ELECTRICAL PHENOMENA OCCURRING AT HIGH LEVELS IN THE ATMOSPHERE.

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1. It is well known that the properties of the atmosphere are different in important respects above and below a fairly well-defined surface of separation, which is usually situated at a height of about 10 or 15 kilometres from the ground. The layer beneath this surface is called the troposphere, and is characterized by the presence of much convective motion; the temperature in this layer consequently diminishes upwards. In the upper layer, or stratosphere, the temperature shows no systematic variation with height, so that here there must be radiative equilibrium, little disturbed by convective mixing. The stratosphere has been explored to a height of 25 or 30 kilometres by means of *ballons-sondes* bearing meteorological instruments.

The electrical phenomena which have so far formed the subject-matter of atmospheric electricity, as ordinarily understood, relate mainly to the troposphere and the lower part of the stratosphere. Such, for instance, are thunderstorms, the surface variations of electric potential gradient, and changes in the ionic content of the air. The electrical phenomena which will be considered in this paper occur at "high" levels above the regions just named—probably above even the greatest heights yet attained by meteorological balloons.

They make themselves apparent in two principal ways. Some of them, though not all, are accompanied by luminosity; this, being observable chiefly towards the polar regions, is known as the aurora polaris. They also produce magnetic effects, which constitute our other source of information. The changes of magnetic force at the earth's surface are continuously recorded at a widely distributed network of observatories. These changes originate mainly in the upper atmosphere, directly or indirectly. The direct part is due to electric currents in the atmosphere, the indirect to secondary currents induced by the former in the conducting earth; the ratio between the two corresponding portions of the magnetic effect at the surface is 2 or 3 to 1. The earth currents flow at greater or lesser depths according to the rapidity with which the external currents vary; those associated with the regular daily magnetic variations flow chiefly at 200 or more kilometres below the surface. At times of magnetic disturbance the changes are much more rapid, and the earth currents do not penetrate so far down; telegraphic engineers know, to their cost, of the enhanced value of the currents in the surface strata at such times. The detailed relations between earth currents and the magnetic variations have not yet been fully elucidated,

but the matter cannot be entered upon here, where attention will be confined to the primary phenomena occurring in the atmosphere.

Auroræ and the magnetic variations valuably supplement one another as sources of information of these electrical phenomena. Each affords certain data which are not deducible, or deducible only with difficulty, from the other. On the whole, the magnetic variations form the richer and more available fund of knowledge, since they are observable over the whole accessible portion of the earth, and, moreover, *continuously* observable—by day or night, and independently of the state of the sky. Auroræ, on the other hand, can be seen only over a comparatively limited region, and even there not by day, nor at night when the sky is cloudy or too brightly illuminated by scattered moonlight. Naturally, however, both groups of phenomena have been concurrently investigated, a proceeding assisted by the study of the changes in progress on the sun—i.e. of prominences, sunspots, and other surface features—with which auroræ and the magnetic variations are closely associated.

2. My aim in this paper has been to give a general outline of the subject, without detailed argument or references. The account is not limited to what can be regarded as certain conclusions; without, I hope, departing too far from the basis of observational evidence, conjectural views have also been admitted—a course which seems both the most interesting and appropriate method of dealing with a science of which, as of this, our knowledge is rapidly advancing. For the materials used in this synthesis the writings of many authors have been utilized: particularly, as regards the magnetic variations, the papers of Professor Schuster, Dr. Chree, Mr. Maunder, and Dr. Moos; and as regards auroræ, those of Professor Birkeland, Professor Störmer, and Dr. Vegard. While expressing indebtedness to these investigators, I do not wish to be taken as implying their agreement with all the theoretical interpretations here described, some of which are due to these and other writers, while others are independently advanced.

3. The magnetic variations with which we shall be concerned are (a) the regular daily variations characteristic of magnetically "quiet" days, and (b) the irregular, intermittent changes associated with magnetic disturbances, which when particularly intense are known as magnetic storms. On ordinary days the daily magnetic variation, approximately freed from irregular fluctuations by averaging for several days,

consists of two parts: that mentioned under (a) together with an additional portion introduced by, and proportional to the intensity of, the existing disturbance. The second portion, or disturbance diurnal variation, represents an inequality in the incidence of disturbance effects round the circles of latitude; the causes which produce it are those responsible for magnetic disturbance, and differ from those which originate the undisturbed or quiet daily variations. Probably no day is completely "quiet" magnetically: in the polar regions of the earth especially, magnetic disturbance is particularly intense and almost always present: here the disturbance daily variation usually considerably exceeds the constant, quiet-day portion. But the two parts of the daily variation can be separated to some extent by comparing the daily changes on quiet and highly disturbed days, and are found to be of quite distinct types. The disturbance daily variation is approximately the same, except in intensity, when derived by comparison of specially quiet days with days of magnetic storm, or with all days.

Both the disturbed and quiet day changes of magnetic force depend on locality, season, and local time. They vary also in intensity—and the disturbance changes vary in frequency—with the state of activity on the sun's surface. The solar activity, the magnetic variations, and auroræ, all manifest the cycle of change which is most familiarly known as the 11-year cycle of sunspot frequency.

The moon, as well as the sun, affects the earth's magnetic field, and there are lunar diurnal magnetic variations, depending on the moon's hour angle (or local lunar time), which are of as great interest as the ordinary solar diurnal variations, though of inferior magnitude.

4. In discussing these phenomena it is desirable to consider the earth as a whole, instead of restricting attention to the sequence of events at one or two localities on it; and to regard it as viewed from the bodies which govern its magnetic and meteorological changes; that is, from the sun mainly, but in the case of the lunar diurnal variations from the moon also.

The solar and lunar diurnal changes depend principally on the latitude of the station and the local time (neglecting, for the time being, the dependence on the sunspot epoch). These variables merely define the position of the station relatively to the sun (or, in the case of lunar time, to the moon). Locally regarded, the changes represent the effect of the moving sun, the effect being approximately reproduced at all stations round a given parallel of latitude as the sun "moves round the earth." Viewed from the sun, they appear as the passage of conditions at each station through stages characteristic of positions fixed relative to the sun, as the earth's rotation carries a given station through a succession of such positions. In so far as the earth is symmetrical about its axis of rotation, these stages do not vary throughout the daily revolution, and the changes in any locality depend on latitude and local time, without reference to longitude. The inclination of the magnetic to the geographic axis, however, and the geographical inequalities on the earth, preclude the exact fulfilment of this condition.

From the sun, the earth is seen to be moving along in its orbit from right to left (cf. Fig. 1), and to be turning about its axis so that the front, sunlit, hemisphere is moving from left to right; provided that the observer on the sun is supposed to stand perpendicular to the plane of the earth's orbit, so as to view the North pole of the earth above the South pole. Since the sun itself is turning about its own axis in the same direction as the earth, any emission from its surface which happened to be directed towards the earth would sweep the latter, like water from a fire-hose, from right to left. Again, the moon's orbital motion round the earth is in the same direction as the earth's diurnal rotation.

FIG. 1.—Illustrating the motions of the earth, moon, and solar streamers as viewed from the sun (§ 4).

NMS = Noon meridian.
NS₁S = Sunrise meridian.
NS₂S = Sunset meridian.

The day or sunlit hemisphere is directly visible, the night or dark hemisphere is behind; the P.M. and A.M. hemispheres are respectively to the right and left of the noon meridian.

Over the right-hand half of the earth the sun has "crossed the meridian," and the local time is after noon. This hemisphere will therefore be termed the P.M. (*post meridiem*), and the left-hand the A.M. (*ante meridiem*) hemisphere. Similarly we may speak of the sunlit and dark, or day and night hemispheres, which are separated by the "twilight circle" of the earth. This circle is composed of the sunset and sunrise meridians (on the right and left respectively), which with the noon and midnight meridians (in the plane containing the sun) divide the earth into four equal quadrants.

5. Before describing to what causes the quiet-day and disturbance magnetic variations are due, it is well to exclude explicitly certain possibilities which, though they naturally suggest themselves, are not confirmed on examination. The magnetic variations are not caused by direct magnetic action on the part of the sun or moon: nor do they represent the varying magnetic field of streams of electric charges of one kind, moving separately from charges of the opposite

kind, whether within or outside the atmosphere. They are, in fact, variations in the magnetic field of electric currents of the ordinary type flowing in more or less horizontal layers in the upper atmosphere; that is, currents in which the magnetic field is unaccompanied by any appreciable electrostatic field. They are produced, moreover, in essentially the same way as are the currents generated in ordinary commercial power stations, i.e. by electromagnetic induction. In the present instance the earth's permanent magnetic field (the origin of which is still unknown) constitutes the magnetic field of the terrestrial dynamo. The atmosphere, itself in motion owing to various causes, is the armature; while certain layers which are specially ionized (mainly by solar action) are the conductors in which the flow of electric current takes place.

The atmospheric motions concerned are of two

FIG. 2.—Lines of equal pressure (dotted) and of instantaneous direction of motion in a tidal system of circulation in the earth's atmosphere, viewed from the tide-producing body (§ 6).

In this drawing there is supposed to be no lag of phase, so that maximum pressure occurs at M and minimum at M'. The opposite side of the earth resembles that shown here. The meridians NZS are lines of zero pressure, separating regions over which the pressure is in excess and defect respectively.

kinds, one set being associated with the quiet-day magnetic variations, while the other set is connected with magnetic disturbance. The latter motions originate in and are confined to a region high up in the stratosphere: the former extend throughout the troposphere and a large part of the stratosphere, but are electromagnetically effective only at a considerable height above the base of the stratosphere. Below this level the air is not sufficiently conducting to allow any appreciable flow of current, so that the irregular convective motions in the troposphere (§ 1) have no part in producing the magnetic variations.

6. The set of atmospheric movements which gives rise to the quiet-day diurnal magnetic variations consists of two great world-wide circulations of tidal type. One is a true tidal motion, due to the moon.

The other, of similar character but of different phase and fifteen-fold the amplitude, is of solar origin; it is mainly produced by thermal—not tidal—action. The difference in phase indicates a difference of orientation of the two systems of circulation relative to their governing bodies the sun and moon. Moreover, the orbital motion of the moon causes the lunar tidal system of circulation to shift relative to the solar system, completing one revolution, in the same sense as the earth's diurnal rotation, in a lunar month.

In each case the movement of the air is mainly horizontal. The current-lines in the case of such tidal motions are indicated in Fig. 2, where for simplicity a particular phase, different from that of either the solar or lunar circulations, has been adopted. The maximum velocity occurs at the equator, and in the

FIG. 3.—Electric current-lines (dotted) and lines of horizontal magnetic force at the earth's surface, resulting by electromagnetic induction from the tidal atmospheric circulation of Fig. 2 (§ 6).

The layer in which the electric currents flow is for simplicity assumed to be of uniform conductivity. The obliquity of the magnetic to the geographical axis of the earth is neglected. The above curves give an approximate representation of the semi-diurnal component of the diurnal magnetic variations (except as regards phase), viewed from the sun or moon.

solar case is approximately 1 kilometre per hour. The velocity is nearly the same at all levels up to a considerable height; the solar diurnal circulation, however, seems not to extend so far up as the lunar circulation: the latter is present in the auroral layer, at a height of 100 kilometres, while the solar diurnal movement does not seem to exist there.

Like all tidal circulations, these two movements are of semi-diurnal type; that is, the motion in either case is the same over the two halves of the earth separated by any meridian plane. The motion being horizontal, the induction takes place across the vertical component of the earth's magnetic force. This component, it should be recalled, is downwards in the Northern, and upwards in the Southern hemisphere, but is otherwise nearly symmetrical with respect to the equator. The

induced electromotive force is perpendicular to the direction of horizontal motion, to the left in the Northern, and to the right in the Southern hemisphere.

The systems of electromotive force, like those of atmospheric motion, are semidiurnal (cf. Fig. 3); but the systems of horizontal electric currents impelled by those forces, in the layer which is sufficiently conducting to give scope to them, are not of this type. They are not identical over the two halves of the earth separated by any arbitrarily chosen meridian plane: their intensity is, in fact, much greater over the sunlit than over the dark hemisphere. This is shown by the considerably enhanced activity of the solar and lunar diurnal magnetic variations resulting from these currents, during the hours of solar daylight, and during the season of the year (summer) when, at a given station, the rays of the sun are most directly received. The lunar diurnal magnetic variations exhibit the effect particularly clearly; since the lunar tidal system of circulation progressively advances relative to the sunlit hemisphere (*vide supra*), the lunar hours during which the electromagnetic effect is magnified regress throughout the lunar month; the character of the lunar diurnal magnetic variations consequently changes regularly in the course of a lunation, the activity being greatest during the hours of solar daylight at each epoch.

Besides this daily and seasonal variation in the intensity of the quiet-day magnetic changes, the latter vary considerably in intensity (while preserving their type almost unaltered) throughout the cycle of solar activity. The one variation indicates a dependence on the position of a station relative to the sun, the other on some intrinsic solar factor affecting the earth as a whole. Both effects are explained by supposing the electric *conductivity* of the layer of air in which the currents flow to vary in the manner described; and that this is because the conductivity is produced by some solar ionizing agent. This agent, as I have shown elsewhere (in a paper communicated to the Cambridge Philosophical Society) is ultra-violet radiation, which must be emitted more strongly at sunspot maximum than at sunspot minimum. It is shielded from the dark hemisphere, but over the sunlit hemisphere it penetrates to a considerable depth in the earth's atmosphere, much below the under limit of the auroral layer (about 100 kilometres above the ground). It seems likely that it is the lower surface of the layer thus ionized by solar radiation which is responsible for bending "wireless" waves round the earth, and so increasing the distance over which messages can be transmitted in this way. Professor G. N. Watson has recently given conclusive proof that, unless prevented by the presence of such a conducting layer, the electric waves would in large part travel outwards into space, instead of, as they are observed to do, round the globe.

The ionization produced by the ultra-violet radiation (which is all absorbed in the atmosphere at a great height above the ground) is most intense over regions which receive the sun's rays vertically, and it diminishes to a low value near the twilight circle and over the dark hemisphere. If the ionization is associated with the production of luminosity, we are prevented from

observing the latter owing to the presence of daylight, so that the quiet-day magnetic variations are unaccompanied by any visible atmospheric phenomena. The auroræ are *not* associated with these electromagnetic effects, of whose existence the quiet-day diurnal magnetic variations afford the sole indication.

7. The magnetic variations to which auroræ are related are the magnetic *disturbance* changes, including, of course, the disturbance diurnal variation. As regards the sun, moreover, auroræ are connected with *locally* agitated regions on its surface, instead of to the surface as a whole (whence, it seems probable, there proceeds the æthereal radiation which ionizes the lower conducting layer in the earth's atmosphere, as just described).

Magnetic disturbances and auroræ are produced by the injection into the earth's atmosphere of electric corpuscles projected in confined streams from disturbed regions on the sun. These streams may be emitted in any direction, so far as we know at present; their existence is made known to terrestrial observers only when a stream is projected so that, in the course of the solar rotation, it sweeps over the earth. The streams are often of considerable angular diameter, e.g. 10 degrees or more. As the angular diameter of the earth, viewed from the sun, is only 18.6 seconds of arc, it becomes completely enveloped in the streams; and often remains so for hours or even days, notwithstanding that the relative speed of the streams at the distance of the earth enables them to sweep right across the earth in 35 seconds. The latter fact explains why magnetic storms, the particularly intense and world-wide disturbances which occur when the earth is enveloped in a dense solar stream, are observed to commence at almost the same instant all over the earth. Again, since disturbed regions on the sun often continue to emit streams of electric corpuscles in the same relative direction for a period of more than one solar rotation, a given stream may traverse the earth more than once. This accounts for the observed tendency for magnetic conditions to recur after an interval equal to the time taken by a stream to reach the earth again, after a complete rotation with the sun. This, which is shown by quiet, no less than by disturbed conditions (corresponding respectively to the absence and presence of streams in the earth's neighbourhood) is only a tendency and not a definite periodicity: for the sequence of streams existing at any given time is continually being interrupted by the cessation, or alteration of direction, of old streams, and the initiation of new ones.

8. The streams seem to consist entirely or predominantly of corpuscles having the same sign of electric charge. They are ejected from the sun with a speed comparable with that of light, and travel outwards approximately in straight lines. When they approach the earth, however, their rectilinear motion becomes modified owing to their entry into the earth's magnetic field. A magnetic field, of course, exerts a force on a moving electric charge, perpendicular to the plane containing the direction of the magnetic force at the point instantaneously occupied by the charge, and to the line of motion of the charge. In a uniform magnetic field an electric charge will, in general, describe a spiral path, the axis

of the helix lying along the direction of the magnetic force. In the earth's field, which is uniform neither in direction nor in intensity, the motion of the solar corpuscles is more complicated, and the problem of calculating their paths has not yet been completely worked out. Some important results have, however, been arrived at. It appears that, though in an intense stream the particles seem to impinge upon the atmosphere from all sides, there is a strong tendency for them to be drawn in towards the earth's magnetic poles; yet not so as to fall most numerous at the magnetic poles themselves, but rather around two zones, one centred at each such pole. The radius of the zones can be calculated approximately, but depends upon the nature and speed of the particles. The zones are naturally identified with the zones of maximum auroral frequency; these are centred as described, and have a radius of about 20 degrees. This is much greater than the radius calculated on the assumption that the solar corpuscles are β -particles (i.e. negative electrons, having a mass much less than that of a hydrogen atom, though travelling with great speed). On the other hand, the observed agrees pretty closely with the calculated radius, if the particles are supposed to be α -particles, positively charged, but otherwise identical with ordinary atoms of helium moving with great velocity.

9. Three principal consequences follow from the injection of the solar corpuscles into the earth's atmosphere. First, the particles break up many of the molecules which they encounter before being brought to relative rest in the atmosphere. This means that the layer in which the retardation takes place is ionized; during times of magnetic disturbance, therefore, there are two conducting layers instead of only one. Secondly, where the ionization is particularly intense it is accompanied by luminosity, observed as auroræ; this accounts for the polar distribution of auroræ, and their association with magnetic disturbance. The production of the latter depends on the third effect mentioned, viz. the electrification of the air. This is accompanied by electrostatic forces of sufficient intensity to impart an important degree of motion to the extremely rarefied air. This is the second of the two types of motion referred to in § 3.

The general nature of the movement can be readily inferred. The mutual repulsion of the entangled charge spread over the world-wide spherical layer produces an upward, outward movement, as in a charged soap-bubble. Thus the air travels vertically upwards—except during the first few minutes of a magnetic storm. For at first the downward momentum of the injected particles depresses the air, before the electricity has accumulated sufficiently to reverse the motion.

In the process of electromagnetic induction the vertical movement acts by cutting across the horizontal component of the earth's magnetic force. Since the latter is directed from North to South, the upward motion induces an electromotive force from East to West, while the initial downward velocity induces one in the opposite sense. An electric current flowing from West to East, as in the latter case, will increase

the horizontal magnetic force at the earth's surface; this is what is usually observed in middle and lower latitudes during the first few minutes of a magnetic storm. Afterwards the reversal of motion of the air, and of the resulting electromotive force, causes a diminution in the horizontal magnetic force; this is one of the most characteristic features of magnetic storms.

10. The electromagnetic effects of a storm are not quite of the simple type which might be expected from the remarks of § 9. The complication arises mainly from the unequal distribution of the corpuscular injection. This inequality is not altogether due to the deflection of the particles by the earth's magnetic field; in part it is due to the circumstances of emission from the sun. Over any given region near the auroral zone, for instance, visual observation of the auroræ strongly suggests that the injection is both "patchy" and intermittent.

This causes the ionization of the air to vary considerably from place to place, and the inequalities of conductivity thus set up are likely to endure for some hours. Consequently, even if the electromotive force were quite uniform in direction and intensity, the current-flow would be far from uniform. As the inequalities of conductivity are probably greatest in the polar regions, we have an explanation of why the magnetic disturbances in those parts are specially irregular. The great *intensity* of disturbance there is due to the high average value of corpuscular injection and ionization around the poles. I have found evidence, which will be discussed in a future paper, that the conductivity in the "maximum auroral zone" is particularly intense.

Besides these comparatively small-scale inequalities of precipitation and conductivity, the study of the disturbance portion of the diurnal magnetic variations (which represents the inequality of disturbance round the circles of latitude) shows that the solar corpuscles fall more intensely over the P.M. than over the A.M. hemisphere. Thus the two solar ionizing agents have different "most favoured hemispheres"—the sunlit one being that most affected by the other agent, the ultra-violet wave radiation.

This longitudinal inequality of conductivity in the auroral layer (here regarded as extending all round the globe, whether or not luminous effects are visible) shows itself in the production of a greater diminution of the horizontal magnetic force, in middle and equatorial latitudes, over the P.M. than over the A.M. half of the earth. This appears clearly from the disturbance diurnal variation of horizontal magnetic force in the latitudes mentioned (cf. Fig. 4); it would necessitate too long a digression to explain how the disturbance diurnal variation in the other magnetic "elements" and in other latitudes likewise indicates the existence of excessive precipitation of corpuscles over the P.M. hemisphere and round the "auroral maximum" zone.

11. One interesting circumstance connected with the non-uniform injection of charge is that, while it results in the existence of inequalities of electrical conductivity over the spherical layer affected, the charge itself is continuously re-distributed so as to

keep the surface density of electrification practically uniform. This is true, of course, of any spherical electrified shell of sufficient (though not necessarily uniform) conductivity. In the case before us the conductivity seems quite large enough to permit the re-distribution to take place with a rapidity altogether exceeding that of the escape of the charge right away from the atmosphere—an escape which does, however, ultimately result (in the course of a few hours or days, according to the duration of precipitation) from the upward motion referred to in § 9. The re-distribution seems to be of an oscillatory character, and so to be accompanied by the propagation into space of Hertzian waves of wave-length approximately equal to the

FIG. 4.—Current-lines (dotted) and lines of horizontal magnetic force at the earth's surface, corresponding to the disturbance portion of the solar diurnal magnetic variation (§ 10), as viewed from the sun. The complications near to the pole, resulting from the specially high electrical conductivity of the upper atmosphere in the auroral zone, are neglected in this diagram.

diameter of the earth. The period of these waves is about one-twentieth of a second.

The surface density of charge thus being maintained uniform over the earth, the upward electrostatic force tending to produce the vertical motion of the air is likewise uniform. The vertical motion itself, however, will not be uniform, since it will be unequally resisted by the mechanical force acting downwards on the induced currents, tending to prevent their production. This mechanical force is proportional to the intensity of the horizontal currents and of the horizontal component of the earth's magnetic force. The latter is least at the poles and greatest at the equator, while the former is probably greatest in the auroral zone. It is therefore not very easy to estimate the distribution of the vertical motion over the layer.

One further circumstance in this connection deserves

mention: the precipitation of electric charge into the atmosphere does not produce an "electric storm" at the earth's surface, as well as a magnetic storm (or minor magnetic disturbance). During a world-wide magnetic storm, indeed, in which the extension of the corpuscularly ionized layer all round the earth permits a uniform re-distribution of the charge, no change in the electrostatic field at the earth's surface would be expected—for a charge on the outside of a conductor does not produce any electric force in its interior. But even in the case of a minor disturbance, due to a stream of corpuscles which falls upon, and renders conducting, only a limited portion of the upper atmosphere, no electrostatic change at the earth's surface is observable. This seems to be owing to the electric shielding effected by the other ionized layer, which extends all round the earth (though it is most conducting over the sunlit hemisphere). This layer is lower than the other, so that local charges in the auroral layer do not electrically affect the interior of the "diurnal variations" layer (§ 5).

The grounds for the conclusion that the latter is lower than the auroral layer may be briefly described here.* If the solar semi-diurnal atmospheric circulation, which is produced by thermal action at or near the earth's surface, extended up into the auroral layer, the conductivity existing there at times of magnetic disturbance would permit an increased induction of "diurnal variation currents" at such times. In particular, the semi-diurnal component of the solar diurnal magnetic changes should be increased; this is not found to occur, the modification in these changes due to disturbed conditions being of quite different type (cf. Figs. 3 and 4). The lunar atmospheric tide, on the contrary, is produced by forces acting on each portion of the air throughout its whole extent, so that it should extend higher up than the solar diurnal circulation; and this is confirmed by the fact that the lunar semi-diurnal magnetic variation is increased at times of disturbance. Hence the layer in which the quiet-day magnetic changes are produced must be lower than the auroral layer. Assuming that the latter is situated at approximately the same height in all latitudes (i.e. that the penetrating power of the corpuscles is independent of the latitude to which they are deflected), the former layer may be ascribed to a lower level than 100 kilometres.

12. Before proceeding to consider the physical nature of the solar corpuscles, and their connection with the ultra-violet light which ionizes the lower conducting layer of the atmosphere, some of the principal features of auroræ must be touched on.

The existence of a zone of maximum auroral frequency round each pole of the earth's magnetic axis, and of radius about twenty degrees, has already been mentioned. Near these zones auroræ are visible on almost every night on which the conditions of seeing are suitable. When specially intense streams of corpuscles are in the earth's neighbourhood, however, precipitation of intensity sufficient to produce luminosity occurs over a more extended region. At such

* They are given more fully in a paper communicated to the Cambridge Philosophical Society, December 1918.

times, which are marked by the occurrence of unusually violent magnetic disturbance, i.e. by magnetic storms, auroræ are observed over a large range of latitude, simultaneously in each hemisphere. Occasions on which auroræ are thus visible so far south as London, for instance, occur on an average about six times a year.

There are many different forms of auroræ—in particular, arcs, streamers, curtains and coronæ. But it seems not unlikely that all, or nearly all, these are merely different aspects of aggregations of one elemental unit, the simple streamer or ray. When curtain auroræ are viewed from a point directly beneath them they are seen to consist of a thin wavy and discontinuous series of parallel streamers. The auroral corona appears to be formed of a rather different arrangement of similar rays. This unity of composition agrees with the evidence of height determinations (which show that all types of auroræ come down to approximately the same level) in indicating that there is no essential physical difference between the various forms. The lower limit of height is 100 kilometres above the ground, very nearly, in all cases. Vegard states that no auroræ has been certainly proved to extend downwards below a height of 95 kilometres. The great majority lie between 100 and 130 kilometres, and within this range there are two well-marked levels of maximum frequency of occurrence, corresponding to lower limits of 100 and 106 kilometres. This indicates that the solar corpuscles probably fall into two homogeneous groups, travelling with rather different speeds and therefore having different powers of penetration. The heights named do not seem to vary with latitude, or from year to year; thus the degree of activity on the solar surface does not affect the nature and speed, but only the intensity and frequency, of corpuscular emission from the sun.

13. There is a tendency for the brightest part of auroral bands and rays to occur at their lower edge, though in the case of rays it is occasionally found some distance above this level. The fact has a bearing on the question as to the precise nature of the solar particles, tending to confirm Vegard's hypothesis that they are α -particles, as the radius of the maximum auroral zone suggests (§ 8).^{*} Such particles, of molecular mass, are found to penetrate to a definite distance when projected into a gas; they travel in practically straight lines for this distance and then come to a relatively dead stop when their velocity is reduced to that of the surrounding molecules. The ionization (and luminosity, if such is produced) is greatest shortly before they reach their limit of penetration. These features, as we have seen, are manifested by auroræ, and are quite distinct from those which characterize the projection of negative electrons, β -particles, into a gas. Moreover, a stream of α -particles has much greater power than has a stream of β -particles of being projected intact in free space to a great distance; for the charge on an α -particle is only twice that of a β -particle, while the momentum of the α -particle is far greater than that of the other. It is thus better able to resist the dispersing influence of the electrostatic repulsion mutually exerted by the members of a stream of particles all of one sign

of charge. A further argument tending to the same conclusion rests upon the explanation which has been given of the increase in the earth's horizontal magnetic force during the first few minutes of a magnetic storm. This (§ 9) was attributed to the downward momentum of the injected particles, and the fact that the momentum is able to manifest itself in this way is much less surprising if the particles are as heavy as helium atoms than if they are mere negative electrons.

14. Two further points which arise for consideration relate to the circumstances of the corpuscular emission from the sun, and to the connection between the ultra-violet wave-radiation and the corpuscles. These, if α -particles, may possibly be products of radio-active processes occurring on the sun. This would explain, in a way not easy on any other hypothesis, the high speed and homogeneity of the corpuscular rays (§ 12). Again, the suggestion derives support from the existence of the other solar ionizing agent, the ultra-violet light radiation, which, as we have seen, is more penetrating than the corpuscular emission. In the past, before the evidence for the effective presence of *both* kinds of radiation was recognized, discussion concerned itself with the relative merits of the two—corpuscles and ultra-violet light—regarded as *alternative* ionizing agents. Two of the difficulties were as follows: in the case of the corpuscles, the accumulation of charge in the earth's atmosphere was mentioned as an argument against them—in the present review, the escape of accumulated charge is put forward as a main factor in the production of the magnetic storms associated with solar disturbance; in the case of the alternative agent, it seemed hard to understand how the ultra-violet light, supposed absorbed in the earth's atmosphere (since it does not reach the ground-level), could escape from the sun's atmosphere. Moreover, regarding the ultra-violet light as simply part of the ordinary radiation of the sun, treated as an incandescent "perfect" or "black-body" radiator, Swann had shown that the amount, even if the whole escaped from the sun, was quite inadequate to produce the observed ionization of the upper atmosphere. Both these difficulties are avoided if we suppose the ultra-violet light to consist of γ -rays, i.e. the extremely penetrating wave-radiation which in certain radio-active processes accompanies the emission of α -particles and β -particles. These γ -rays are immensely more penetrating than either β - or α -particles, so that as the latter prove able to escape from the sun's atmosphere, it is natural that the γ -rays should likewise do so; how far the speed of the particles is reduced in the solar atmosphere we cannot say, but the γ -rays which escape will maintain their superior penetrating power, and so ionize a layer in the terrestrial atmosphere lower than the auroral layer. The rays do not travel to a definite distance before absorption, as do the α -particles; their intensity diminishes exponentially with the mass of the gas traversed. As the density of the earth's atmosphere increases approximately exponentially with depth (reckoned from the outside), it is probable that the lower ionized layer in the atmosphere is ill-defined both above and below; the higher-lying auroral layer, on the contrary, though ill-defined above, has a sharply-marked lower limit.

The fact that both ionizing agents, though of such distinct kinds, are more intense during years of great than during years of little solar activity, argues for the existence of some physical connection between them, and is thus accordant with the hypothesis of their radio-active origin. The γ -radiation, however, seems to vary continuously and gradually, while the streams of corpuscles are discontinuous and intermittent. I am inclined to attribute this to the fact that the radiation, whether produced locally or, as seems more likely, all over the sun's surface, will spread out in all directions—what we receive at the earth coming from the whole of the emitting area. In the case of the corpuscles, probably they either cannot escape at all from the sun's general magnetic field, or can do so only in diffuse masses, except where the intense magnetic fields which Professor Hale has shown to exist over sunspots provide a "guide," analogous to a channel, along which they can stream outwards. The undoubted connection between disturbed areas on the sun and magnetic storms tends to support some such conclusion. Perhaps the study of the magnetic fields of sunspots will in time enable us to refer a given magnetic storm to a particular disturbed region on the sun, by indicating which region is associated with lines of magnetic force directed towards the earth; attempts by other methods to establish such a connection have never yet met with success. Hitherto there has been great uncertainty as to the time taken by the solar corpuscles to reach the earth; if they are α -particles, the time of passage can be assigned within fairly narrow limits, as from about two to three hours.

Nothing has so far been said about the β -particles emitted during the radio-active processes mentioned. It may be that these negative particles escape from the sun diffusely, or, if in streams with the α -particles, that they become dispersed, owing to their much greater deviability, before they reach the earth. Certainly they must escape from the sun in some way, as it is not to be supposed that the sun is steadily accumulating a negative charge; while there seems to be no evidence that two kinds of corpuscles reach the earth.

If the above suggestion is confirmed, that radio-active transformations on the sun are responsible for the emissions which affect the earth's atmosphere, such processes must play a much greater part in the economy of the sun than has generally been supposed; and they must be intimately connected with the cycle of variation of solar activity, for the ultra-violet wave radiation (here identified with γ -rays) is twice as intense at some sunspot maxima as at sunspot minima.

15. This completes the present account of the high-level atmospheric electrical phenomena which it has been my task to pass rapidly under review. The subject is by no means "cut and dried," and I have failed if any other impression of it has been given than that of a field of investigation which is unsurveyed on many sides, though across the unknown territory some well-explored regions can be glimpsed. So far as concerns the restricted aspect of it which has been considered here, the subject may seem to be a branch of meteorology, that, namely, which deals with the upper atmosphere not directly within the reach of our instru-

ments. As yet it is too early to say how far a knowledge of these phenomena of the upper stratosphere is likely to assist in solving the important practical problem of weather prediction. These phenomena are, however, even more closely connected with solar physics—certainly, at any rate, in a more varied way—than is general meteorology, or than the latter is with the subject of this paper: and the study of them seems likely to contribute reciprocally to the advancement of solar physics in a way of which ordinary meteorology shows no promise. The secondary currents induced within the earth by those flowing in the upper atmosphere, again, extend the subject into a region quite distinct from atmospheric dynamics and thermodynamics, and provide one of the few means of research into the properties of the deep-lying interior of the earth.

While these studies may be expected to further other branches of science, those by the aid of which they must themselves be advanced are very numerous. Among them general physics—particularly electromagnetism, radio-activity, and spectroscopy—and mathematics, in addition to the sciences already named, come foremost. On the observational side the opportunities for valuable research are likewise numerous and varied, and, as in the case of astronomy, though to a less extent, many of them have been ably utilized by amateurs, as well as by those who have worked under the auspices of institutions maintained for the purpose of research. Probably few electrical engineers have leisure to devote themselves personally to the study of these somewhat remote ramifications of the science of electro-magnetism, but I hope that it may not be without interest to them to consider briefly such examples of how the principles underlying the more familiar applications of electricity are illustrated, in various ways and on a large scale, in Nature.

NOTE (*Added 15 July, 1920*): During the 15 months which have elapsed since the above paper was written, further study has led to the recognition of new facts and considerations which necessitate revision of some of my statements, in important though not fundamental respects. Professor Lindemann has published a criticism of part of my theory of magnetic storms, and proposed an alternative version. For reasons which cannot be entered upon in this Note, I am unable to accept this version, and I adhere to the view that storms are produced by streams composed mainly though not entirely of one sign of charge. The lunar diurnal magnetic variation proves to be more complicated than I had anticipated, and tends to suggest that there are *three* and not only two ionized atmospheric layers associated with the magnetic variations. Again, the escape of the charge during a magnetic storm would seem to involve less motion of the air than I had hitherto supposed, since the ions have a considerable free range in the rarefied air. A consideration of the different degrees of mobility of the positive and negative ions leads me to conclude definitely that the corpuscles responsible for a magnetic storm are negatively charged, so that the suggestion that they are α -particles must be withdrawn.