol{B}$ and $\boldsymbol{H}$ or $\boldsymbol{E}$ and $\boldsymbol{D}$, since as electrons and protons do not possess magnetic and electric susceptibilities $\mu = \varepsilon = 1$. Even complex ions would not give any noticeable effect. The only contribution from matter will be currents and space charges. The Maxwell equations will therefore be written as

$$\operatorname{curl}\boldsymbol{B} = \frac{4\pi}{c}\boldsymbol{j} + \frac{1}{c}\boldsymbol{E}\,, \tag{1}$$

$$\operatorname{curl}\boldsymbol{E} = -\frac{1}{c}\boldsymbol{B}\,, \tag{2}$$

$$\operatorname{div}\,\boldsymbol{E} = 4\pi\lambda\,, \tag{3}$$

$$\operatorname{div}\,\boldsymbol{B} = 0\,, \tag{4}$$

where $\boldsymbol{B}$, $\boldsymbol{E}$, $\boldsymbol{j}$, λ are the magnetic field, electric field, electric current density and charge density, respectively.

Maxwell equations are Lorentz-invariant, while the normal hydrodynamical equations are only Galilei-invariant. To have a consistent formulation and in order to avoid fictitious effects arising from inconsistent transformation rules we will make Maxwell equations also Galilei-invariant.

Let us have two reference systems Σ and Σ', the latter one moving with a constant velocity $\boldsymbol{w}$ with respect to the first one. Assuming $E^2 \ll B^2$ and neglecting the displacement current we apply the following nonrelativistic transformation rules:

$$\boldsymbol{B}' = \boldsymbol{B}\,, \tag{5}$$

$$\boldsymbol{E}' = \boldsymbol{E} + \frac{\boldsymbol{w}}{c}\cdot\boldsymbol{B}\,, \tag{6}$$

$$\boldsymbol{j}' = \boldsymbol{j}\,, \tag{7}$$

$$\lambda' = \lambda - \frac{\boldsymbol{w}\cdot\boldsymbol{j}}{c^2}\,, \tag{8}$$

$$\nabla' = \nabla\,, \tag{9}$$

$$\frac{\partial}{\partial t'} = \frac{\partial}{\partial t} + \boldsymbol{w}\cdot\boldsymbol{\nabla}\,. \tag{10}$$

It can now easily be shown that Maxwell equations are Galilei-invariant according to the above transformation rules. The displacement current can be neglected if the electric fields are small compared with magnetic fields and if the characteristic velocities in a plasma (for example the phase velocities of waves) are small compared with the velocity of light.

2˙2. – Maxwell equations have to be supplemented by a relation between the current density and the electric field. If $\boldsymbol{v}$ is the velocity of the plasma, this relation, Ohm's law for a moving fluid, has the form

$$\boldsymbol{j} = \sigma\left(\boldsymbol{E} + \frac{\boldsymbol{v}}{c}\times\boldsymbol{B}\right), \tag{11}$$

where the electric conductivity σ is a constant of the material. This equation also fulfills the above transformation rules.

2˙3. – The macroscopic velocity of the plasma is determined by the momentum equation of hydrodynamics, to which, however, we have to add a term to take into account the force exerted by the magnetic field on the plasma.

One way of deriving this force is through the energy equation for the electromagnetic field. This can be derived multiplying (11) by $\boldsymbol{j}$, and using (1) neglecting displacement current to obtain

$$\frac{j^2}{\sigma} = \frac{c}{4\pi}(\operatorname{curl}\boldsymbol{B}\cdot\boldsymbol{E}) + \frac{1}{c}(\boldsymbol{v}\cdot\boldsymbol{B}\times\boldsymbol{j}) \tag{12}$$

and combining this equation with the following vector identity:

$$\frac{c}{4\pi}\operatorname{div}(\boldsymbol{E}\times\boldsymbol{B}) = \frac{c}{4\pi}\boldsymbol{B}\cdot\operatorname{curl}\boldsymbol{E} - \frac{c}{4\pi}\boldsymbol{E}\cdot\operatorname{curl}\boldsymbol{B}\,. \tag{13}$$

Applying Maxwell eqs. (2) and (1) and adding, we obtain the energy equation

$$-\frac{1}{8\pi}\frac{\partial}{\partial t}B^2 = \frac{j^2}{\sigma} + \frac{1}{4\pi}\operatorname{div}(\boldsymbol{E}\times\boldsymbol{B}) + \frac{1}{c}(\boldsymbol{v}\cdot\boldsymbol{j}\times\boldsymbol{B})\,. \tag{14}$$

On the left-hand side we have the change in time of electromagnetic energy ($E^2 \ll B^2$) and the terms on the right-hand side are the dissipation of Joule heat, the divergency of the Poynting energy flux and the work done by the force of the magnetic field on the plasma, respectively. This force is

$$\boldsymbol{k} = \frac{1}{c}\boldsymbol{j}\times\boldsymbol{B}\,. \tag{15}$$

This force can also be written, making use of

$$\boldsymbol{k} = \frac{1}{4\pi}(\operatorname{curl}\boldsymbol{B}\times\boldsymbol{B}) \tag{16}$$

and using the expansion of the curl of a vector product

$$\boldsymbol{k} = -\frac{1}{8\pi}\operatorname{grad}B^2 + \frac{1}{4\pi}(\boldsymbol{B}\operatorname{grad})\boldsymbol{B}\,. \tag{17}$$

We may notice incidentally at this point that the magnetic force could have been derived from the Maxwell stress tensor $\overleftrightarrow{T}$

$$\boldsymbol{k} = \operatorname{div}\overleftrightarrow{T}\,, \tag{18}$$

where $\overleftrightarrow{T}$, in a system aligned with the magnetic lines of force is

$$\overleftrightarrow{T} = \begin{pmatrix} -\frac{1}{8\pi}B^2 & 0 & 0 \\ 0 & \frac{1}{8\pi}B^2 & 0 \\ 0 & 0 & \frac{1}{8\pi}B^2 \end{pmatrix}, \tag{19}$$

with a general element given by

$$T_{ik} = -\frac{1}{4\pi}\left(B_i B_k - \frac{1}{2} B^2 \cdot \delta_{ik}\right) \tag{20}$$

(δ_{ik} is the Kronecker delta).

The equation for conservation of momentum then becomes, neglecting viscosity,

$$\varrho \frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = -\operatorname{grad} p + \frac{1}{c}[\boldsymbol{j} \times \boldsymbol{B}] , \tag{21}$$

where ϱ is the mass density and p is the pressure.

2·4. – The mass density can be obtained from the equation of continuity for the mass

$$\frac{\partial \varrho}{\partial t} + \operatorname{div}(\varrho \boldsymbol{v}) = 0 \tag{22}$$

and the energy equation is the equation connecting density and pressure, which, neglecting viscosity and heat conduction, is

$$\frac{\mathrm{d}p}{\mathrm{d}t} = \gamma \frac{p}{\varrho}\frac{\mathrm{d}\varrho}{\mathrm{d}t} + \frac{\gamma - 1}{\varrho}\frac{j^2}{\sigma} , \tag{23}$$

whith γ representing as usual the ratio of specific heats.

2·5. – The quasi-neutrality of the plasma implies through (3) the smallness of the electric field. This means that N_p, the number density of protons is almost equal to N_e, the number density of the electrons, so that at any point the relation

$$\frac{\lambda}{e} = |N_p - N_e| \ll N_p + N_e \tag{24}$$

holds.

This condition will be violated for a plasma at thermal equilibrium at distances which are small compared with the Debye length

$$h = \sqrt{\frac{kT}{4\pi N e^2}} = 12 \sqrt{\frac{T\ (^\circ\mathrm{K})}{N\ (\mathrm{cm}^{-3})}} . \tag{25}$$

We can therefore redefine a plasma as a gas where the characteristic length is larger than the Debye length. If deviation from quasi-neutrality would occur