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Space Physics

the study of plasmas in space

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Editors' foreword

SPACE physics can cover a wide variety of topics and conjure up in the mind a whole range of applications spreading into engineering, geology, and many other fields. This text is concerned not with the wide range of specialized applications, however, but rather with the basic *physics* to be associated with space and its properties. In order to encompass a coherent presentation in one small volume a selection even from within the field of basic physics has to be made, and as Professor Boyd explains in his introduction, he has concentrated on the physics of matter filling most of space—i.e. *plasmas*—and left the consideration of the solid state to later books in the series.

It is probably somewhat surprising to most of us that the universe is composed almost wholly of plasmas, but as more detailed investigations take place this becomes increasingly evident—the solar wind and corona, the material expanding into space from supernova explosions, and the regions around neutron stars and black holes being a few examples. It is clear, therefore, that any understanding of the physics of space will need, as part of its foundation, an understanding of the nature and properties of plasmas and of the methods used to study them—and it is just such an understanding that this book seeks to give.

The different types of plasma that can occur are taken up in the different sections of the text, the first chapter dealing with 'ionospheres', including their discovery and properties, while the second chapter moves on to 'magnetospheres', and starts with the discovery of the earth's radiation belts by the first American satellite that was launched. Throughout the text there is a careful balance between theory and experiment—and in a subject like this the experimental methods are in the forefront of modern technology, with satellite probes playing a major part.

The Oxford Physics series has been particularly fortunate in securing Professor Boyd as an author on this topic since he himself has pioneered the use of satellite probes in this country and can write with a personal authority on them which is evident from his fascinating accounts of their use. This book is one of the optional texts of the series and is intended to fit into a course at the end of the first year, or during the second year of studies. Thus, although the topics covered by this text are not reckoned as essential to every course in physics, the book has nevertheless been designed to fit in with the core volumes of the series on *Electromagnetism*, *D.c. and a.c. circuits*, *Radiation and quantum physics*, *Atoms and their structure*, *Atoms in contact*, *Interactions of particles*, and *Nuclear physics*. These core texts relate closely to each other and lead on to second- and third-year topics in quantum mechanics, statistical mechanics, solid state, and surface physics. This particular volume also links on directly with a group of texts in astronomy which are being prepared, and in this way the whole series is designed to reflect and match the more flexible nature of the new physics courses that are being designed at the moment to give variety of approach but, at the same time, an integrated and coherent picture.

D.J.E.I.

Preface

SINCE the launching of the first artificial Earth satellite in 1957 the word *space* has become an adjective commonly used to denote activities involving *space*craft. Space research, space physics, space chemistry, space biology, and so on refer to studies made possible by rocket propulsion although astronomy, astrophysics, lunar chemistry, and even some theoretical planetary biology all have a longer history. It is in the sense of depending on rocket techniques that *Space physics* is employed as the title of this book.

The popularity of that most ancient branch of applied physics, astronomy, has increased greatly of recent years no doubt partly because of the stimulus of space research and partly because it at least seems to embrace the glamour and mystery inherent in a fundamental science while offering no threat to mankind either through misuse of the environment or from human strife.

The Oxford Physics Series is to include a number of texts aimed to make available to the undergraduate early in his studies, an authoritative account of several topics of a generally geophysical, astrophysical, or cosmological character so as to aquaint him with some of the exciting developments and imperious questions being actively pursued in his subject. This book is concerned with researches in which space techniques have played a major part, other than those concerned with solid systems (e.g. the Moon and the planets). As the Introduction makes clear, elimination of solid systems leaves by far the greater part of the Universe, both in terms of mass and of space, and nearly all of this material exists in the fourth state of matter—an electrical plasma.

The material in this book is ordered working from the Earth's upper atmosphere outwards. In approaching the subjects in this way we move from a region already extensively studied before the advent of the research rocket to the magnetosphere, whose existence was barely recognized and the delineation of whose properties has been carried out only since the start of space research and mostly by its techniques. Leaving the environment of the Earth we turn to consider the Sun, upon whose behaviour that environment so largely depends. Not only is the subject of solar–terrestrial relations an important link between studies of the Sun and the Earth, but the behaviour of their plasmas in the presence of magnetic fields also corresponds in many ways.

From the Sun we move out again to our galaxy and far beyond to systems quite unknown before the start of astronomy from space vehicles. Here we find that the view of the Universe beyond the obscuring curtain of our atmosphere gives an insight into a variety of phenomena of great cosmological and astrophysical significance: interstellar shock waves from remote supernova explosions, rapid regular and secular variations of X-ray fluxes from neutron stars, with a density like that of nuclei, and the departing footprint of 'black holes'. Yet again in these events where matter is so different from its terrestrial form and where gravity, the weakest of all interparticle forces, holds sway we find the behaviour of plasma in magnetic fields is a controlling influence.

R.L.F.B.

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Introduction

Scope of the book

WHEN we come to study space we find that the Universe is mainly composed of that strange form of matter called *plasma* rather than normal fluid or solid materials. Any book on space physics therefore must be largely concerned with plasmas and must give consideration to the physics of this state of matter in some detail. It is for this reason that the subtitle of this book is *The study of plasmas in space*, and since a book of this length can only deal with certain selected subjects, the physics of the solid planets has been omitted. The general plan of the book has been to select four very different regions of cosmic plasma, to discuss some of their basic properties and to show how space techniques have been, and are being, applied to them. Since the idea of a plasma may well be novel, a brief general introduction to the subject follows before we discuss some different types of plasma more thoroughly in the succeeding chapters.

Plasma

In 1929 Irving Langmuir adopted the term plasma to describe the fluorescent gas in an electrical discharge. The word comes from the Greek for 'something moulded' and aptly describes the way in which the glowing gas fills the shape of the tube and responds to applied fields almost like a living thing. So different is the behaviour of a plasma from ordinary solid, liquid, or gas that it is sometimes referred to as the fourth state of matter.

The special behaviour arises from the fact that an electrical plasma consists of huge but very nearly equal numbers of charged particles of opposite sign. Each particle is surrounded by its Coulomb electric field, which, because this is a very long-range force compared with van der Waals interparticle forces, implies that each charged particle exerts an influence on, and is influenced by, a large number of other particles. It is this property which gives a plasma its coherent behaviour, that makes it capable of oscillating somewhat like a jelly, and forges such a strong link between it and any interpenetrating magnetic field.

Plasmas in general are very good conductors of electricity and, because of the high mobility of electrons, are also good thermal conductors. As a result of their high conductivity they have the peculiar property of not being able to support appreciable d.c. electric fields (except normal to any magnetic field present). This comes about because a d.c. field causes a movement of charges towards or away from the electrodes producing the field, according to their sign. The *space charge*, resulting as positive charges move towards a negative electrode and negative charges move away from it (and vice versa), screens the plasma from the field and localizes it in a *sheath* around the electrodes.

Debye, in studying the theory of strong electrolytes which are themselves plasmas, showed that this sheath screening effect is not limited to electrodes but occurs around each individual charged particle so that its field is modified from the simple Coulomb form and limited to a region of the order of the so-called Debye length given by $69(T_e/n_e)^{\frac{1}{2}}$ m. where T_e is the electron temperature and n_e the number of electrons per cubic metre.

When there is a magnetic field present or when the electric field is transient or alternating, the situation is changed. We shall see in Chapter 2 that a magnetic field inhibits a flow of charged particles across it, so that significant electric fields can then arise in that direction. Moreover, a changing magnetic field induces large currents which tend to neutralize the change in the magnetic field, with the result that mutual motion between plasma and magnetic field is restricted.

Plasmas in space

The ionosphere, the magnetosphere, the interplanetary medium, the interstellar medium, and the intergalactic medium (if such there is) are all plasmas. The atmosphere of the Sun and stars, the material from supernova stellar explosions, the shock-wave excited media from cosmic explosions, the region around neutron stars and black holes, the mysterious jet from the galaxy M87 (see Fig. 4.3), and other similar, and indeed many dissimilar, cosmic phenomena are plasma. It is hardly surprising, therefore, that this book on space physics is so largely concerned with space plasma.

Since selection of material is essential besides restricting the book to space plasma, the author has drawn much from the research of the Mullard Space Science Laboratory of University College London, which is situated in a beauty spot in the Surrey hills. After all, if one has to select there is something to be said for selecting that of which one has direct experience. The underlying link that has always influenced the choice of the Laboratory's programme is that which relates and dictates the subjects of this book—what parts of space present us with interesting and exciting plasma phenomena amenable to the diagnostic techniques made available by spacecraft?

In ordering this work we move from ionospheric plasma near the Earth, which can be probed directly, to magnetospheric plasma, where the vital role of magnetic fields is introduced, and out to the Sun, which presents us with a huge intensely hot coronal plasma which is both more rarified than can be reproduced in the laboratory and sufficiently extensive for interaction between radiation and particles to be significant. Finally, we turn to a new and most exciting branch of astronomy, where plasmas at tens to hundreds of millions of degrees radiate many billions of megawatts and are heated by such exotic processes as conversion of gravitational potential energy, huge cosmic dynamos, or shock waves in space.

The origin of space plasmas

It is not our business here to discuss the detailed physics and chemistry of plasmas in space, but rather to describe how they may be studied and what are the highlights and gaps in the picture as we have it. Before such a study is undertaken we must get some understanding of the origin and nature of the phenomena.

Plasmas in space, as in the laboratory, result from one or more of three main production mechanisms. The first of these is thermal ionization as in the carbon arc, thermo-nuclear fusion experiments, and the outer atmosphere of the Sun and stars (we shall discuss this in Chapters 3 and 4). In the first laboratory case the energy input is ohmic in character, in the second it can be compression of the plasma, in the Sun's case it is dissipation of shock-wave energy, while in some X-ray stars it is gravity. A special laboratory case is that of the low-pressure arc plasma, where the high value of E/p (electric field/pressure) results in mean electron energies one or two orders of magnitude higher than those of the ions or neutral particles. In the laboratory it is usually the loss of ions to the walls which is responsible for the great disparity between the temperature of the charged species, and it is questionable whether comparable ratios of T_e/T_+ ($\sim 10^2$) occur in accessible space situations. It is very important to remember this when comparing theory and experiment of probe electrodes used in the laboratory with their behaviour in space. Moreover, in the low-pressure arc plasma, because of the spatial distribution of E/p imposed by the boundary conditions of walls, cathode, and anode, the energy distributions of the charged species are often far from Maxwellian in form. Departures of T_e/T_+ from unity do occur in space even in the absence of significant electric fields (for example, in the topside ionosphere during daylight $T_e/T_+ \sim 2$), and there may be discharge types of phenomena or regions of high E/p (connected, for example, with aurorae) where considerably higher values will be found. On the whole, however, it is often safe to assume that true temperatures exist for the ions and electrons in space plasmas, though they are not by any means always in thermal equilibrium with each other.

The second main plasma-production mechanism is that of energetic streams of particles, as in some electron-bombardment ion sources for mass spectrographs or isotope separators. There are many space examples of this process. The normal auroral and the polar-cap absorption ionization arise respectively from electron and from proton streams. The ionization in the lowest part of the ionosphere is produced by the primary cosmic rays and their energetic secondaries. A case in which both the initial components are uncharged is the phenomenon of formation of luminous and ionized meteor trails in which there is ionization of metal atoms, evaporated from meteors, on collision with atmospheric atoms and molecules. Instrumentation to study the ionosphere must take account of the possible effects of streams of particles. Of course, not only the ambient plasma but these particles may themselves be the object of the measurement (see Chapter 2).

The other main source of space plasma is photo-ionization, indeed in the ionosphere this is predominant. If the photons have an energy greater than twice the ionization energy of the gas with which they are reacting, the ejected electrons may themselves contribute to further ionization, and in any case any excess energy may result in heating. The production of energetic photo-electrons is especially significant when the electron mean free path is long, for then the effects to which they give rise may occur far away from the region where the photon is absorbed, perhaps even, in the case of the ionosphere, in the other hemisphere of the Earth. Because the Coulomb force acts over long ranges, the photo-electrons can exchange energy readily with ambient electrons and so raise their temperature above that of the ions and neutral particles. These processes are especially important in the topside ionosphere.

Methods of studying plasmas

Ionized regions where the free positive and negative charges cancel to a high degree are studied, whether in the laboratory or in space, by four main diagnostic techniques. These are:

(1) the examination of the electromagnetic radiation to which they give rise;
(2) the examination of particles leaving them;
(3) the study of currents to electrodes (probes) immersed in them;
(4) the study of their effects on electromagnetic radiation passing through them.

Of these methods (1), the examination of radiation from ionized regions, forms the subject *per force* of space astronomy and so of Chapters 3 and 4, although in Chapter 3 (2), the flux of particles from the solar plasma, is involved, since we can study particles leaving the solar plasma at the Earth and in interplanetary space. The study of radio propagation—method (4)—has been the historical approach to the ionosphere and to some extent to the magnetosphere. The advent of spacecraft has enabled extensive use of this method, especially in studying the otherwise largely inaccessible topside ionosphere. Being able to put one or other, or both, of the transmitting or receiving terminals in a spacecraft greatly increases the flexibility of the method.

In this book we shall content ourselves with emphasizing the continuing importance of radio propagation in ionospheric and in magnetospheric studies, and will limit our discussion of ionospheric experiments to the direct probing techniques (2) and (3).

In the case of the ionosphere and magnetosphere the distinction between studying particles leaving the plasma and studying currents to electrodes immersed in the plasma is somewhat blurred. There is however an important practical consideration which can mark the difference. Particles that have energy large compared with that represented by the difference in potential between the spacecraft and its surrounding plasma can be thought of as in category (2). For these the energy (and velocity) of arrival at some sampling orifice on the craft is scarcely dependent on the potential of the spacecraft. In category (3) are the thermal distributions of charged particles around the craft. These have a controlling influence on its potential, and their fluxes are therefore strongly dependent on the potential of the sampling electrode system.

Contents

1. Ionospheres

Discovery of the ionosphere

THE first cosmic ionized medium or plasma to be recognized was, naturally enough, the terrestrial ionosphere, and although we will mention the ionospheres of other planets which are now becoming accessible to direct probing methods, it is the envelope of ionized gas around the Earth that has been most studied and is the main concern of this chapter. The ionosphere's existence was postulated in 1882 by the Scots physicist Balfour Stewart, in an article in the famous ninth volume of the Encyclopaedia Brittanica, and it is interesting to note how broad his predictions were, and how correct.

The basic evidence from which Stewart reasoned was the clear connection between the Sun and geomagnetism, shown by the fact that the regular diurnal variations of the compass are greater by 50 per cent at sunspot maximum over the excursions at sunspot minimum. To account for this he postulated (1) that the magnetic variations are due to electric currents in the high atmosphere; (2) that the upper air is rendered conducting by the action of the solar radiation upon it; (3) that the currents are induced by the dynamo action of the region's motion across the geomagnetic field as a result of global winds; (4) that the atmosphere is more highly conducting during the day, in the summer hemisphere, and at sunspot maximum.

It was, however, twenty years before Marconi's celebrated transatlantic radio transmission, on 12 December 1901, provided fresh and irrefutable evidence for the existence of the ionosphere. Heaviside and Kennelly drew attention independently to this corollary of Marconi's experiment and Kennelly wrote: 'As soon as long-distance wireless waves come under the survey of accurate measurements we may hope to find ... data for computing the electrical conditions of the upper atmosphere'.

These 'accurate measurements' were awaited for another twenty-two years, until the pioneering work of Appleton in the U.K. and Breit and Tuve in the U.S.A. Appleton concentrated on interferometric studies of ionospheric reflections using continuous-wave transmission, and so was concerned with the path of the ray measured in wavelengths λ, while the American workers used pulses of radio transmission and measured the travel time of a pulse or wave packet moving at a speed c, a technique which nowadays we should associate with radar. In each case the frequency $f(=c/\lambda)$ of the probing wave was an important parameter, since in the ray theory reflection occurs when the sine of the angle of incidence on the reflecting layer is equal to the refractive index of the layer (just as total internal reflection in optics occurs in passing from a medium of refractive index μ_1 to one of index μ_2 when $\sin i =$