ATMOSPHERIC ELECTRICITY

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PREFACE

No comprehensive text-book on all aspects of Atmospheric Electricity exists in the English language. The only works hitherto available have been Schonland's monograph on the subject (written in 1932), and three chapters in the volume on *Terrestrial Magnetism and Electricity* in the 'Physics of the Earth' series.

The present volume is intended to fill the gap and to serve both as an introduction to the subject for the uninitiated and also as a work of reference for workers on the various branches of the subject.

Certain aspects of what might broadly be termed 'Atmospheric Electricity' have been omitted. No mention is made of the exploration of the ionosphere by radio methods, since these results are quite unconnected with the other phenomena of atmospheric electricity. Again, the subject of cosmic rays, which formed a considerable portion of Schonland's monograph, is not dealt with; it would need a volume the size of the present one or greater to give an adequate account of cosmic rays now, and they have little effect upon the rest of atmospheric electricity beyond that of producing ionization. Also, no mention is made of 'Earth Currents' which appear to be quite independent of atmospheric electricity in most cases.

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J. A. C.

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CHAPTER I

HISTORICAL INTRODUCTION

1. Early observations. THE study of atmospheric electricity originated in the identification of the well-known phenomena of thunder and lightning with effects that could be obtained on a smaller scale in the laboratory with ordinary static electricity. Although the effects of thunder-storms have been of interest, not to say terror, to the human race from the earliest times, it is only comparatively recently that the nature and origin of thunder and lightning have been discovered, and he would be a bold physicist who would claim to be able to explain all the electrical phenomena of a thunder-storm.

After the discovery of electricity and its various manifestations, it was not long before the identity of lightning with an electrical discharge was suggested. The first reference to this seems to have been made by Wall (222), who, in 1708, observed cracklings and a flash with amber held at a small distance from his finger and said that 'it seems in some degree to represent thunder and lightning'. Gray (76) in 1735 observed an 'electric fire' and considered that 'it seems to be of the same nature with that of thunder and lightning'. Before long, the development of electric machines and the Leyden jar made it possible to obtain larger quantities of electricity and larger sparks, making the analogy with lightning much more obvious. In 1750 Franklin suggested that it might be possible to obtain electricity from thunder-clouds by means of pointed conductors.

2. Electricity from thunder-clouds. Franklin's prediction was verified two years later when Dalibard (41) obtained sparks during a thunder-storm from an iron rod 40 feet high, the sparks being first noticed by an old soldier named Coiffier who had been left in charge of the apparatus. A month later, and before he had heard of Dalibard's results, Franklin (59) himself obtained electricity from a thunder-cloud by means of a kite with a conducting string. Although Dalibard and Franklin obtained only small sparks, these were sufficient to prove the presence of electricity in thunder-clouds. But more evidence was needed in order to establish the identity of lightning with electric discharge, and this was provided by de Romas (163), who, quite independently of Franklin, also used a kite and obtained much more intense results, getting a spark 3 metres long and 3 cm. in diameter with 'more noise than a pistol shot'. The most intense effect of this nature occurred in the case of the unfortunate Professor Richman of St. Petersburg (Leningrad) who was killed by a lightning-flash from an insulated conductor exposed above his laboratory; presumably an actual lightning-flash struck his conductor.

The early experimenters used the production of sparks for the identification of their electrical effects and therefore were able to recognize only effects of some magnitude. Except in the case of Richman, all the results so far discussed were produced by the process now described as point discharge.

3. Electricity of fine weather. One of the earliest imitators of Dalibard was Lemonnier, who set up a wooden pole with a pointed iron rod fixed to the top. An iron wire was attached to the rod and entered a building without making any contacts, ending on a stretched silk fibre. In addition to obtaining sparks under suitable conditions, Lemonnier found that particles of dust were attracted to the iron wire when electrified. This method is much more sensitive than that of the observation of sparks and can show electrification which is too feeble to give sparks.

By this method, Lemonnier (108) first observed that effects could be obtained even in fine weather. This result was quite unexpected and was perhaps even more important than those of Franklin and Dalibard. Lemonnier also introduced a new method of obtaining electrification, using a stretched wire without points in place of the pointed conductor; in modern terminology, this must have acted as a weak collector, slowly acquiring the potential of its neighbourhood. De Romas, almost at the same time as Lemonnier, and independently, found electrical effects in fine weather, using his kite for the purpose.

Lemonnier suspected a variation in the electrical effects of fine weather with the time of day, though some of his results were due to poor insulation at night. It was left to Beccaria (11), who also used a stretched wire, to confirm the existence of a daily variation, as a result of nearly twenty years' observations. Beccaria first applied to atmospheric electricity the conception, then newly put forward, of the two signs of electricity. He showed that his wire received a positive charge in fine weather, while during thunder-storms the charge was sometimes positive and sometimes negative.

4. Work of de Saussure. The next advances are associated with the name of de Saussure (166), who devised new methods of measurement. In place of the rather crude earlier methods, he made a form of electrometer, consisting of two fine silver wires carrying small balls of elder pith, the whole being enclosed in a glass vessel with metal casing; this was much more sensitive than previous methods. De Saussure also introduced a new method of observation, that of a movable conductor; the principle of this is best understood by reference to the modern explanation of the phenomena of atmospheric electricity in terms of a vertical field (or potential gradient). An earthed conductor has a certain quantity of charge 'bound' to its surface, the amount of this charge depending on the field strength in the neighbourhood; this can be pictured in terms of lines of electric force ending on the units of charge on the conductor. If this earthed conductor is moved upwards in the air, where there is a vertical field, then the conductor is brought close to layers of air which are normally at higher potential and so the field in the neighbourhood of the conductor is considerably increased; this means that the lines of force become more concentrated and so the bound charge on the conductor is correspondingly greater. Now if, instead of being earthed, the conductor is connected by a conducting wire to an insulated electrometer initially at earth potential, then the increase in the bound charge on raising the conductor can only come from within the system and so must be balanced by an equal and opposite charge on the portion of the system away from the conductor, i.e. on the electrometer, thereby causing a divergence of the pith balls. De Saussure made the important discovery that this effect disappears on lowering the conductor to its original position, showing that the conductor has received no charge from outside the system.

De Saussure's method differs fundamentally from those of previous workers, in which effects depended on the actual collection of charge from the air by conduction. If the air were a perfect insulator, then the methods of Lemonnier and Beccaria would not have shown any effects, but those of de Saussure would still have done so. De Saussure realized that the effect was that of electrostatic induction, and he considered it, as did many after him, to be due to positive charges in the air above his instrument. De Saussure also found that he could obtain a permanent charge on his electrometer if he earthed his conductor when at the highest point and then lowered it insulated. He also used a lead ball, which he threw into the air, having a wire attached to the electrometer, but breaking connexion when the ball was in the air; the ball then takes its charge with it and leaves the electrometer with the charge of opposite sign.

De Saussure discovered that there is an annual variation in the magnitude of the effects in fine weather, which are greater in winter than in summer.

5. Early theories. In the time of de Saussure it was considered that the phenomena of atmospheric electricity could be explained by supposing that the air carried a positive charge, increasing with the height above the earth, which would account for the positive charge obtained by a point or stretched wire, and also for de Saussure's induction effects. It was not then possible to estimate the variation of field with height, and so to obtain the space charge, and thus it was not realized that the positive charge does not reside in the lowest layers of the air.

It was still necessary to suggest an origin for the positive charge thought to reside in the air, and this was provided by Volta (217), who put forward the theory that the effects were due to electrical separation of charge which accompanies a change in the state of water from liquid to vapour. Volta believed that some amount of positive electricity, as well as latent heat, was necessary for the conversion of water into vapour, thus giving a negative charge to the earth (apparently the first recognition of this charge) and a positive charge to the water on re-condensation in the clouds.

Unfortunately this attractive and simple theory, which even now with slight modification could give a good account of many of the phenomena of atmospheric electricity, has found no support from experiment in spite of numerous searches, starting with Volta himself, for electrical effects accompanying the change of state.

6. The flame collector. Volta was the first to make use of an important new method of measurement. He found that if he placed a candle or lighted fuse in contact with an exposed conductor, the latter acquired a charge of the same sign as that obtained by a point, but of increased magnitude; and that this was not due to any electrical effect of the combustion was proved by finding no charge in a control experiment carried out in an enclosed room. Moreover, after the conductor has been earthed, the charge reappears almost immediately instead of taking some time as it does in the absence of the flame. The flame may be considered to have the property of bringing the conductor to the potential of its surroundings quickly, while the ordinary conductor takes a considerable time to do so. The use of a flame allows of the measurement of short period changes in the field.

7. Theory of the charge on the earth. The idea that the phenomena of atmospheric electricity could be accounted for by the earth's being charged, without any charge in the lower air, was first brought forward by Erman (55), who showed that similar effects to those of de Saussure could be obtained by moving a conductor horizontally from an exposed to a sheltered site. But Erman did not develop his ideas very far, nor does he seem to have realized that there must be, somewhere in the air, a positive charge equal and opposite to that on the earth.

It was left to Peltier (156) to confirm the ideas of Erman. He put forward again the hypothesis of an original permanent negative electrification of the earth, without at first discussing its origin or realizing the necessity of discussing its replenishment. Peltier showed how the results of de Saussure and of Erman could be accounted for by the induction from a negatively charged earth, and he pointed out the importance of realizing that an electrometer only measures the difference between the charges on the cage and the moving system (gold-leaf or pith balls), thus explaining why an earthed electrometer does not show any effect due to the negative charge on the earth.

Peltier attempted to account for the phenomena by the possibility that water-vapour leaving the earth might carry with it some of the earth's negative charge, thus giving an explanation of annual and daily variations, the electrical effects of clouds, etc. But this theory never found any experimental support and there are many facts not covered by it.

Peltier, and many others after him, did not realize that the air can conduct electricity to a certain extent so that the negative charge on the earth is dissipated at an appreciable rate and requires some mode of replenishment.

8. Mathematical principles. With the theory of Peltier, the ground was prepared for the introduction of mathematical methods and this was first done by William Thomson (afterwards Lord Kelvin), who introduced the idea of 'potential' and made use of the ideas of Faraday in regard to 'lines of force'. These showed that a vertical field of force (or vertical potential gradient) is associated with a charge on the earth's surface, the lines of force ending on charges residing on conductors. He showed that the use of a flame or fuse, as described by Volta, or the use of a water-dropper, which he himself invented, serves to equalize the potential of a conductor with that of the air in its neighbourhood. He also showed clearly that the increase of effect produced by raising a conductor in the air must be ascribed to an increase in potential, but not necessarily to any increase in potential gradient or field strength, and that the results might be explained by a constant field with, therefore, no need for any positive or negative charge in the lower air. This raised the question of the location of the other ends of the lines of force which start on the earth's surface; in normal fine weather the charge on the earth is negative and therefore the problem is that of the location of the corresponding positive charges. Do these charges exist in the air itself, perhaps higher than can be reached by any easy means of measurement, or do the lines of force extend to infinity? In other words, is there a resultant charge on the earth and its atmosphere as a whole, or is the charge on the earth balanced by a charge in the atmosphere? Thomson realized that the question could not be given a definite answer from measurements made only at the earth's surface, but that, for discussion of effects at and near the earth's surface, the answer to the question is immaterial. More recent work has shown the existence of a conducting layer or layers in the upper part of the earth's atmosphere, and so the lines of force from the earth must end on this layer if not before. It is still not possible to answer the question whether there are lines of electric force outside this layer, for the layer acts as a screen for electrostatic effects, so that charges or fields outside the layer cannot affect the earth inside.

Thomson realized the importance of continuous measurement of the field, because this fluctuates so much that isolated measurements can never be trusted to give a good picture of the facts. He set up the first instrument for the purpose, using his newly invented quadrant electrometer, with a water-dropper as collector (see § 59).

9. Work of Exner. It was realized by Exner (56) that the absolute value of the field (potential gradient), and hence of the charge per unit area of the earth's surface, could not be obtained by Thomson's method, because the collector disturbs the field. Exner, followed by Elster and Geitel (51), devised methods for obtaining the absolute potential gradient. Pursuing Peltier's theory that the variation of the field is due to the passage of some of the negative charge on the earth into the air by means of the water-vapour, he thought he obtained a relation between the field and the humidity in agreement with this theory. Confirmation of this would be obtained if it were found that the field increased with the height above the ground, for there would be extra lines of force from above ending on negative charges on the water-vapour in the lower regions of the atmosphere. But observations have shown that, at any height above some hundred metres, and probably also lower, the field decreases with height, so that the charge in the lower air is positive not negative.

10. Conductivity of the air. Among the earlier experimenters, Coulomb and Matteucci had established that the air is a conductor of electricity, but the importance of this was not realized until the observations of Linss (112), who pointed out that if the rate at which charge leaks from the earth owing to the conductivity of the air were maintained, then the whole charge on a portion of the earth would leak away in a period of about 10 minutes; or, to put it slightly differently, the positive charge reaching a portion of the earth's surface by conduction amounts, in a period of 10 minutes, to the negative charge permanently on the surface. And yet the earth retains its negative charge!

This has raised what has become one of the most important problems of atmospheric electricity, the question of how the earth's negative charge is maintained, and various theories have been put forward to account for a regular passage of negative electricity to the earth, often termed the 'supply current'. It is now fairly generally agreed that it is in stormy weather that the negative charge comes to the earth to balance the positive charge arriving in fine weather.

Much work has also been done on the nature of the conductivity of the atmosphere. Elster and Geitel (52) and Wilson (235) demonstrated the existence of 'ions', particles of molecular size or larger, carrying positive or negative charges. Following on this discovery, Langevin (106) found 'large' ions and Pollock (160) and others have found ions of intermediate size.

11. The origin of atmospheric ionization. The properties of ions in the atmosphere have been investigated by many workers, and it has been discovered that ions constantly disappear by combination with ions of opposite sign or are transformed into ions of different size by combination with uncharged particles. It thus becomes evident that there must be some mechanism for the production of these ions. The most obvious agent would seem to be the radioactive bodies in the earth itself, but this would lead to the prediction that the conductivity of the air would decrease as we rise above the earth. Measurements, first by Hess (84) and Kolhörster (103), have, however, shown that there is, in fact, a very considerable increase on rising above the earth, and this cannot be due to effects of terrestrial origin. Further work has established beyond any reasonable doubt the existence of highly penetrating radiation entering the earth's atmosphere from all directions in space. These so-called 'cosmic rays' are capable of reaching the earth's surface through the atmosphere and even of penetrating an appreciable distance into the earth, and thus are an effective source of atmospheric ions at all levels, though the ionization is greater at greater altitudes. Another, less penetrating, radiation reaches the earth's atmosphere from the sun; this makes an important contribution to the ionization of the highest levels of the atmosphere where the conducting layers are situated, but is absorbed before reaching the lower layers. The origin and nature of the primary cosmic rays and the processes by which secondary rays are produced will not be dealt with here; from the point of view of atmospheric electricity, all that matters is the fact that there is ionization which increases on rising above the earth, and that for the greater part of the atmosphere the ionization is independent of solar or sidereal time. Close to the earth, ionization due to radioactivity is important.

12. The thunder-cloud. A considerable part of the work on atmospheric electricity during the present century has been concerned with the electrical nature of the thunder-cloud and the processes by which the separation of charge within the cloud is effected. The names chiefly associated with this subject are Wilson (238) and Simpson (205), and there was for some time a controversy between the two as to the polarity of a thunder-cloud, i.e. whether it was to be considered to have a positive upper part and a negative base or vice versa. Simpson favoured the theory of the positive base, largely on the ground that photographs of lightning-flashes show that those from cloud to earth are almost always branched downwards, and that laboratory photographs of sparks show branching from the positive pole. Simpson accounted for this negative polarity of a cloud on the theory of the separation of charge by the breaking of drops. Wilson, on the other hand, insisted that observations by himself and others on the fields and field changes of thunder-clouds could only be interpreted reasonably if the cloud had a positive polarity, i.e. a negative base. Spark discharges under conditions more close to those of lightning have shown (Schonland and Allibone, 179) that the direction of branching is not a criterion of polarity, and more recent work, using balloons (Simpson and Scrase, 209) has shown that the top of the cloud is positive, with a negative charge below and in some, perhaps all, cases, there is a positive charge in the base as well.

13. Modern advances. The most recent work on atmospheric electricity has been on many lines. A considerable part of it has been concerned with the two problems mentioned above, that of the supply of negative charge to the earth and that of the separation of charge in thunder-clouds. Other problems that have attracted attention include the nature of the lightning-flash, the electrical charge on rain, and the equilibrium of ionization in the atmosphere.

CHAPTER II

FUNDAMENTAL PRINCIPLES AND GENERAL SUMMARY

14. Scope of the chapter. THERE are a number of fundamental principles and general results that are made use of in the study of atmospheric electricity, and it is convenient to collect these together and to state them in the form in which they will be used in later chapters.

The various phenomena of atmospheric electricity are so much interconnected that a detailed study of any one branch requires a knowledge of some of the facts and ideas of other branches, and it is therefore not possible to adopt a completely logical order for the whole subject. For the benefit of the reader who has no previous knowledge of the subject, it has seemed advisable to give in this chapter a general outline of the phenomena and their relations, leaving the details until the appropriate chapters.

15. Potential. The idea of the electrical 'potential' at a point, first introduced by Kelvin, is very important in connexion with the subject of atmospheric electricity. The definition of the potential difference between two points is that it is the mechanical work necessary to move unit positive charge from one point to the other; it follows that, unless there is a current flowing, there is no potential difference between any two points of a conductor. The potential at a point can be obtained by choosing an arbitrary zero of potential and finding the work done in bringing the unit positive charge from the zero to the point in question. In theoretical electrostatics, the zero of potential is conveniently chosen as the potential of a point far removed from all electric charges, and it therefore follows that an isolated uncharged body has zero potential. In the case of atmospheric electricity, it is not possible to choose such a zero, for we cannot find the work done in bringing a charge from an infinite distance to the earth's surface, since we know nothing about electrical conditions outside the conducting layer in the upper atmosphere.