PHYSICS OF IONIZED GASES

BORIS M. SMIRNOV
Russian Academy of Sciences

With the editorial collaboration of Howard R. Reiss

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This book is printed on acid-free paper. ♾

Published simultaneously in Canada.

Library of Congress Cataloging in Publication Data:

Smirnov, B. M. (Boris Mikhailovich), 1938-
Physics of ionized gases / Boris M. Smirnov
p. cm
Includes bibliographical references and index
ISBN 0-471-17594-3 (cloth : alk. paper)
1. Plasma (Ionized gases) I. Title.

QC718.S5635 2001
530 21.--dc'4 00-047761

Printed in the United Kingdom

10 9 8 7 6 5 4 3 2 1

CONTENTS

3 THE IDEAL PLASMA 36

4 ELEMENTARY PLASMA PROCESS 45

5 PROCESSES INVOLVING CHARGED PARTICLES 63

6 RAREFIED AND DENSE PLASMAS 77

9 PHYSICAL KINETICS OF GASES AND PLASMAS 123

10 TRANSPORT PHENOMENA IN GASES 147

11 CHARGED-PARTICLE TRANSPORT IN GASES 164

12 SMALL PARTICLES IN PLASMAS 177

13 PLASMA IN EXTERNAL FIELDS 205

PREFACE

This book is based on lecture courses on plasma physics given by the author in various educational institutions in Russia and other countries during the last thirty years. The courses were intended for both beginning and advanced graduate students in the physics and engineering professions. The notes for these lectures are the basis for eight previous books on the physics of ionized gases. The present book uses some of the material of the earlier ones, but many new developments in the physics of ionized gases and plasmas are included here.

The main goal of the book is to acquaint the reader with the fundamental concepts of plasma physics. It can be useful both for students and for mature scientists who work in diverse aspects of this area of investigation. The book is designed to preserve the level of sophistication of contemporary theoretical plasma physics, while at the same time using simple, physically motivated descriptions of the problems. These requirements may seem to be contradictory. Nevertheless, the author tried to achieve these goals by using limiting cases of problems to reduce the obscuring complexity of fully general treatments, and to employ simple models that have proven their value. It has been found possible to expound the contemporary state of the physics of ionized gases in a relatively accessible form.

A small part of the book where an introduction to some problems is given (as in Chapter 1) contains an entirely qualitative description. In the main part of the book, guided by the insight of specialists, the author avoids an overly descriptive approach to the problems treated. In this way, attention can be focused on the fundamental physics of the problems treated to allow the reader to develop his independent insight into the details, while preserving the modern level of understanding of these problems.

Since this book presupposes the active participation of the reader, it contains up-to-date information in the text ot its tables and in the appendices. The bibliography is selected to allow one to study in detail specialized subjects in this area of investigation. Because some chapters of the book relate to distinct applications of plasma physics, portions of these chapters may be studied independently of other chapters.

The author thanks Professor Howard R. Reiss, who prepared the excellent English version of this book.

BORIS M. SMIRNOV

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CHAPTER 1

PLASMA IN NATURE AND IN LABORATORY SYSTEMS

1.1 PLASMA AS A STATE OF MATTER

The name "plasma" was introduced into physics in the 1920s to describe a conducting gas. Charged particles in a conducting gas result from detachment of electrons from atoms or molecules. In order to understand the conditions for the existence of such a system, we compare it with an ordinary chemical system. Let us consider, for example, atmospheric air, consisting mainly of nitrogen and oxygen molecules. At high temperatures, along with the nitrogen and oxygen, nitrogen oxides can be formed. The following chemical equilibrium is maintained in air:

$$N_2 + O_2 \leftrightarrow 2NO - 41.5\,\text{kcal/mol}. \tag{1.1}$$

Here and below, the sign ↔ means that the process can proceed either in the forward or in the reverse direction. According to the *Le Chatelier principle*, an increase in the temperature of the air leads to an increase in the concentration of the NO molecules.

A similar situation takes place in the case of formation of charged particles in a gas, but this process requires a higher temperature. For example, the ionization equilibrium for nitrogen molecules has the form

$$N_2 \leftrightarrow N_2^+ + e - 360\,\text{kcal/mol}. \tag{1.2}$$

Thus, the chemical and ionization equilibria are analogous, but ionization of atoms or molecules proceeds at higher temperatures than chemical transformations. To illustrate this, Table 1.1 contains examples of chemical and

TABLE 1.1. Temperatures Corresponding to Dissociation of 0.1% of Molecules or Ionization of 0.1% of Atoms at a Pressure of 1 atm

Chemical Equilibrium	T, K	Ionization Equilibrium	T, K
$2CO_2 \leftrightarrow 2CO + O_2$	1550	$H \leftrightarrow H^+ + e$	7500
$H_2 \leftrightarrow 2H$	1900	$He \leftrightarrow He^+ + e$	12000
$O_2 \leftrightarrow 2O$	2050	$Cs \leftrightarrow Cs^+ + e$	2500
$N_2 \leftrightarrow 2N$	4500		
$2H_2O \leftrightarrow 2H_2 + O_2$	1800		

ionization equilibria. This table gives the temperatures at which 0.1% of molecules are dissociated in the case of chemical equilibrium or 0.1% of atoms are ionized for ionization equilibrium. The pressure of the gas is 1 atm. Thus, a weakly ionized gas, which we shall call a *plasma*, has an analogy with a chemically active gas. Therefore, though a plasma has characteristic properties which we shall describe, it is not really a new form or state of matter as is often asserted.

In most actual cases a plasma is a weakly ionized gas with a small degree of ionization. Table 1.2 gives some examples of real plasmas and their parameters—the number densities of electrons (N_e) and of atoms (N_a), the temperature (or the average energy) of electrons (T_e), and the gas temperature (T). In addition, some types of plasma systems are given in Figs. 1.1 and 1.2.

It is seen that generation of an equilibrium plasma requires strong heating of a gas. One can create a conducting gas by heating the charged particles only. This takes place in gaseous discharges when an ionized gas is placed in an external electric field. Moving in this field, electrons acquire energy from the field and transfer it to the gas. As a result, the mean electron energy may exceed the thermal energy of neutral particles of the gas, and the electrons can produce the ionization which is necessary for maintaining an electric current in the system. Thus, a gaseous discharge is an example of a plasma which is maintained by an external electric field. If the temperatures of electrons and neutral particles are identical, the plasma is called an *equilibrium* plasma; in the opposite case we have a *nonequilibrium* plasma. Figure 1.3 gives some examples of equilibrium and nonequilibrium plasmas.

TABLE 1.2. Parameters of Some Plasmas[a]

Type of Plasma	N_e, cm^{-3}	N, cm^{-3}	T_e, K	T, K
Sun's photosphere	10^{13}	10^{17}	6000	6000
E-layer of ionosphere	10^5	10^{13}	250	250
He–Ne laser	3×10^{11}	2×10^{16}	3×10^4	400
Argon laser	10^{13}	10^{14}	10^5	10^3

[a] N_e, N are the number densities of electrons and neutral atomic particles respectively, and T_e, T are their temperatures.

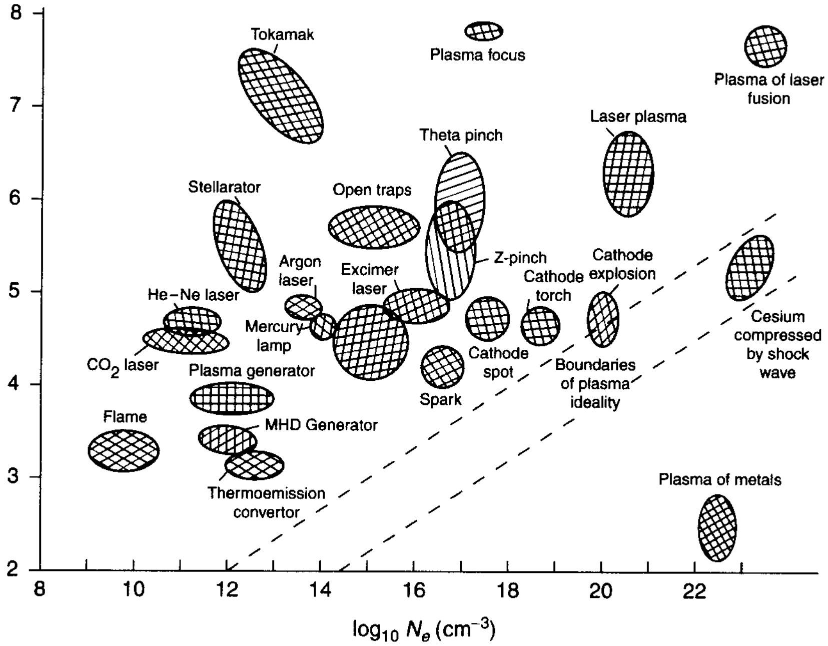

Figure 1.1 Parameters of laboratory plasmas.

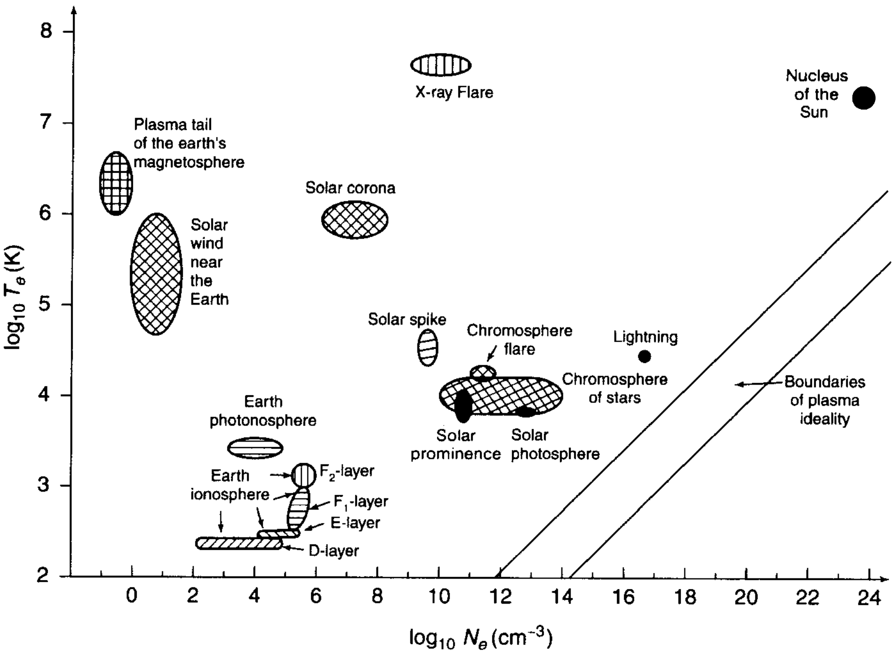

Figure 1.2 Parameters of plasmas found in nature.

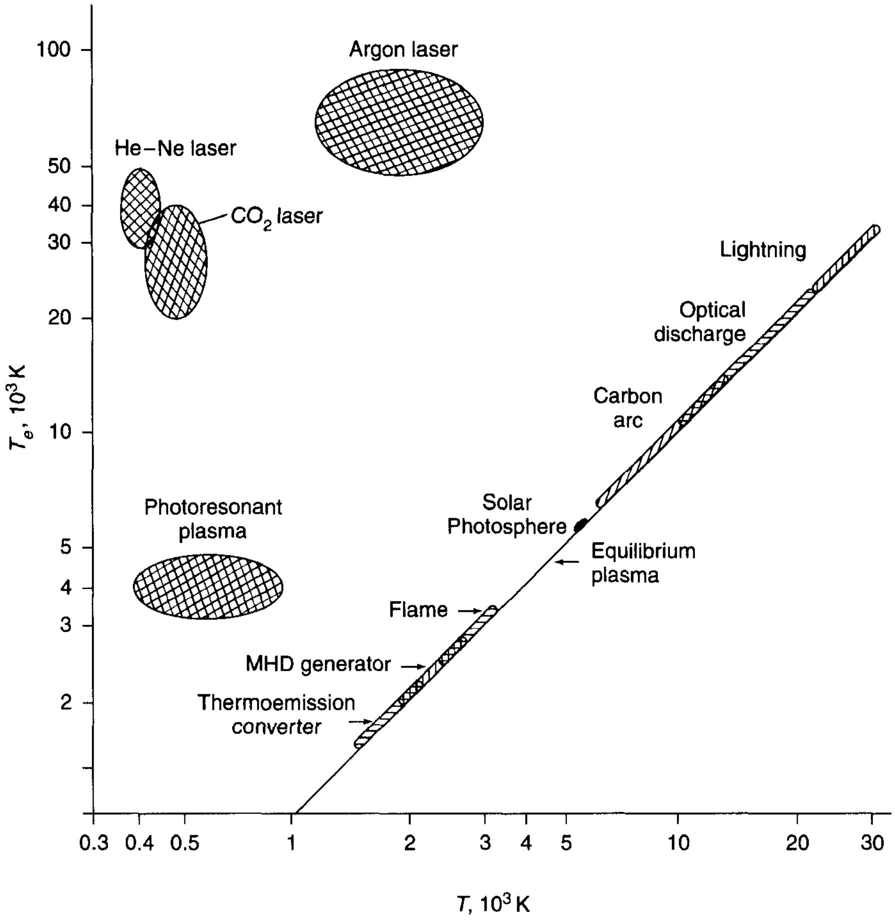

Figure 1.3 Electron and gas temperatures of laboratory plasmas. The straight line corresponds to the equilibrium plasma whose electron and gas temperatures are the same.

Thus, plasma as a physical object has definite properties that characterize it. The presence of charged particles makes possible various types of interaction with external fields that lead to a special behavior of this object, which is absent in ordinary gaseous systems. Furthermore, it creates a variety of means for generation and application of plasmas, which will be considered below.

1.2 METHODS OF PLASMA GENERATION

Let us review methods of plasma generation. The simplest method uses the action of an external electric field on a gas to produce electrical breakdown of the gas. Gaseous discharge and gas discharge plasma have a long history.

We can date the start of its study from 1705, when the English scientist Francis Hauksbee made an electrostatic generator whose power allowed him to study luminous electric discharges in gases. In 1734, Charles Francois de Cisternay Dufay (France) discovered that air is conducting in the vicinity of hot bodies. In 1745, E. J. von Kleist (Germany) and P. V. Musschenbroek (Netherlands) constructed independently a type of electric capacitor named the Leyden jar. It made possible the study of electrical breakdown in air. In 1752, the American scientist and statesman Benjamin Franklin created a theory of lightning on the basis of experiments. He considered the phenomenon to be a flow of electricity in accordance with its contemporary understanding. Thus, the above investigations gave the first understanding of the processes of passage of electric charges through gases, and were connected more or less with gaseous discharges.

A gas-discharge plasma is a common form of plasma which can have a variety of parameters. It can be either stationary or pulsed, depending on the character of the external fields. An external electric field may cause electrical breakdown of gas, which then generates different forms of plasma depending on the conditions of the process. In the first stage of breakdown, a uniform current of electrons and ions may arise. If the electric field is not uniform, an ionization wave can propagate in the form of an electron avalanche streamer. In the next stage of the breakdown process, the electric current establishes a distribution of charged particles in space. This is a gaseous discharge, which can exist in a variety of forms.

After the external electric field is switched off, the plasma decays as a result of recombination of electrons with ions, and spatial diffusion of the plasma occurs. Plasma in these conditions is called an *afterglow* plasma, and is used for study of recombination and diffusion processes involving charged and excited atoms.

A convenient way to generate plasma uses resonant radiation, that is, radiation whose wavelength corresponds to the energy of atomic transitions in the atoms constituting the excited gas. As a result of the excitation of the gas, a high density of excited atoms is formed, and collision of these atoms leads to formation of free electrons. Thus the atomic excitation in the gas leads to its ionization and to plasma generation. This plasma is called a *photoresonant* plasma. The possibility of generating such a plasma has improved with the development of laser techniques. In contrast to a gas discharge plasma, a photoresonant plasma is formed as a result of excitations of atoms and therefore has special properties. In particular, the temperature of the excited atoms can be somewhat in excess of the electron temperature. This plasma has various applications: it is used for generation of multicharged ions, as a source of acoustic waves, and so on.

A laser plasma is created by laser irradiation of a surface and is characterized by parameters such as the laser power and the time duration of the process. In particular, if a short (nanosecond) laser pulse is focused onto a surface, material evaporates from the surface in the form of a plasma. If the number density of its electrons exceeds the critical density (in the case of a neodymium laser, where the radiation wavelength is 1.06 μm, this value is 10^{21} cm^{-3}), the evolving plasma screens the radiation, and subsequent laser radiation goes to heating the plasma. As a result, the temperature of the plasma reaches tens of electron volts, and this plasma can be used as a source of X-ray radiation or as the source of an X-ray laser. Laser pulses can be compressed and shortened to $\approx 2 \times 10^{-14}$ s. This makes possible the generation of a plasma during very short times, and it permits the study of fast plasma processes.

If the laser power is relatively low, the evaporating material is a weakly ionized vapor. Then, if the duration of the laser pulse is not too short (more than 10^{-6} s), there is a critical laser power (10^7–10^8 $\mathrm{W/cm^2}$) beyond which laser radiation is absorbed by the plasma electrons, and *laser breakdown* of the plasma takes place. For values of the laser power smaller than the critical value, laser irradiation of a surface is a method for generating beams of weakly ionized vapor. This vapor can be used for formation and deposition of atomic clusters.

A widely used method of plasma generation is based on the passage of electron beams through a gas. Secondary electrons can then be used for certain processes. For example, in *excimer lasers*, secondary electrons are accelerated by an external electric field for generation of excited molecules with short lifetimes. The electron beam as a source of ionization is convenient for excimer and chemical lasers because the ionization process lasts such a short time.

A chemical method of plasma generation is the use of flames. The chemical energy of reagents is spent on formation of radicals or excited particles, and chemoionization processes with participation of active particles generate charged particles. The transformation of chemical energy into the energy of ionized particles is not efficient, so the degree of ionization in flames is small.

Electrons in a hot gas or vapor can be generated by small particles. Such a process takes place in products of combustion of solid fuels.

Introduction of small particles and clusters into a weakly ionized gas can change its electrical properties because these particles can absorb charged particles, that is, electrons and ions, or negative and positive ions can recombine on these particles by attachment to them. This process occurs in an *aerosol plasma*, that is, an atmospheric plasma that contains aerosols. On the contrary, in hot gases small particles or clusters can generate electrons.

Plasma can be created under the action of fluxes of ions or neutrons when they pass through a gas. Ionization near the Earth's surface results from the decay of radioactive elements which are found in the Earth's crust. Ionization processes and the formation of an ionized gas in the upper atmosphere of the Earth are caused by energetic radiation from the Sun. Thus, methods of plasma generation are many and varied, and lead to the formation of different types of plasmas.

1.3 PLASMAS IN LABORATORY DEVICES

Various laboratory devices and systems contain a plasma. This plasma is called a low-temperature plasma or a hot plasma, depending on the temperature of the charged particles. In a hot plasma the thermal energy of the atomic particles exceeds a characteristic atomic value (which may be the ionization potential of the plasma atoms), and in a low-temperature plasma, it is much less. Correspondingly, plasma devices containing hot plasmas or low-temperature plasmas are different in principle. An example of a hot plasma is a thermonuclear fusion plasma, that is, a plasma for a controlled thermonuclear reaction. This reaction proceeds with participation of nuclei of deuterium or of tritium—isotopes of hydrogen. In order to achieve this reaction, it is necessary that during the time of plasma confinement, that is, during the time when ions of deuterium or tritium are present in the reaction zone, these ions have a chance to participate in a thermonuclear reaction. Both a high ion temperature (about 10 keV) and a high number density of ions must be present if the thermonuclear reaction is to proceed. The threshold number density of ions (N_i) for the thermonuclear reaction depends on the plasma lifetime τ in such a way that the product of these values, $N_i\tau$, must exceed a certain value. This condition is called the *Lawson criterion*. At temperatures of several keV, the Lawson criterion corresponds to an onset value of $N_i\tau = 10^{16}$ cm^{-3} s for a deuterium plasma, and 10^{14} cm^{-3} s for a deuterium-tritium plasma. These values are reached in contemporary plasma fusion devices.

The other method to solve the problem of thermonuclear fusion uses pulsed systems. In this case a deuterium pellet is irradiated on its entire surface by a laser pulse or a fast ion beam. When the pulse impinges on the pellet, the pellet is heated and compressed by a factor 10^2–10^3. The heating and compression is intended to promote a thermonuclear fusion reaction. Note that the dense hot plasma that is formed during compression of the pellet is a special state of matter that does not have an analog in an ordinary laboratory setting.

A hot plasma is used in plasma engines. There, a flux of plasma causes the motion of a system in the opposite direction according to Newton's third law. The plasma flow velocities may attain 10^8 cm/s, and exceed by one or two orders of magnitude the corresponding value for conventional chemical-fuel engines. Therefore, despite producing power small compared to that of chemical engines, plasma engines are used in space engineering where the problem of the weight of fuel is critical.

The low-temperature plasma differs from a hot one in both its parameters and its applications. Since the most widespread methods of plasma generation under laboratory conditions are based on gas discharges, most gas lasers and light sources use such discharges. Let us first consider installations using a low-temperature plasma for generation of electrical energy. The magnetohydrodynamic (MHD) generator uses a stream of hot, weakly ionized gas

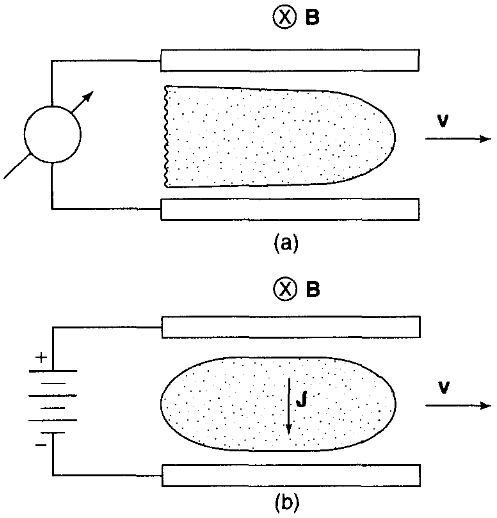

Figure 1.4 A schematic diagram of an (a) MHD generator and (b) an ion engine. In the first case the electric field is generated by the motion of a plasma in a magnetic field. In the second case electrons and ions are accelerated as they pass through crossed electric and magnetic fields.

flowing in a transverse magnetic field. This induces electric current in a direction perpendicular to the directions of the stream and magnetic field, to permit the system to transform the energy of flow into electrical energy (see Fig. 1.4a). The efficiency of this transformation is quite high because the flowing gas is hot. The principles of action of MHD generators and plasma engines bear a resemblance to each other (see Fig. 1.4), and an MHD-generator may be adapted as a plasma engine (Fig. 1.4).

There are stationary MHD generators which may be used as components of electric power stations, and there are pulsed MHD generators. The pulsed MHD generator can be regarded as a gun where a weakly ionized plasma is used instead of a shell. The plasma is formed as a result of combustion of gunpowder or some equivalent source of propellant gas. When this plasma passes through a region with an external magnetic field, electric power is created. In order to estimate the possibilities of this system, let us make a simple calculation. Assume the plasma velocity equals the velocity a bullet acquires in a gun. Take the efficiency of energy transformation to be of the order of 50%, and the length of the region with a magnetic field to be 1 m. Then the specific power of this generator is of the order of 10^8 W/g, and the pulse duration is $\approx 7 \times 10^{-4}$ s. Thus the power of a pulsed MHD generator, for this brief instant, corresponds to the total power of all the electric power plants of the world if the mass of the powder used is of the order of 10 g. The pulsed MHD generator transforms the chemical energy of the powder into electrical energy. Due to the simplicity and yield parameters of these systems, they are convenient for special applications as autonomous pulsed sources of electric energy.

The other system where a plasma is used for generation of electric energy is the *thermoemission converter*. It contains two parallel metal plates with different work functions (the *work function* is the binding energy of an electron at a surface). One of these plates is heated and emits electrons which reach the other plate. An electric current is created. Connection of the plates through a load leads to the release of electrical energy in the load. It is evident that a plasma is not the underlying basis for this device. Nevertheless, the use of a plasma in the gap between the plates makes it possible to overcome an important difficulty attendant on this system. If there is no plasma in the gap, electron charge is accumulated in this region and creates an electric potential between the plates that increases with electron number density in the gap, and is opposite in direction to the potential that initiated the phenomenon. Beyond a certain level the counterpotential will stop the generation of electric energy. For typical energy fluxes in these systems (~ 1 W/cm^2) the distance between plates must be less than 10 μm. It is difficult to combine this condition with a high temperature of the heated plate (≈ 2000 K). Introduction of a plasma in the gap between plates provides a means of overcoming this difficulty.

In various applications of a plasma with an intense input of energy, the plasma is generated in a moving medium. The source of this plasma is called a *plasmatron* or plasma generator. It is usually an arc discharge established in a flowing gas or vapor. Such plasma generators produce plasma torches, which have wide application to various technological problems, including incineration of waste and special medical uses. Many plasma applications are based on the possibility of introducing a high level of electrical energy into the plasma. It leads to the creation and maintenance of an ionized gas containing active atomic particles: electrons, ions, excited atoms, radicals. These particles can be analyzed by a variety of techniques, and therefore a plasma can used not only in energetic systems, but also in measuring instruments. In particular, plasma-based methods of spectral analysis are widely practiced in metallurgy. In these methods a small amount of metal in the form of a solution or powder is introduced in a flowing discharge plasma, and spectral analysis of the plasma makes it possible to determine the metal composition. The accuracy of spectral determination of admixture concentration with respect to a primary component is of the order of 0.01–0.001%.

It is interesting that the principles of operation of MHD generators, thermoemission converters, and plasmatrons were suggested as early as the end of the nineteenth century. Now, with the advantage of contemporary materials and technology, these devices have acquired a new life.

The *optogalvanic* technique in plasma diagnostics uses another principle. The weakly ionized gas in a gas discharge (usually it is a glow gas discharge) is irradiated by a tuned laser, and the discharge electric current is measured as a function of the radiation wavelength. If the laser radiation is resonant with atomic transitions of atoms in the discharge plasma, this radiation causes photoionization at a rate strongly dependent on the identity of the atoms being irradiated. The measured effect is a change in the discharge current. Thus, measured current jumps can be associated with the presence of particular atoms in the discharge plasma. The degree of certainty in the identification of the atom is greatly increased if many resonances can be identified. The optogalvanic method makes it possible to identify admixtures in a plasma with concentration of the order of 10^{-10}–10^{-12} with respect to the principal component of the plasma. An appreciation of the precision of this method can be gained by noting that its accuracy is comparable to having knowledge of the total population of the Earth to within an accuracy of one individual. Thus, a plasma is a uniquely useful tool for a variety of applications.

1.4 PLASMA IN CONTEMPORARY TECHNOLOGY

Plasmas are currently widely employed in industry, and their range of application broadens continuously. The usefulness of plasmas in technology can be ascribed to two qualities: Plasmas make available much higher temperatures than can be achieved with chemical fuel torches; and a large variety of ions, radicals, and other chemically active particles are generated therein. Therefore, either directly within a plasma or with its help, one can conduct technological or chemical processes of practical importance. Another advantage of a plasma follows from the possibility of introducing large specific energies in a simple fashion.

The oldest applications of a plasma as a heat-transfer agent are in the welding and cutting of metals. Since the maximum temperature in chemical torches is about 3000 K, they cannot be used for some materials. The arc discharge (electric arc) makes it possible to increase this temperature by a factor of three, so that melting or evaporation of any material is possible. Therefore the electric discharge has been used since the beginning of this century for welding and cutting of metals. Presently, plasma torches with power up to 10 MW are used for melting iron in cupolas, for melting scrap, for production of steel alloys, and for recovering steel in tundishes.

Plasma processing is used for extraction of metals from ores. In some cases plasma methods compete with traditional ones which are based on chemical heating. Comparing the plasma with chemical methods in cases when either can be used, the conclusion is that plasma methods provide a higher specific output, a higher quality of product, and a smaller amount of waste, but require a larger energy expenditure and more expensive equipment.

Another application of a plasma as a heat-transfer agent relates to fuel energetics. The introduction of a plasma in the burning zone of low-grade coals leads to improvements in the efficiency of the burning with an accompanying reduction in particle emissions, in spite of a relatively small energy input from the plasma. Plasmas are used also for pyrolysis and other methods of processing and cleaning of fuel.

Plasmas have been employed extensively for the processing and treatment of surfaces. The good heat-transfer capabilities of a plasma are useful for treatment of surfaces. During plasma processing of surfaces the chemical composition of the surface does not change, but its physical parameters may be improved. Another aspect of the processing of a surface by a plasma refers to the case when active particles of the plasma react chemically with the surface. The upper layer of the surface can acquire a chemical composition different from that of the substrate. For example, plasma hardening of a metallic surface occurs when metal nitrides or carbides are formed in the surface layer. These compounds are generated when ions or active atoms in the plasma penetrate into the surface layer.

A third mechanism for the plasma action on a surface is realized when the surface material does not itself participate in the chemical process, but material from the plasma is deposited on the surface in the form of a thin film. This film can have special mechanical, thermal, electric, optical, and chemical properties that are useful for specific problems and requirements. It is convenient to use for this purpose plasma beams that flow from jets. Such beams can give rise to clusters as a result of expansion of the beam. The *ion-cluster beam* method is used for deposition of thin films. Because of the smaller heat release during the deposition of clusters than during the deposition of atoms, the ion-cluster beam method provides improved quality of films formed thereby, even though ion-cluster beams have a lower intensity than beams of atoms or atomic ions. Beam methods for deposition of micrometer-thickness films are widespread in the manufacture of microelectronics, mirrors, and special surfaces.

In addition to the deposition processes resulting from plasma flows containing atoms or clusters, a plasma spraying process is used for deposition of molten powder particles on a sample. The powder particles are introduced into a plasma jet resulting from the passage of a gas through an arc discharge. These particles are heated and accelerated in the plasma jet, which is directed onto a target. Molten particles impinge with high velocities on the surface, adhere, and form a covering layer.

An important area of plasma applications—*plasma chemistry*—relates to production of chemical compounds. The first industrial plasmachemical process was employed for ammonia production at the beginning of the twentieth century. It was later replaced by a cheaper method that produced ammonia from nitrogen and hydrogen in a high-temperature, high-pressure reactor with a platinum catalyst. Another plasmachemical process is to produce ozone in a barrier discharge. This method has been used for several decades. Large-scale development of plasma chemistry was long retarded by the required high power intensity. When other criteria became the limiting factors, new plasmachemical processes were mastered. At present, the array of chemical compounds produced industrially by plasmachemical methods includes C_2H_2, HCN, TiO_2, Al_2O_3, SiC, XeF_6, KrF_2, O_2F_2 and many others. Though the number of such compounds constitutes a rather small fraction of the products of the chemical industry, this fraction is steadily increasing. The products of a plasmachemical process may exist either in the form of a gas or in the form of condensed particles. Plasmachemical industrial production of ceramic-compound powders such as SiC and Si_3N_4, or powders of metals and metal oxides, leads to an end product of high quality.

Plasmachemical processes with participation of organic compounds are used as well as those with inorganic materials. Organic-compound applications include the production of polymers and polymeric membranes, fine organic synthesis in a cold plasma, and so on. In a qualitative assessment of the technological applications of plasmas, we conclude that plasma technologies have a sound basis and present prospects for important further improvements.

Plasma processing for environmental applications is developing in two directions. The first is decomposition of toxic substances, explosive materials, and other hazardous wastes, which can be decomposed in a plasma into their simple chemical constituents. The second is improvement of air quality. A corona discharge of low power is used for this purpose. The discharge generates active atomic particles such as oxygen atoms. These atoms have an affinity for active chemical compounds in air, and react with them. Such discharges also destroy microbes, but present no hazards to humans because of the low concentrations of these particles.

1.5 TERRESTRIAL ATMOSPHERIC PLASMA

It is convenient to categorize plasmas occurring in nature as terrestrial plasma (in the Earth's atmosphere or in near-Earth space), solar plasma, and cosmic plasma. Properties of the plasma of the Earth's atmosphere depend on the altitude of the atmospheric layer in which it occurs. At low altitudes the plasma is maintained by ionization of air under the action of cosmic rays and of atmospheric electric fields. Near the Earth's surface, a portion of the ionization of air arises from the decay of radioactive elements of the Earth's crust. Plasma in lower layers of the atmosphere is characterized by a low density of charged particles. The presence of plasma is limited by the tendency of electrons to attach quickly to oxygen molecules, forming negative ions. Therefore, plasmas in the lower atmosphere contain negative charge in the form of negative ions. If aerosol particles are present in air, ions may attach to them. Therefore charged aerosol particles play a role in this plasma.

Atmospheric plasma underlies the electrical phenomena of the atmosphere. One of them is lightning—electrical breakdown under the action of electric fields in the atmosphere. Lightning is one of the processes in the atmosphere which originate in the formation of clouds, and arises from the charging of aerosols and clouds. As a result, electric fields occur in the