FUNDAMENTALS OF AERONOMY

Whitten and Poppoff

SPACE SCIENCE
TEXT SERIES

Fundamentals of Aeronomy

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Fundamentals of Aeronomy

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Reprinted from Nature, June 17, 1933

Fine-Structure of the Ionosphere

I WAS much interested in the letter by Messrs. Schafer and Goodall in NATURE of June 3 dealing with the results of their experiments on the radio exploration of the ionosphere in the United States, since an independent set of observations in Great Britain, which are dealt with at length in a paper now awaiting publication, have led to very similar conclusions.

The method[1] used in the British series of observations has been to measure the maximum ionisation content of the various upper atmospheric regions by finding the critical penetration frequencies.

The British series of observations suggests therefore that there are four main components in the ionosphere caused by the influence of ultra-violet light from the sun. Such a composite structure is not considered unlikely when it is remembered that Pannekoek[3] has shown that the level of maximum ionisation caused by ultra-violet radiation depends on the ionisation potential of the gaseous constituent. It is tempting to associate the four components with the four ionisation potentials of oxygen and nitrogen atoms and molecules, and the suggestion that F^{II} is due in this way to oxygen atoms and F^{I} to oxygen

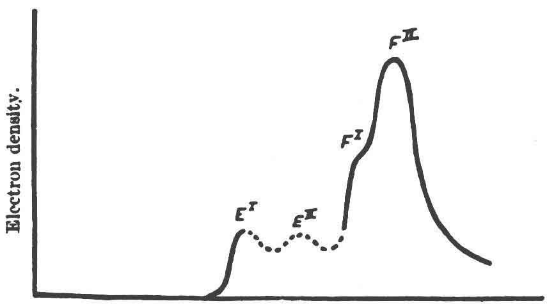

FIG. 2.

molecules has, indeed, already been made by T. L. Eckersley[4], who independently obtained evidence indicating a dual structure for region *F*.

E. V. APPLETON.

Halley Stewart Laboratory,
King's College,
London.
June 3.

Preface

Atmospheric phenomena have been the objects of curiosity for millenia and of more serious scientific study for centuries. Unlike the situation in areas of physics which have developed more recently such as elementary particles, the basic physical principles of atmospheric processes are well established. Nevertheless, the manner in which these principles are involved in many geophysical phenomena is poorly understood. This is particularly true of the science of the upper atmosphere, first called *aeronomy* by Nicolet some years ago. Despite the lack of new principles to be discovered, aeronomy has been a very active research field in recent years. This activity has been due mainly to great strides in observational techniques (i.e., by use of rockets and spacecraft), and to a lesser extent to developments in the ancillary sciences such as plasma physics and atomic physics. In fact, much of the impetus behind the recent revival of interest in the latter is due to the demands of aeronomy.

Although the field of aeronomy is now quite well developed, no textbook has previously been published. It is true that a number of excellent monographs, which are cited at appropriate places in the book, have appeared in recent years. However, for a number of reasons, they are not completely satisfactory for classroom use. It is our aim to remedy this deficiency with the present book by developing the principal themes of aeronomic science from basic physical principles. We try to emphasize the fundamental physics throughout rather than concentrate on the results of the most recent work in each area. This has the advantage of saving the student from a mass of confusing detail which may be obsolete tomorrow. Of course, a sizable portion of the text is descriptive in nature, particularly the chapter on optical phenomena. This approach is unavoidable in a text on geophysics. Although the earth is understandably given most emphasis, the upper atmospheres of other planets are also discussed to the extent that present knowledge permits. In any case, the methods developed for dealing with the earth's upper atmosphere are directly applicable to the atmospheres of other planets.

We introduce and develop those topics which seem to us to be of greatest significance to aeronomy and which should, in our opinion as practitioners of the science, be included in a course on the subject. The book is *not* based on classroom notes, and although we make no apology for this, we do wish that there might have been more opportunities for classroom trial. We were fortunate in having the advice and criticism of students of Rice University and the U.S. Naval Post Graduate School and their suggestions have been followed in many instances.

Fundamentals of Aeronomy is intended for use in a two-semester course at the senior or first year graduate level. The student is assumed to have a basic knowledge of mechanics, electrodynamics, kinetic theory of gases, thermodynamics, and atomic physics, as well as undergraduate mathematics through differential equations and vector analysis. As a refresher, the basic physics is reviewed at some length in Chapter 2. Subsequently we discuss the structure of the neutral upper atmosphere (Chapters 3 to 5), aurora and airglow (Chapter 6), ionospheric phenomena (Chapters 7 to 10), and electromagnetic waves in the ionosphere (Chapter 11). General as well as specific references and a set of appropriate problems are given at the end of each chapter. The specific references are by no means exhaustive; they have not been offered to support particular statements but to aid those students who wish to consult original sources.

We are indebted to the aurhors of all the books and papers we have read, to all the lecturers we have heard, and to all the colleagues we have known. Specifically we wish to thank Dr. Donald M. Hunten of Kitt Peak National Observatory for many helpful comments and much useful advice, as well as Professors A. J. Dessler and R. F. Stebbings of the Department of Space Science at Rice University, Professor Otto Heinz of the Department of Physics at the U.S. Naval Post Graduate School, Dr. C. A. Riegel of the Department of Meteorology at San Jose State College, and Professor R. Parthasarathy of the Geophysical Institute at the University of Alaska for helpful criticism. We also wish to express our thanks to Mrs. Jane Gutter for typing the final manuscript. Lastly, we thank our families for their encouragement and their forbearance.

R. C. WHITTEN

September, 1970 I. G. POPPOFF

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1

Introduction

"There are two things which I am confident I can do very well: one is an introduction to any literary work, stating what it is to contain, and how it should be executed in the most perfect manner; the other is a conclusion, shewing from various causes why the execution has not been equal to what the author promised to himself and to the public."

—Samuel Johnson

We cannot help but be interested in the atmosphere: It affects our attitudes, it limits our endeavors, it causes tragedies, it provides spectacular scenery. The atmosphere cannot be ignored, it is our environment. We are curious and want to know the how's and why's of atmospheric processes. We are practical and want to control, or at least make good use of, the vital forces we observe. We are also artistic, poetic, philosophical and religious; we are awed by phenomena that affect all our senses and constantly remind us of the crudeness of our knowledge, the vulnerabilities of our lives and endeavors, the infinite complexities of nature, and the sheer beauty of our world. It is no wonder, then, that the study of the atmosphere should be one of the oldest intellectual pursuits and, at the same time, perhaps the most disorganized.

The lower atmosphere of the earth has been studied intensively and formally for many generations as an area of knowledge known as *meteorology*. Meteorology deals with the lower regions of the atmosphere, regions that are accessible by ship, automobile, shank's mare, ladder, kite, aircraft and balloon. Meteorology is mainly concerned with dynamics, the heating and transport of dense gases, interactions with the surface of the earth, and to a smaller extent, the physical chemistry involved in the formation of rain and snow. Many volumes have been written and many scholars and practitioners have been trained in meteorology.

This book, on the other hand, is concerned with a much newer study, at least newer as a formal endeavor. The study is called *aeronomy* and encompasses the upper atmosphere, a region that is only accessible with rockets, satellites, and radiowaves and is studied mainly on the atomic and molecular scale. Inásmuch as the research techniques have required the use of very recently developed technology, knowledge of the upper atmosphere is very recent. Consequently, few textbooks have been written and few classes have been taught. Academically, then, aeronomy is comparatively new, even the name is not universally accepted; however, as an intellectual pursuit, studies of the upper atmosphere may well be as old as mankind.

There is a natural division between the lower and upper atmosphere (and, hence, between meteorology and aeronomy). This boundary is called the tropopause (see Figure 1.5). It is distinguished by marked changes in temperature, structure, dynamics, and constituents, and until recently, it marked the upper limit of accessibility. This boundary also marks a rather distinct change in the kinds of processes that are emphasized in research. Meteorology is principally concerned with hydrodynamics and thermodynamics, whereas aeronomy is concerned with chemical reactions, interactions between photons, protons, and electrons and atoms and molecules, and with the behavior of plasmas.

However, there appear to be important interactions between the macroscopic world of meteorology and the microscopic world of aeronomy. They are not emphasized in this book because they are not yet well delineated. The omission reflects our ignorance rather than a desire to oversimplify the distinction between meteorology and aeronomy.

The basics of aeronomy (or of meteorology) can be applied to any planetary atmosphere, and this will be illustrated throughout the book. The limited successes that have been achieved in applying the principles of aeronomy to the atmospheres of Mars and Venus have strengthened our confidence in the basics of aeronomy, have increased our knowledge of terrestrial processes, and have stimulated the entire field of atmospheric studies.

1.1 Historical Notes

1.1.1 Aurora†

The mysteries of the upper atmosphere have fascinated mankind since the first human observed an aurora. Greek writers described auroras (which are rare occurrences in the Mediterranean area) as early as the sixth century B.C.

† The historical notes on Aurora and Airglow are based largely on the writings of an illustrious pioneer in the field of aeronomy, the late Professor Sydney Chapman (*see* General References).

Aristotle discussed auroras in his work, *Meteorologia*, in the fourth century B.C.; he called them *chasmata*, which may have implied that he thought they were chasms or cracks in the sky.

A French mathematician and astronomer, P. Gassendi, described an outstanding display observed in sourthern France on September 12, 1621, and named the phenomenon *aurora borealis* (northern dawn). About a century later, on March 16, 1716, the British astronomer, Halley, observed a great aurora in London. He formulated a theory that involved magnetic particles flowing along magnetic lines of force and exciting luminescence of the atmosphere; his theory included field lines around a uniformly magnetized sphere. Considering the data he worked with, Halley's theory showed a remarkable insight. The first work devoted entirely to the aurora was written by a member of the French Academy of Sciences, J. J. de Mairan, in 1733. He debunked the popular notion that aurora was simply the reflection of sunlight on snow and ice. He also criticized the theory proposed by Halley as well as a theory proposed in 1724 by the Swiss mathematician, Leonard Euler. De Mairan believed that aurora was related to the sun's atmosphere—which he thought extended as far as the earth. Obviously, both Halley and de Mairan had glimmers of what we now believe to be correct, although it should be added that the full story has not yet been revealed.

The history of auroral research is dotted with scientific notables. The association of magnetic disturbance with auroras was discovered in 1741 by Celsius and Hiorter. Benjamin Franklin proposed an auroral theory to the French Academy in 1779; he suggested that hot air from the tropics rises and travels at a high level to the polar regions where it descends to produce "auroral lightning." The first sighting of the southern aurora was made by the famous explorer Captain James Cook, who named it *aurora australis*. The aristocrat-scientist Henry Cavendish used accounts of auroral observations to deduce the altitude of occurrence of the phenomena; his estimate of 84 to 114 km is reasonable. The atomic chemist John Dalton was among many who compiled auroral catalogs. The prominent yellow-green line emission was found by Ångstrom, though it was not identified until much later.

1.1.2 Airglow

The airglow was discovered in 1901 by Newcomb, who erroneously explained it as light from stars too faint to be seen individually. Much later (1933), Dufay showed that Newcomb's explanation could not be correct and that the source of the "light of the night sky" must be zodiacal light and atmospheric luminescence. Among the many prominent workers who predated Dufay were Van Rhijn, McLennan, and Babcock; the fourth Lord Rayleigh, who also studied auroral spectra intensively, named the airglow