ELECTRIC PLASMAS: THEIR NATURE AND USES

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Taylor & Francis Ltd
London and New York
1983

First published 1983 by Taylor & Francis Ltd,
4 John Street, London WC1N 2ET

Typeset by Gibbons Barford Print, Wednesfield Road,
Wolverhampton WV10 0JA
Printed in Great Britain by Taylor & Francis (Printers) Ltd,
Rankine Road, Basingstoke, Hampshire RG24 0PR

Distributed in the USA and Canada by
International Publications Service Taylor & Francis Inc.
114 East 32nd Street, New York, NY 10016

British Library Cataloguing in Publication Data

Von Engel, A.
Electric plasmas.
1. Plasmas (Ionized) gases
I. Title
530.4'4 QC718

ISBN 0-85066-147-1

PREFACE

Books on electric conduction in gases, ionization phenomena, gas discharges, gaseous electronics and plasma physics abound. What then induced me to write yet another text? There were two main motives for action: for some time the second edition (1965) of my book *Ionized Gases* has no longer been available, in spite of translations into Japanese, Russian and Yugoslavian; languages which neither I nor most students master. I also felt that there was a need for a text in which not only theory but also applied sciences are comprehensively treated. The Oxford University M.Sc. course in "Science and Applications of Electric Plasmas" in which I am engaged has facilitated the selection of problems and the allotment of space. I have attempted to present the subject in the form of extended essays in which elementary arguments are included for reasons best known only to those who actually teach it. I have deviated from the present fashion to collect and edit contributions of experts wallowing in their special fields, although this deprives the reader of accumulating scientific gems and possibly priceless revelations of future trends. On the other hand a 'single author' book provides the reader with a certain uniformity of approach, however biased and incomplete. Moreover, this book gives me the chance to tell a wider circle than that of my colleagues and pupils, various thoughts that I would not be able to publish in learned journals. I am eagerly awaiting letters from those who spot some of the novelties. However, no rewards can be claimed, neither for passing that exercise (modestly described as a treasure hunt) nor for detecting mistakes and omissions.

No one system of units is used consistently throughout. M.K.S. units are more common as much of the research has been, and still is done using those units, and is therefore easier to appreciate in that form. A Table of Units (p. xi) is included for reference, if required. Familiarity with spectroscopic nomenclature is assumed.

In teaching, politics and writing the common maxim holds that to know what to conceal is more important than to know what to disclose and thus, with much regret, I have had to exclude several items from the text. The axed subjects are: coherent and incoherent light sources, i.e., lasers and illumination; transient, pulsed and pulsing discharges; striations, stationary as well as moving; certain electro-mechanical effects; ion beam sources; and spectroscopic diagnostics. Though excluded from the text, references are given at the end of the last chapter. To keep the book to a reasonable length I have also excluded examples and their solutions.

Preface

To mix teaching, research and mini-administration with writing is spending time in a singularly inefficient way—or so I am told by those whose goddess is materialism. Few realize that in order to contribute to problems in physics ample time must be set aside to ponder about them so that the solution is to one's satisfaction. Looking back over the last years, I have enjoyed writing this text and I hope that this will percolate to the reader.

Fortunately I worked for and with a publisher who did not fix a precise delivery date for the manuscript. I am grateful for his advice and help and I owe much gratitude to Bob Noakes for numerous suggestions. The late Professor D. W. Holder, F.R.S. provided the facilities necessary to continue my research. My thanks go to my colleagues and research students for their tolerance and understanding. Raoul Franklin was a helpful pathfinder in the dense forest (or jungle) of publications, capable of providing instant clarification to countless scientific and non-academic questions.

The Warden and the Governing Body of Keble College, Oxford have continued to give me social and other facilities which I value highly and for which I express my thanks. My close relations with Culham Laboratory and some financial and material support is mainly due to Dr. R. S. Pease, F.R.S. whom I thank for his unfailing friendship. I am most grateful to my wife Ilse for painstaking secretarial help and to Dr. Peter Edgley who has cast a critical eye on the manuscript and has suggested various improvements and corrections. My thanks go to Mr. J. H. C. Maple, Culham Laboratory for advice and corrections for chapter 9, and to Dr. J. Cheney, the publisher's Scientific Editor, for his help, patience and counsel. I have benefited from being associated with Professors H. Motz and L. C. Woods, Dr. J. E. Allen, the initiator of the Plasma Course, and Professor K. G. Emeleus of Belfast University. I am indebted to Professor C. P. Wroth, Head of the Engineering Science Department, Col. R. H. Parsons, Administrator and Mrs. Esther Rose, Librarian, for rendering facilities and help which made my life and work a gentle burden. The illustrations have prospered in Mrs. J. Takacs' skilful hands. Finally I wish to remember Billy, my late feline companion for some 17 years, who gracefully acted as a live paperweight.

A.v.E.

PERIODIC TABLE OF THE ELEMENTS

1 H 1·0																	2 He 4·0
3 Li 6·9	4 Be 9·0											5 B 10·8	6 C 12·0	7 N 14·0	8 O 16·0	9 F 19·0	10 Ne 20·2
11 Na 23·0	12 Mg 24·3											13 Al 27·0	14 Si 28·1	15 P 31·0	16 S 32·1	17 Cl 35·5	18 Ar 39·9
19 K 39·1	20 Ca 40·1	21 Sc 45·0	22 Ti 47·9	23 V 50·9	24 Cr 52·0	25 Mn 54·9	26 Fe 55·8	27 Co 58·9	28 Ni 58·7	29 Cu 63·5	30 Zn 65·4	31 Ga 69·7	32 Ge 72·6	33 As 74·9	34 Se 79·0	35 Br 79·9	36 Kr 83·8
37 Rb 85·5	38 Sr 87·6	39 Y 88·9	40 Zr 91·2	41 Nb 92·9	42 Mo 95·9	43 Tc (99)	44 Ru 101·1	45 Rh 102·9	46 Pd 106·4	47 Ag 107·9	48 Cd 112·4	49 In 114·8	50 Sn 118·7	51 Sb 121·7	52 Te 127·6	53 I 126·9	54 Xe 131·3
55 Cs 132·9	56 Ba 137·3	57–71	72 Hf 178·5	73 Ta 180·9	74 W 183·8	75 Re 186·2	76 Os 190·2	77 Ir 192·2	78 Pt 195·1	79 Au 197·0	80 Hg 200·6	81 Tl 204·4	82 Pb 207·2	83 Bi 209·0	84 Po (210)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (227)	89–103	104 Rf	105 Ha													

Lanthanide series	57 La 138·9	58 Ce 140·1	59 Pr 140·9	60 Nd 144·2	61 Pm (145)	62 Sm 150·3	63 Eu 152·0	64 Gd 157·2	65 Tb 158·9	66 Dv 162·5	67 Ho 164·9	68 Er 167·3	69 Tm 168·9	70 Yb 173·0	71 Lu 175·0
Actinide series	89 Ac (227)	90 Th 232·0	91 Pa (231)	92 U 238·0	93 Np (237)	94 Pu (242)	95 Am (243)	96 Cm (245)	97 Bk (249)	98 Cf (249)	99 Es (254)	100 Fm (252)	101 Md (256)	102 No (254)	103 Lr

TABLE OF UNITS

Unit	Abbreviation	Equivalent
Ångström	Å	1 Å $= 10^{-10}$ m $= 0{\cdot}1$ nm
Atomic mass unit	a.m.u.	1 a.m.u. = 1 dalton $\simeq 1{\cdot}6 \times 10^{-24}$ g
Coulomb	C	1 C = 1 A s
Electron volt	eV	1 eV $\simeq 1{\cdot}6 \times 10^{-19}$ J
Erg	erg	1 erg $= 10^{-7}$ J
Farad	F	1 F = 1 C V^{-1}
Gauss	G	1 G $\triangleq 10^{-4}$ T
Hertz	Hz	1 Hz = 1 cycle s^{-1}
Joule	J	1 J = 1 N m
Millimetre of mercury	mm Hg	1 mm Hg $\simeq$ 1 Torr $\simeq$ 133 Pa
Nanometre	nm	1 nm $= 10^{-9}$ m = 10 Å
Ohm	Ω	1 Ω = 1 V A^{-1}
Pascal	Pa	1 Pa = 1 N m^{-2}
Poise	P	1 P $= 0{\cdot}1$ Pa s
Standard atmosphere	atm	1 atm $\simeq$ 101 kPa
Tesla	T	1 T = 1 V s m^{-2}
Torr	Torr	1 Torr $\simeq$ 1 mm Hg $\simeq$ 133 Pa
Volt	V	1 V = 1 J A^{-1} s^{-1}
Watt	W	1 W = 1 J s^{-1}
Weber	Wb	1 Wb = 1 V s^{-1}

CONTENTS

CHAPTER 1

introduction

The rapid advances in physics during this century have introduced a large number of new concepts. This fast expansion of our knowledge has been accompanied by a gradual disappearance of earlier well-established frontiers between the sciences. The boundaries between physics and chemistry, chemistry and engineering, the life sciences and the physical sciences have been torn down. This in turn has been accompanied by a division of the 'main' subjects into smaller and smaller sections. Today we talk about atomic physics, molecular physics, solid-state physics, nuclear physics and chemical physics to mention only a few, plasma physics being one of the more recent additions to this list.

It has often been said that our planet is surrounded by an electric plasma and indeed that the larger part of the Universe is in the plasma state. Yet before we can examine whether this is not merely an exaggeration, intended to make plasma physics look important, it is necessary to enquire into the nature of the plasma state. The kinds of plasma we are going to discuss are usually in the form of a gas and are electrical in origin (figure 1.1).

First we shall try to answer the question "what is a plasma?" and give a simple explanation of the word. A plasma is electrically energized matter in a gaseous state. In general it consists of three components: electrically neutral gas molecules; charged particles in the form of positive ions, negative ions and electrons; and quanta of electromagnetic radiation (photons) permeating the plasma-filled space. The molecules, of which there are often a large number of species, can be either in their lowest ('ground') energy state or in a higher ('excited') energy state of the rotational, vibrational and electronic kind, each molecule consisting of one or more atoms. Positive ions can carry one or more units of charge and, again, may be in their ground energy state or an excited state, whereas negative ions carry only one single charge. Though in most cases such plasmas are caused by an electric discharge in a gas, they may also be produced in other ways: by sudden or continuous heating of matter to high temperatures, by intense laser radiation and by chemical processes. We shall see later on how this can be practically achieved.

From what has been said above, the question arises as to whether the

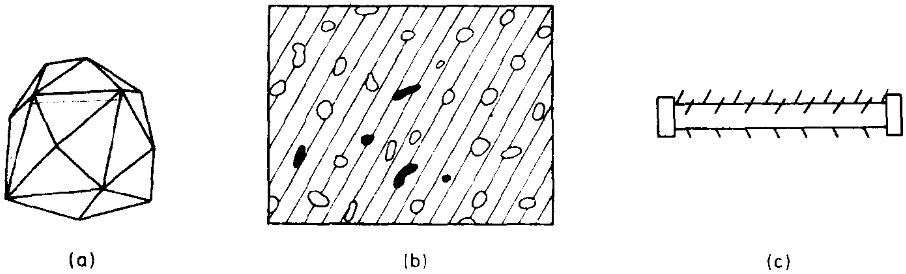

Figure 1.1. Three kinds of plasma.
(*a*) A green variety of quartz.
(*b*) The coagulable part of blood.
(*c*) The electrically conducting gas at low pressure frequently emitting 'cold light'.

structure of a plasma might perhaps be akin to that of an ordinary electrolyte. What is the difference between the two? Firstly, most of the so-called electrolytes are liquids and only a few are solids. Secondly, in electrolytes free electrons and photons are absent; the only charged particles present are negative and positive ions. Finally, apart from certain exceptions, all the electrolyte particles, whether neutral or charged, are in the ground state because they collide frequently with one another.

The somewhat ambiguous term 'plasma' was introduced by Langmuir in 1927. In the course of his studies of electric discharges in mercury vapour at low pressure he found that the ionized gas, which formed a cold luminous column in a long glass tube, showed uniform electric and optical properties along its whole length. From that he concluded, as Crookes had done in 1870, that he was dealing with a particular state of matter. It deserves to be given a special name which conveys that the various constituent particles are moulded together: thus the Greek word *plasso* (to shape or mould). As we shall show later on, his foresight has been confirmed.

Let us approach this subject from another angle. Everyone has observed lightning, and those who have lived sufficiently far north or south must also have seen the aurora (borealis or australis). The 'long sparks' between cloud and ground, and the strange diffuse lights emanating from the cloudless sky are visible evidence of the presence of intense and weak plasmas. Some plasmas emit visible light by virtue of the electric energy supplied to a discharge, for example, sodium or mercury vapour lamps, which also contain a rare gas at low pressure to facilitate starting. Other familiar plasma (cold light) sources are neon lamps and signs. In contrast, high-current electric arcs used for welding in atmospheric air or other gases develop very hot spots at the electrodes. Such bright and noisy arcs are used for joining rails or when the 'gliding shoe' of an electric train passes a connecting section, thereby opening the circuit temporarily; welding arcs are widely used on building sites and shipyards for fabricating metal structures.

Plasma physics is not limited to electric discharges in gases. The application to chemical processes has been studied in recent years with great vigour. It has long been known that certain properties of oils can be impoved by treating them with electric corona-like discharges, which in air or oxygen also produce ozone used for purifying water. Atomic hydrogen generated in hot torch discharges is also used in welding and cutting. Reactions that occur in internal combustion engines and in flames are usually accompanied by ionization and excitation, processes which do not necessarily take place in the hottest part but rather in the chemically most active part of a flame gas. Flame plasmas are another field of plasma study.

Other practical applications include the gas laser, in which a plasma is the active medium. In general, a combination of several gases is used whereby the radiation produced controls the emission of light from certain excited atomic or molecular levels. With the help of an 'optical cavity' an intense beam of coherent monochromatic light is emitted by the plasma. Again, relatively weak glow discharges are employed either for keeping a d.c. voltage constant or replacing mechanical switches in low current circuits. Still weaker discharges occur in gas-filled counters: they develop when a single particle or a single photon enters a chamber, and quenches itself automatically so as to be ready for the next arrival. More powerful temporary discharges are found in spark counters used in cosmic work: the luminous trace which persists when a cosmic particle from outer space has passed through the counter represents its path and is photographed. High-energy particle accelerators are fed from negative or positive ion sources. These are often high-frequency discharge plasmas from which slow ions are drawn into the beam accelerator. In standard electric switch gear, arcs develop between separating contacts before the current is interrupted. These are examples of the applications of discharge and plasma physics, some of which will be discussed in later chapters.

We can listen to radio broadcasts from distant stations because Nature has provided a medium which enables us to receive signals from these far corners; though sometimes faint, they are frequently accompanied by electric disturbances from space, particularly during the summer or periods of unstable weather. This medium, a weak plasma maintained by the Sun's activity surrounding the Earth about 100 km or more above its surface, is called the ionosphere. Owing to its presence we can keep up communication between distant parts of the globe without recourse to satellites. Signals from a transmitter are reflected by this plasma shell, sometimes more than once, provided the signal beam carries sufficient power and has the appropriate frequency to be reflected down to Earth. However, we must not conclude that signals originating from sources at heights above the ionosphere or other planets cannot penetrate the ionosphere. This is shown by the reception of signals from radio stars and space craft.

A field of plasma physics which may be of great benefit is thermonuclear fusion—an exothermal reaction of immense potentiality. Unlike the hydrogen bomb, here the fusion energy is released at a carefully controlled slow rate. In fusion studies plasma physics and nuclear physics overlap. When a pair of light nuclei (deuterium $D = {}^2H$ and tritium $T = {}^3H$) are brought closely together by colliding at high speed, they fuse, a reaction followed by nuclear disintegration into neutrons and other nuclei. Fusion is achieved by heating a rarefied gas mixture of D and T with an electric discharge. The plasma is kept away from the container walls by a magnetic field, until it reaches temperatures of 10^6–10^8 K. Alternatively, giant lasers are being operated now to fuse D and T together. Yet after more than 25 years of intense research in various countries we still seem to be a long way from our scientific goal and still further from the power station of the future housing a fusion reactor.

There is another venture in which the study of plasma physics may possibly bring success: that is by producing electrical energy through driving a hot plasma across a magnetic field, which is analogous to replacing the rotating copper rods or wires in an ordinary generator or dynamo by a flow of gas of high electrical conductivity. Alas, the results up to now are not what we hoped for, though such magnetohydrodynamic generators have been used to provide quite large electric power pulses for a very short period of time at low efficiency.

CHAPTER 2

nature, structure, state and generation of plasma particles

2.1. Neutral atoms and molecules

The mass of an atom is essentially concentrated in its nucleus or core, which is usually composed of protons and neutrons (exceptions are hydrogen and positronium). An early model of the neutral atom is that of Niels Bohr. This consists of negative electrons, of mass small compared with that of the positive nucleus, which move in selected circular or elliptical orbits around the nucleus. By knowing the number of electrons in the orbit and the type of orbit (energy level), the potential energy (state of excitation) of the atom can be found. When a bound electron in a lower level is moved to a higher empty level, i.e., from an inner to a larger outer shell, the atom's excitation energy is raised. However, the number of electrons that can occupy a shell is restricted, since Pauli's exclusion principle stipulates that each atomic electron differs from all the others by at least one of its quantum numbers, which characterizes its property in the shell structure. Similarly, members of a large family are identified by their family name plus at least one different forename. In terms of this model, at least four numbers are needed to describe an atomic state: the principal quantum number n, describing the electron's orbital angular momentum, the azimuthal quantum number l, describing the ellipticity of the electron's orbit, the orbital magnetic quantum number m_l and the electron spin quantum number m_s.

After half a century this simple picture has been replaced by a more sophisticated concept based on quantum mechanics (see, e.g., *Elementary Quantum Mechanics* by N. F. Mott, Wykeham Science Series No. 22). However, what has really been superseded is the idea of an electron literally rotating like a planet around the Sun in an orbit that can be traced. The quantum numbers, the energy states and the exclusion principle remain. Though one speaks now of 'orbitals' and 'energy levels', not of orbits, and thereby strengthens our belief in the wave character of the electron, an outline picture of the Bohr atom is still very valuable. It is used in the same way as are the particles in the classical kinetic theory of gases, where molecules are described as massive elastic spheres, or in chemistry where molecules are depicted as spherical atoms held in a scaffolding of bonds.

2.2. Positive ions

On the left of figure 2.1 is the simplest atom, hydrogen, with the proton at its centre and a single electron in the atom's ground state, i.e., in an orbit of least radius (the Bohr radius $a_0 = 5{\cdot}3 \times 10^{-11}$ m). The radius of the proton is about $1{\cdot}2 \times 10^{-15}$ m, and the classical radius of the electron, $r_e = 2{\cdot}8 \times 10^{-15}$ m, so the intervening space is apparently empty, i.e., free of 'particles' with inertial mass. On the right of figure 2.1 a single proton is shown which can be obtained by removing the electron from a neutral hydrogen atom. The spatial distribution (topology) of the electric field is of interest. There is the 'closed field' structure of the neutral hydrogen atom, where the circling electron charge prevents the electric field of the nuclear proton from penetrating much further than the innermost orbit. In contrast, the proton's (H^+) electric field with its radially diverging field lines, ending at the electron nearby or at infinity, exemplifies an 'open structure'. In larger neutral atoms the positive charge at the centre is surrounded by electrons circulating in various orbits whose planes are differently oriented. However, here the electric field at larger distances from the nucleus is gradually screened off by the electrons. Thus, the stray field outside the large atom has a structure which is more open the greater its size. The increase in polarizability with increasing atomic radius or atomic number confirms this view (figure 2.5, p. 12).

The more strongly bound the outermost electron is to an atom, the larger is the energy needed to excite it or to ionize it. Another related fundamental atomic property, affecting the 'shape' of particles and the path of moving charges, is their electric polarizability. It is a measure of the elastic deformation of the electronic charge distribution around the nucleus. Induced polarization occurs when an electric field E acts on the atom's electron cloud and displaces its centre by a distance δa relative to the nucleus. This results in an induced electric dipole moment

$$M_e = q\delta a = \alpha E$$

where α is called the polarizability and q the total electronic charge.

The order of magnitude of α is easily estimated by balancing the internal against the applied (distorting) field. Since the internal field E_0 at the innermost orbit, a_0, is $e/4\pi\varepsilon_0 a_0^2$ (where e is the electron charge, $1{\cdot}6 \times 10^{-19}$ C, and ε_0 is the vacuum permittivity, $8{\cdot}85 \times 10^{-12}$ F m^{-1}) and the applied field E changes a_0 by $\delta a \ll a_0$, $E/E_0 \simeq 4\delta a/a_0$, and $\alpha \simeq 0{\cdot}25\alpha_0^3 > 0{\cdot}25 \times 10^{-30}$ m^3 in agreement with observations (table 2.1). Figure 2.6 shows how α depends on the atomic number Z, i.e., the number of positive nuclear charges; it confirms that the values of α of rare gases are associated with minima, due to their closed shells, and those of

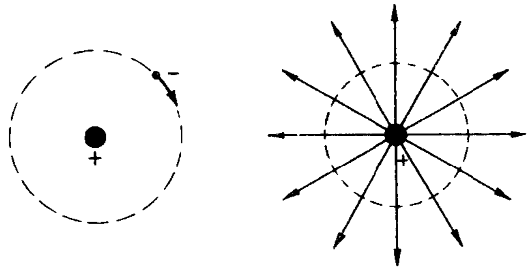

Figure 2.1. H atom and H^+ ion (proton).
Dashes = electron orbit; arrows = electric field.

alkali atoms with maxima, owing to their open structure causing strong chemical activity. Excited atoms, positive ions and molecules have low values of α. Polarizability is of considerable interest in ion-cluster formation, mobility theory, collision theory and kindred subjects.

Bohr's picture of the atom requires various amendments but only one, namely the assumed 'point charge' of the electron, will be discussed. In accordance with the uncertainty principle, the electronic charge must be taken as being 'smeared out', that is, it has a radial and azimuthal distribution; the former has been deduced from the observed intensity distribution of X-rays that are scattered by orbital electrons. Figure 2.2(*a*) shows the results for He and Ne. The maximum intensity for He is seen to be at the radius of its orbit $n=1$, while the maxima for Ne are at about the first and second orbital radii ($n=1$, $n=2$) just as quantum mechanics predicts. It is thus impossible to locate precisely the position of the electron at any instant. Heisenberg's uncertainty principle applied to circular motion states that the uncertainty in the angular momentum ΔJ and the uncertainty in the angular co-ordinate $\Delta\phi$ must satisfy the inequality $\Delta J \times \Delta\phi > h/2\pi$ ($h \simeq 6 \times 10^{-34}$ J s). If we take $\Delta J = m_e \times \Delta(v \times r)$, where v is the electron velocity corresponding to the ground-state energy ($n=1$) of H (which works out to be 2×10^6 m s^{-1}) and the electron mass $m_e = 9 \times 10^{-28}$ g, then the uncertainty Δr comes to $r \simeq 5 \times 10^{-11}$ m which is the same as the Bohr radius a_0. We conclude that this forecast is consistent with experiment. The radial and azimuthal charge distribution helps to answer the question of why the revolving charge does not emit radiation as demanded by classical (point-charge) theory: the elements of radiation emitted by the revolving element of the electron cloud annul each other by interference.

The ellipticity of discrete electron orbits is replaced in quantum mechanics by boundary surfaces (orbitals) which indicate the charge distribution in given

Table 2.1. Polarizability α of neutral unexcited atoms (in 10^{-24} cm^3).

Atom	He	Ne	Ar	Kr	Xe	H	Be	O	Hg	Li	Na	K	Rb	Cs
α	0·21	0·4	1·65	2·5	4·04	0·67	9·3	0·15	5·2	20	27	38	50	50