A THEORY OF AURORAS AND MAGNETIC STORMS*

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Abstract

The physics of the atmosphere of the earth under a quiet sun is discussed in detail. The daytime temperatures above 100 km increase with the height to roughly 1000°K at a 400 km level; new tables of the molecular density of the atmosphere to great heights are given. In the region above 450 km, where the molecular free paths are very long, a portion of the highly absorbed ultra-violet light of the sun is converted into kinetic energy, by processes of atomic excitation and ionic recombination, and produces 10^6 atoms cm^{-2} sec^{-1} which fly out from the earth with velocities of 10 km sec^{-1} or more. The atoms attain levels of 30000 to 50000 km in 3 hours and are then ionized by the ultra-violet sunlight. The ion pairs thus formed spiral about the lines of force of the earth's magnetic field and a majority are guided to the polar latitudes. They fall into a zone roughly 25° from the magnetic poles and give rise to the *auroras* there; this is the observed zone of maximum auroral frequency. It takes the ions 9 hours to travel from the equator to the poles, and therefore the aurora occurs more often in the early hours of the night than in the later hours, as is observed. The fact that short wireless waves traverse polar regions supports the view that the ionization is due to the ion influx from lower latitudes; for the sunlight is too weak to make many ions there. It is assumed that the sun, when active, emits a sudden (1/2 hour) blast of ultra-violet light. For example, if 1/10000 part of the solar surface, normally at a temperature of 6000°, were removed and there were exposed the black-body radiations at 30000°, the solar constant would be increased by 1 percent and the ultra-violet energy, λ500 to 1000A, by 10^5. This ultra-violet energy, completely absorbed in the high lying (200 km) atmospheric gaseous layers, blasts out these layers to produce ions up to 40000 km. Due to gravity and the earth's magnetic field the first effect of the high flying ions is to produce a sudden current, 10^6 amperes, in planes parallel to the equator, which causes a magnetic field 10^{-3} gauss simultaneously over the whole earth, as is observed in the first phase of the world-wide magnetic storms. Numbers of ions descend to the zones 23° from the magnetic poles and form there diamagnetic concentrations of considerable intensity (also give rise to the auroras). On the assumption that the blast of ultra-violet light does not die away abruptly but continues with lessening intensity for a day or so, the diamagnetic concentrations wax with the day and wane with the night. The changes in the earth's magnetic field caused by this diamagnetism are found to agree in nearly every detail with the observed complicated diurnal storm variations in the three magnetic field components at all latitudes.

1. *INTRODUCTION.* The temperatures and pressures of the gases of the atmosphere up to heights of 200 km above the surface of the earth and the ionization in these regions caused by the ultra-violet light of the sun have been discussed in two recent papers [1,2]. The ionization was found to be in keeping with that inferred from the behavior of wireless waves; the increase and decrease in the ionization with day and night was shown[3] to give rise to magnetic effects in complete agreement with the observed diurnal var-

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[1] Maris, Nature, **120,** 839 (1927); Ter. Mag. and Atmos. Elec. **33,** December (1928).
[2] Hulburt, Phys. Rev. **31,** 1018 (1928).
[3] Gunn, Phys. Rev. **32,** 133 (1928).

iations in terrestrial magnetism. It has been the purpose of the present paper to examine into the physics of the atmosphere in regions above the 200 km levels, regions extending to 50000 km from the surface of the earth. It may be stated in advance that in this outlying domain, which verges into interplanetary space, are found ions and electrons ejected from the terrestrial atmosphere by the ultra-violet light of the sun. The effects of these high flying electrified particles afford a comprehensive explanation of the characteristics of the aurora and of the complicated variations in the magnetic field of the earth at all latitudes during a magnetic storm.

Sections 2 to 9 deal with the atmosphere under conditions of solar quiet, i.e. no terrestrial auroras or magnetic storms, sections 10 to 16 deal with the case of an active sun.

2. *The atmosphere to 500 km; quiet sun.* Earlier calculations [4,5] of the pressures of the constituent gases of the atmosphere were based on the assumptions of a constant temperature, 222° at great heights, of complete diffusion below a level, known as the "diffusion level," which was taken without justification to be 0 to 50 km, and of gravity equilibrium above this level. No differences between night and day or winter and summer were recognized. It was clearly realized that the assumptions were at best only approximate and would be expected to break down entirely at great heights. The whole matter was gone over again from the beginning several years ago[1] and the diffusion level was shown to be at about 160 km for a summer day, and at 130 km at night, by considering the time it would take a thoroughly mixed atmosphere to settle out and reach gravity equilibrium. The diffusion level is a little different for each gas. The heating of the atmosphere by the sunlight was calculated and complete tables[1] of the molecular densities were given approximately valid to about 150 km levels.[6]

For the purposes of the present discussion the tables have been extended to greater heights. The night-time values of the temperature T°K and the molecular density n, i.e. the total number of molecules or atoms of all sorts per cm^3, are given in columns 2 and 3, Table I; these are the same as in the earlier tables.[1] The daytime values, columns 4 and 5, Table I, were gotten by calculating the heating by the sun step by step in each level of the atmosphere, using the ultra-violet and infra-red absorption coefficients of ozone and assuming the proportion of ozone to remain constant above 60 km, on the idea that the ozone is created by the sunlight at each level. The sun was assumed to be quiet, i.e. no terrestrial auroras or magnetic storms, and the solar spectral energy to be that of a black body at 6,000°K. Because of the unequal balance at cold temperatures between the solar energy absorbed in the ultra-violet by the atmospheric gases and the energy re-emitted in the infra-red by the gases, the daytime (i.e., the sun directly overhead) temperatures above 50 km increased with the height as shown in column

[4] Chapman and Milne, Roy. Meteor. Soc., Quarterly Jr. **46,** 357 (1920).

[5] Humphreys, "Physics of the Air," (1920).

[6] Gowan, Proc. Roy. Soc. **128,** 655 (1928), has recently considered the heating in much the same way, neglecting day and night differences.

4 of the table. The complete tables of the partial pressures of the atmospheric gases and the details of the calculations are too long to give here. The daytime diffusion level is at about 250 km, which is a little higher than before[1] because of the greater temperatures at the greater heights. An estimate of the temperature of the upper atmosphere may be made from the width of the non polar aurora green line λ5577.35A in the night sky, which was observed by Babcock[7] to be not more than 0.035A wide. With

TABLE I. *Atmospheric temperatures and densities at various altitudes.*

	Quiet Sun				Active Sun	
Height	night		day		day	
	T	n	T	n	T	n
0 km	288°K	2.56×10^{19}	288°K	2.56×10^{19}	288°K	2.56×10^{19}
10	228	8.26×10^{18}	228	8.26×10^{18}	228	8.26×10^{18}
20	223	1.91×10^{18}	228	1.90×10^{18}	230	1.89×10^{18}
40	232	9.37×10^{16}	280	8.22×10^{16}	390	5.90×10^{16}
80	232	2.81×10^{14}	560	1.23×10^{15}	1120	2.10×10^{15}
100	232	1.59×10^{13}	620	3.49×10^{14}	1220	9.23×10^{14}
150	232	1.60×10^{10}	1000	2.15×10^{13}	1500	1.64×10^{14}
200	232	1.78×10^{7}	1000	3.97×10^{12}	1500	4.55×10^{13}
250	232	6.98×10^{5}	1000	7.98×10^{11}	1500	1.47×10^{13}
300	232	2.78×10^{5}	1000	1.66×10^{11}	1500	4.98×10^{12}
400	232	4.42×10^{4}	1000	7.40×10^{9}	1500	6.00×10^{10}
500	232	7.51×10^{3}	1000	3.66×10^{8}	1500	6.29×10^{11}
600	232	1.31×10^{3}	1000	2.08×10^{7}	1500	8.86×10^{9}
800	232	4.73×10	1000	3.68×10^{6}	1500	2.01×10^{8}
1000	232	2.07	1000	1.75×10^{5}	1500	5.90×10^{6}

this value and taking the oxygen atom[8] to be the emitting particle, the temperature calculated on the theory of Doppler broadening[9] came out to be 880°K, an upper limit. One would expect the conditions in the high atmosphere to be ideal for the Doppler broadening theory. This is higher than the night values of Table I, but serves perhaps as some justification for the general idea of high temperatures in the outer atmosphere.

At 400 km in the daytime only about 1/10,000 of the atmosphere is helium, the rest being mainly oxygen and nitrogen; above 800 km helium predominates. Following Chapman and Milne[4] it has been assumed that there is no hydrogen in the high atmosphere; at a 400 km level, however, the inclusion of hydrogen would make little change, at greater heights the effect of hydrogen would be important. The presence or absence of hydrogen can not be regarded as settled at the present time. The assumption which we have used about ozone can hardly be correct and the values in Table I can at best only be approximately true. One should consider as well the

[7] Babcock, Astrophys. J. **57,** 209 (1923).
[8] McLennan, Proc. Roy. Soc. **120,** 357 (1928).
[9] Fabry and Buisson, Jour. de Physique, **9,** 189 (1919).

other gases, such as nitrogen, helium, etc., but the light absorption coefficients (transition probabilities) are not known, and any calculations based on them would have little meaning.

3. *The atmospheric spray up to 50,000 km levels.* From Table I at 450 km $n=1.60\times10^9$ in the day. The free path of a particle of diameter 10^{-8} cm is of the order 10^2 km at this height and increases rapidly with the height. Above 450 km there are 10^{16} molecules cm^{-2}; these experience 10^{11} collision per second at the 450 km level. Approximately 10^{16} molecules of diameter 10^{-8} cm will just fit into an area of 1 $cm.^2$ Therefore above 450 km there are practically no collisions and the values given in column 2 to 5, Table I, above this level, which were based on assumptions of kinetic gas equilibrium, have little meaning; they had to be worked out of course in order to reach this conclusion. The 10^{16} molecules dance up and down, receiving upward thrusts from thermal impacts below and falling back under gravity. At 1000°K the thermal velocities of a nitrogen molecule, a helium atom and a hydrogen atom are 0.9, 2.3 and 4.6 km sec^{-1}, respectively. With these velocities of projection the respective particle will reach heights of about 1000, 2000 and 5000 km above the surface of the earth. For these calculations and others, given later, see any chapter on central orbits.[10]. Therefore, omitting hydrogen, due to temperature velocities alone we may expect a fringe of 10^{16} molecules, or atoms, in a 1 cm^2 column extending from 450 km up to 2000 or 3000 km, but hardly above this.

In the high fringe of the atmosphere calculations based on kinetic theory averages begin to break down, and therefore we pass, as we should, from macroscopic to microscopic considerations and examine the behavior of individual particles. The sunlight, particularly in the wave-lengths less than 1200A, in addition to heating the atmosphere, causes excitation, dissociation and ionization of the atmospheric atoms and molecules. Neutral particles which collide with the excited ones, or with particles undergoing recombination, may receive some or all of the excitation or recombination energy in the form of kinetic energy. *It is assumed that a portion of the energy of the short wave-length ultra-violet light of the sun causes some neutral atoms or molecules to move at speeds as great as 10 km sec*$^{-1}$. In illustration, if a helium atom collides with another helium atom excited to 4 volts, each acquires a velocity of 10 km sec^{-1}; or a helium atom which releases by collision 2 volts excitation energy from a nitrogen or oxygen molecule acquires a velocity of 10 km sec^{-1}; about this same velocity is given to an oxygen atom which releases 13.5 volt excitation energy from an oxygen molecule, or to a nitrogen atom which collides with another nitrogen atom excited to 15 volts. Eddington[11] calls collisions of this sort "superelastic collisions," Frank[12] calls them "collisions of the second kind." Direct experimental evidence of the assumption is found in the observed fact[13] that the luminous particles in a

[10] For example, Taite and Steel, "Dynamics of a Particle," page 113 (1889).
[11] Eddington, "The Internal Constitution of the Stars," page 373 (1926).
[12] Frank and Jordan, "Anregung von Quantensprüngen durch Stösse," (1926).
[13] Russell, Dugan and Stewart, "Astronomy," **1,** 441 (1926).

comet's tail ejected from the nucleus move with velocities of several kilometers per second, velocities which are recognized to be unexplainable by light pressure.

We give a quantitative turn to the assumption of the preceding paragraph and assume that, of the 10^{14} collisions which the 10^{16} molecules of a 1 cm^2 column of the atmospheric fringe make per second, 2×10^6 are of a sort to give a neutral atom a velocity about 10 km sec^{-1}. There may be velocities less and greater than this, of course. Thus there are 2×10^6 cm^{-2} sec^{-1} high speed atoms, one half of which fly downward to be lost in the atmosphere below, and the other half upward. The orbits[7] of particles projected with a velocity of 10 km sec^{-1} at angles of 1°, 22°, 45° and 60° with

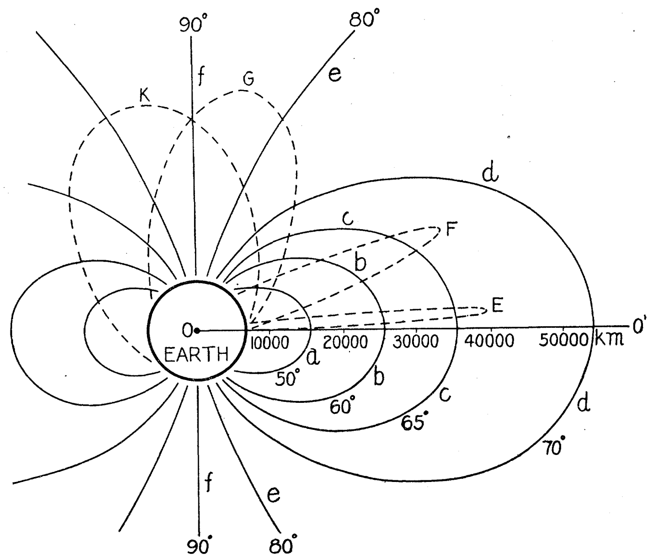

Fig. 1. Curves *aa*, *bb*, etc., are the magnetic lines of force of the magnetic field of the earth. The number near each curve is the magnetic latitude where the line touches the earth. Curves *E*, *F*, *G* and *K* are the orbits of particles projected from the earth with a velocity of 10 km sec^{-1} at angles to the vertical of 1°, 22°, 45° and 60° respectively.

the vertical are given in the dotted curves *E*, *F*, *G* and *K*, respectively, of Fig. 1. The figure is drawn to the scale marked on $00'$. Particles projected vertically upwards with velocities 10 and 10.5 km sec^{-1} reach heights 45,000 and 100,000 km from the center of the earth in 3.0 and 15.4 hours, respectively. (The velocity for projection to infinity is 11.18 km sec^{-1}). Thus on the sunlit side of the earth there is a spray of atoms and molecules extending out to 50,000 km or so.

4. *Ionization of the high flying atoms and molecules by the ultra-violet light of the sun.* The high flying atoms (or molecules) are ionized by the ultraviolet sunlight in a time t sec given by the relation

$$t = w/I_0(1-e^{-\beta}), \tag{1}$$

where w is the ionization potential of the atom, β the atomic absorption coefficient and I_o the intensity of the ionizing light. A more detailed theory than the present would consider the value of β for each wave-length of the light, etc.; this is not done here. β is defined in the usual way by the equation

$$I = I_0 e^{-\beta n x}, \tag{2}$$

where I is the intensity of the light after passing through x cms of atoms, or molecules, of density n. (1) is derived from (2) by assuming that all of the absorbed energy goes to produce ionization, and by noticing that $w = t(I_o - I)$. The ionization potentials of oxygen, nitrogen and helium atoms are 13.56, 17 and 24.6 volts, respectively, corresponding to ionizing wave-lengths 912, 725 and 502A. The total energy of the sunlight in the wave-lengths from 0 to 502A falling on the earth is 1.2×10^{-11} erg cm^{-2} sec^{-1}, from 502 to 725A is 2.1×10^{-5} erg cm^{-2} sec^{-1}, and from 725 to 912A is 1.15×10^{-2} erg cm^{-2} sec^{-1}, calculated on the assumption that the sun is a blackbody at 6000°K and taking the solar constant, i.e. the solar energy in all wave-lengths, to be 1.35×10^6 erg cm^{-2} sec^{-1}. Approximately we take $I_o = 10^{-4}$ erg cm^{-2}, and $w = 3.1 \times 10^{-11}$ ergs corresponding to 20 volts. The value of β, which is of course Einstein's "probability of transition," is taken to be 3×10^{-11}. With these values in (1) t is 10^4 sec, or about 3 hours, and we see that the high flying atoms of velocities about 10 km sec^{-1} become ionized after reaching 40,000 to 50,000 km levels.

The values used in (1) to give $t = 10^4$ sec. are rough averages of quantities which are not known with certainty. A value of 10^{-4} for β may be rather high (reference 2, page 1026), and the value for I_o may be low, for the solar energy curve in the ultra-violet in all probability departs from the blackbody curve (reference 11, page 328) and may be rather in the nature of line emission; similarly the absorption of the far ultra-violet light in the terrestrial atmosphere is probably line absorption.

5. *The high flying ions follow the lines of force of the magnetic field of the earth.* The high flying atoms, once ionized, are caught on the magnetic lines of force of the earth. These lines are drawn in aa, bb, cc, ee, etc., Fig. 1 the numbers written at each line giving the magnetic latitude where the line touches the surface of the earth. The lines are plotted from the usual formula for a uniformly magnetized sphere,

$$r/r_0 = \cos^2 \alpha / \cos^2 \alpha_0, \tag{3}$$

where r and α are the polar coordinates of a point on the line, r_o being the distance from the centre of the earth 0 and α the angle measured from 00,′ Fig. 1. r_o and α_o are the coordinates of the point where the line crosses the surface of the earth. The strength H of the magnetic field at any point (r,α) is

$$H = M(1 + 3 \sin^2 \alpha)^{1/2} / r^3, \tag{4}$$

where M is the magnetic moment of the earth. In general the path of an ion moving under the influence of the earth's gravitational and magnetic fields is very complicated. It is sufficient here to discuss a simple case. The radius ρ of the spiral which an ion of mass m, charge e, and velocity v normal to a magnetic field H, is, using throughout c.g.s electromagnetic units,

$$\rho = mv/He. \tag{5}$$

At a height of 40,000 km, H is of the order 10^{-3} gauss from (4), and for an oxygen atom moving at a velocity of 5 km $\sec^{-1}$ ρ is only 4 km from (5) for smaller velocities and lighter atoms ρ is less than 4 km. It is considered that velocities greater than 5 km $\sec^{-1}$ at these heights will be relatively rare, (a particle projected upwards with a velocity of 10.5 km $\sec^{-1}$ has a velocity of 2.7 km $\sec^{-1}$ at a height of 53,000 km) and therefore the ions formed from the high flying atoms move in a tight spiral path along the magnetic force lines, the positive ion going around in one sense and the negative electron in the opposite sense, the ion stream remaining on the whole neutral.

6. *Concentration of the ions in polar regions; the characteristics of the aurora.* In an earlier paper[14] the total energy of a strong auroral display was estimated to be roughly 10^{15} erg $\sec^{-1}$, and a theory was outlined which attributed the energy of the aurora to arise from the recombination of ion pairs which were formed at lower sunlit latitudes and drifted to the polar regions along the magnetic field lines of the earth. In the following paragraphs the theory is developed in some detail. The important facts[15] of the aurora are that the aurora occurs more often in the early hours of the night than in the late hours, that there is no marked seasonal variation in the frequency of auroral occurrence, possibly an uncertain maximum at equinox, and that there is a zone of maximum auroral frequency at about 23° from the magnetic pole. The average number of aurora displays in a year is plotted in curve 1, Fig. 2, as ordinate against the magnetic latitude as abscissa. The maximum is at 67°; at latitudes above this the curve is dotted, for no data are given, merely the statement that in the high latitudes the aurora is less frequent.

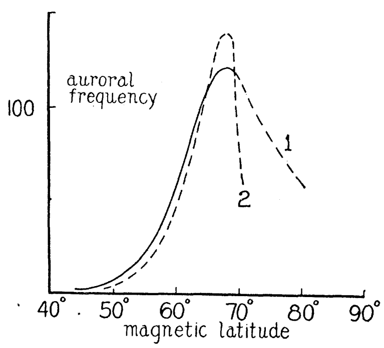

Fig. 2. Curve 1 is the average number of auroras plotted against the magnetic latitude; curve 2 is a theoretical curve of auroral frequency based on a number of assumptions.

In order to find out where the high flying ions come down to the earth and hence to determine the geographical distribution of their flux density, the distribution of velocities of ejection of the high flying neutral atoms, from which the ion pairs are formed, must be specified. This is not known—in earlier paragraphs we have merely assumed that there are some neutral atoms with velocities as great as 10 or 10.5 km $\sec^{-1}$ —but an illustrative calculation may be made on the assumption that the velocities are equally distributed among the atoms. In this case the number of atoms with a speci-

[14] Hulburt, Phys. Rev. **31,** 1038 (1928).
[15] Chree, Encyclopaedia Britannica. 13th ed., **2,** 927 (1926).

fied energy is proportional to the square root of the energy. Assuming always 3 hours for ionization an atom with velocity 10.2 km sec^{-1} is ionized at 40,000 km above the centre of the earth in the tropical or temperate zones, and upon moving up or down the magnetic line arrives at the earth at the magnetic latitude 69° (north or south). Whereas an atom with velocity 9.5 km sec^{-1} reaches its maximum height of 29,000 km in 2.4 hours, falls back to 25,000 km in 0.6 hours where it is ionized, and thence arrives at the earth at latitude 59°. A complete table was worked out for various velocities and from this, with the assumption of equal distribution of velocities among the atoms, the intensity of the ion flux was determined for each latitude. This is plotted as ordinate in curve 2, Fig. 2, in arbitrary units. If the aurora derives its energy from the ion flux, curve 2 is also a theoretical curve of aurora intensity, and hence of aurora frequency; the curve agrees roughly with the observed curve 1 up to the magnetic latitude 67°.

Above the latitude 67° the theoretical curve 2 should fall to lower values in accord with qualitative observation. It is possible that this may be due to the effect of the centrifugal force of the earth's rotation on the high flying ions. This effect, if it exists, becomes important above 40,000 km. At a distance 42,200 km from the center of the earth the centrifugal force is equal to the earrh's gravitational attractive force, as found by solving for r in the equation $MG/r^2 = r\omega^2$, where M is the mass of the earth 6×10^{27} grams, G the Newtonian constant 6.66×10^{-8} and ω the velocity of angular rotation of the earth about its axis. The calculation refers to the equatorial plane and neglects the angle between the magnetic and geographic axes. Therefore if the centrifugal force is operative ions at or above 42,200 km will rarely return to the earth. Since the line of magnetic force at this level descends to the earth at latitude 67°, few ion pairs will reach latitudes above this, only those in oblique orbits such as G, Fig. 1. This is a possible explanation of the maximum in the auroral frequency curve. If, on the other hand, the centrifugal force effect does not exist, one must have recourse to special hypotheses to explain why the aurora is less frequent at latitudes above 67°, namely, one may suppose that few ion pairs reach levels where they may be guided to the high polar zones on the idea that either the neutral particles are ionized too quickly or that they do not have sufficiently great velocities of projection. The question of the centrifugal force is discussed further in section 9. The influence of radiation pressure on the atmosphere has been neglected. Although classical calculation indicated that this effect was relatively small, it may turn out to be of importance.

It takes a 10.2 km sec^{-1} atom 3 hours to reach 40,000 km levels (and a 9.7 km sec^{-1} atom 3 hours to reach 34,000 km), and another 6 to 14 hours to fall down to the polar regions. Meanwhile the earth turns an hour or two under the flying atom; after being ionized the atom is constrained by the magnetic field to have the same angular rotation velocity as the earth. Since the ions are produced by the ultra-violet light of the sun the maximum rate of production occurs at noon. Therefore, the maximum ion flux in the polar regions occurs in the early part of the evening, 9 hours or more after noon, just as is observed for the aurora intensity. The fact that there is no very marked seasonal variation in the aurora intensity is in keeping with the present ideas, for the theory, at least in its present rough form, indicates no marked influence upon auroral occurrence of the tilts in the geographic and magnetic axes.

Because of winds the high atmosphere is not uniform, and there may be here and there pressures of, say, nitrogen greater or less than the average. Under the solar excitation, which is also variable, one may expect fitful gusts and clouds of high flying atoms. After being ionized these descend to the auroral zones lengthening into streaks and, being touched into luminosity, form the auroral streamers. Certain groups homogeneous in velocity may descend in thin sheets to form the auroral curtains and draperies.

7. *The energy of the aurora.* In order to determine the rate of transfer of energy by the high flying ions from the sunlit lower latitudes to the auroral zone, we deal only with the ions with velocities around 10 km sec^{-1}, which attain 40,000 km levels, and assume that the number of these which move outward in a direction at an angle θ with the line joining the earth and the sun is proportional to $cos\ \theta$; c.f. Lambert's law for light reflected from a diffusing surface. Practically all of the 10 km sec^{-1} atoms moving outward in directions embraced in a 90° cone, as in the orbits E, F and G, Fig. 1, are concentrated at the earth in the 65° region. These comprise 3/4 of the total number ejected in all directions, as found by a simple integration. The other 1/4 are sent out at angles less than 45°, as in orbit K, Fig. 1, and upon being ionized, eventually are scattered over the magnetic polar regions and elsewhere without marked concentration. The target area of the earth is $\pi r_0^2 = 1.3 \times 10^{18}$ cm^2, the radius of the earth r_0 is 6400 km; the area of the auroral zone, between magnetic latitudes 65° and 70° and longitudes 180° apart, is 2.17×10^{16} cm^2, and as there are two such zones one in the north and one in the south, the total area is 4.34×10^{16} cm^2. According to the assumption of section 4 there are 10^6 cm^{-2} sec^{-1} high flying atoms produced by the sunshine. 10^{-5} erg cm^{-2} sec^{-1} is required to give these a velocity of 10 km sec^{-1} (actually, 1.16×10^{-5} and 0.33×10^{-5} for nitrogen and helium atoms, respectively) and 3.1×10^{-5} erg sec^{-1} to ionize them at 20 volts, a total of 4.1×10^{-5} erg cm^{-2} sec^{-1}, or $4.1 \times 10^{-5} \times 1.3 \times 10^{18} = 5.3 \times 10^{13}$ erg sec^{-1} for the sunlit hemisphere. Three fourths of this, or 4×10^{13} erg sec^{-1}, goes to the auroral zones and is available as auroral energy. This is somewhat less than 10^{15} erg sec^{-1} estimated for a strong auroral display. This is as it should be, and we have chosen the numerical estimates to give this result on the idea that there are no auroras in the intervals of solar quiescence. If the ultra-violet sunlight is increased in intensity, as in a time of solar disturbance, then the energy carried to the auroral zone is greater than usual and an auroral display results. This is discussed in section 11.

The foregoing estimates are based on the assumption that a portion of the solar energy is transferred continually into auroral energy. This may not actually be the case, for it may be that the polar energy is stored up for a time in the atmosphere until it finds, or gives rise to, conditions suitable for its release. On the whole this discussion can only be regarded as the preliminary framework of a more complete development. Such a development will require, among other things, complete knowledge of the energy levels, metastable states, and transition probabilities of the atmospheric atoms and molecules, as well as of the exact atomic processes which give rise to the aurora light.

8. *The connection between the present calculations and the theory of the Kennelly-Heaviside layer.* The ionization in the 100 to 200 km levels, known as the Kennelly-Heaviside layer (wireless wave propagation phenomena depend for the most part on this ionization) has been shown[2] to be due to the solar ultra-violet light, an energy flux of 4.5×10^{-3} erg cm^{-2} sec^{-1} normal to the sun's rays, causing a production of 2×10^{8} ion pairs cm^{-2} sec^{-1}, being necessary to account for the more prominent wireless facts. In the present case we have brought into view effects due to 4.1×10^{-5} erg cm^{-2} sec^{-1} ultra-violet radiation flux, which for the most part is so highly absorbed that the ionization which it produces is above a 200 km level. The point to be emphasized is that the present notions supplement, without disturbing, the Kennelly-Heaviside layer theory. In one instance they contribute an explanation of a fact about which the older theory was none too clear. The fact, which was discovered while the older theory was being developed, is that wireless signals of short wave-length, 16 meters or so, traverse polar regions without being lost. This is shown by certain round-the-world signals, and by the excellent direct communication being maintained with short waves between this Laboratory and the Byrd expedition in the Antarctic areas. On the earlier theory it was difficult to understand how there could be sufficient ionization to permit this, merely because the sunlight is so weak in the polar regions. It is seen now, however, that a large part of the polar ionization may be due to the influx of high flying ions from the lower sunlit latitudes which may amount to (see section 7) $10^{6}\times 1.3\times 10^{18}\div 4.34\times 10^{16} = 3\times 10^{7}$ ion pairs cm^{-2} sec^{-1} or more in the polar regions.

9. *The ion pairs at 42,200 km, and the sweeping up by the earth of the ions of space.* It was shown in section 7 that due to centrifugal force the ion pairs formed above 42,200 km in the plane of the magnetic equator will rarely return to the earth. The ions will remain at this level and therefore, when they accumulate sufficiently, will form a sort of a ring around the earth. The ion density in the ring will depend upon the rates of loss and supply of the ions. After a sufficient density has been built up in the ring some of the ions may receive velocities, due to collisions, of the proper magnitude and direction to drive them down along the magnetic lines of force to the polar zones of the earth. The density of the ring and this loss is probably not very great during solar quiescence. The rate of loss may be estimated from the frequency of collisions, but the rate of supply is pretty uncertain. There are two sources from which the ions may come, (a) the terrestrial atmosphere and (b) the ions of space which are swept up by the earth as it moves through space. The number of ions from the first source can be estimated from the number of high speed atoms, that from the second may be gotten from

Eddington's[16] estimates of the ion density of interstellar space; it seems that the two effects may be of the same order of magnitude. However, we will not go further with the problem now; a complete solution would involve the description of what happens when a rotating magnetized conducting sphere moves through a pure ion gas. The possible bearing which all of these ideas may have on the escape of planetary atmospheres, solar corona, zodiacal light, rings of Saturn, etc., is left to the future.

It must be pointed out that in the foregoing discussion of the ion ring and in various places throughout this paper we make use of the idea that the ion pairs are caught on the lines of force of the earth's magnetic field as if these lines of induction were material filaments attached to and rotating with the earth. It is clearly realized that such a conception can hardly be entirely correct, but to what extent it is incorrect we are uncertain. Future modifications of the present theory will be involved in the solution of the problem. Theories of unipolar induction (*Vide*, Nat. Res. Coun. Bul., vol. 4, No. 27, 1922) indicate that ion paths near a rotating magnet may be calculated as though the lines of induction rotated with the magnet, and at a distance as though the lines lagged behind the magnet. Such theories require assumptions as to the nature of the magnet and we are not sure to what extent they are capable of describing the effects at a distance from the earth. The reactions of the ions on the field may be important.

10. *Solar activity.* It is assumed that the sun when active sends out a blast of ultra-violet light for half an hour, or 1.8×10^3 sec. For example, if 1/10,000 part of the solar surface, which normally is at a temperature of 6000°K, were removed and there were exposed the blackbody radiations from regions at a temperature of 30,000°K, the total solar radiation in wave-lengths from 0 to ∞ would be increased by 6.3 percent. The solar energy in wave-lengths from 3000A to ∞ would be increased by 0.74 percent, and at wave-lengths 3500, 4000, 5000 and 6000A by 3.2, 1.7, 0.75 and 0.32 percent, respectively. Corresponding values which are observed[17] in the short interval (an hour or so) variations of the solar energy are roughly 1, 8, 2, 1 and 0.2%, and often times more. On the whole the observations indicate a higher temperature of the solar volcanoes than 30,000°K. The hot spot, or spots, will be brighter than the surrounding 6,000° surface by factors of 734, 320, 168, 75 and 32 at wave-lengths 3000, 3500, 4000, 5000 and 6000A, respectively. Whether such bright spots can be, or are observed we do not know—we must leave the question to the astronomer; bright spots, often near the sun spots, and regions bright in particular wave-lengths are of course observed on the sun. Calculations of brightness based on assumptions of black body conditions are at best only approximations, and perhaps very distant ones, in such a case where line emission and absorption undoubtedly play a predominating rôle. When we speak of the flash lasting a "half hour," all that is meant is that the flash remains at full intensity for some minutes

[16] Eddington, reference 11, page 382; Struve, Astrophys. J. **67**, 353 (1928).

[17] Annals of the Astrophys. Observatory of the Smithsonian Institution IV, pages 17 and 207; Smithsonian Miscellaneous collections, **80**, 10 (1927).

or hours and then dies away in a day or so; it might of course flare out again intermittently or irregularly.

In Table II are given the values of the solar energy in erg cm^{-2} sec^{-1} received outside the atmosphere of the earth in various wave-length regions for a quiet sun S_q and an active sun S_a, i.e. the sun with the hot spot, or volcano, of the preceding paragraph, and the ratios S_a/S_q, assuming black-body conditions for the calculations. The table shows that the solar energy in the far ultra-violet is greatly increased when the sun becomes active and that the energy in the longer wave-lengths is little changed.

TABLE II. *Solar energies received outside the earth's atmosphere.*

Wave-length region	Quiet sun S_q	Active sun S_a	S_a/S_q
0 to 800A	4.6×10^{-4}	7.3×10^{2}	1.5×10^{6}
800 to 1000	0.1	8.0×10^{3}	8×10^{4}
1000 to 1500	87	1.3×10^{4}	1.5×10^{2}
1500 to 2000	4.9×10^{3}	2.9×10^{5}	6.0
2000 to 2500	1.6×10^{4}	2.5×10^{5}	1.54
2500 to 3000	2.0×10^{5}	2.3×10^{5}	1.15

11. *Some general effects of the Solar ultra-violet flash on the temperature, winds, ionization, ozone, aurora light, etc., of the high atmosphere, and on comets.* In later sections it is shown in detail how the solar ultra-violet flash gives rise to magnetic storms, but before doing this it is of interest to examine in a descriptive manner the effects of the flash on other phenomena. The actions of the flash will occur mainly in the high atmosphere, for it is largely the wave-length region below λ3000, a region absorbed in the high atmosphere, which varies with the flash. From Table II it is seen that the energy from λ1500 to 3000 is increased roughly 10 times by the solar bright spot. Assuming, as in section 2, that this energy goes into heat the atmospheric temperatures and pressures were calculated just as for the quiet sun, and are given in columns 6 and 7, Table I. The calculation assumed thermal equilibrium above 150 km; an acceptable assumption for it was seen that equilibrium would be reached within a few minutes. The diffusion level was at about 450 km and the level above which there were practically no collisions was at 800 km. Table I shows that the energy blast heated and expanded the atmosphere above 50 km causing it to move upward 100 km or so. Thus the maximum of ionization[2] which for the quiet sun is at 190 km would be moved up to 290 km. Hafstad and Tuve[18] observed an increase in the apparent daytime height reached by 70 meter wireless wave pulses from this Laboratory of about 100 km during the strong magnetic storms of October 7 and 18, 1928. In addition to heat, the ultra-violet blast causes an increase in the high atmospheric ionization which may be felt as low as 100 km where the atmospheric absorption of short wireless waves (less than 100m) occurs. The absorption of these waves is therefore augmented

[18] Hafstad and Tuve, Terr. Mag. and Atmos. Elec. **34,** March (1929).

during solar activity, and it is well known that wireless communication, especially with short waves, is interrupted during magnetic storms. The present theory indicates that the disturbance of wireless should occur a short time after the commencement of the magnetic storm, and a comparison of the wireless log books of this Laboratory with the records of magnetic storms showed that this was less than two hours. Further, the short wave wireless data, for waves below 50 meters, showed that *when the magnetic storm began it was the wireless communication on the daylight side of the earth which was interrupted, and that communication on the night side was not disturbed at all.* The night communication channels were interrupted at dawn, as the rotation of the earth brought them into the sunlight. This is regarded as direct evidence in support of the solar ultra-violet light hypothesis of the present theory and in contradiction to the hypotheses of charged particles ejected from the sun advanced by others [21,25,28] to account for the magnetic storms. For the solar charged particles were supposed to strike the night as well as the daylight side of the earth, and therefore would be expected to disturb wireless on all sides of the earth. The complete investigation will be given in another paper.

One would expect the ultra-violet blast to make an appreciable change in the ozone of the high atmosphere, but there seems to be no clear connection between ozone variations and solar activity.[19] The energy of the light in the ozone-forming spectrum region λ1500 to 2000 or 2300 is increased to be sure, but other factors such as pressure, water vapor, etc., may be as important as light intensity in the production of ozone. The increased pressure gradient from day to night areas in the 50 to 150 km levels (see columns 3 and 7 Table I) will cause strong winds in the high atmosphere which may scatter about any unusual formations of ozone. The potential energy of ionization and excitation in the high atmosphere is increased by the ultra-violet light flash and therefore the light of the night sky, or the non polar aurora, which owes its origin to a portion of this energy,[2] would be expected to increase in intensity during periods of magnetic disturbance. Rayleigh's[20] preliminary measurements indicate this; he observed an average increase in the night sky luminosity during four years of increasing sunspots. Babcock[7] observed an unusual brightness in the non polar aurora during the nights of July 11-12 and 12-13, 1922. There was a strong magnetic storm (strength 2) from June 27 to July 4, an unusual length, and a moderate one (strength 1) from July 13 to 20, 1922.

The number of ions and excited atoms above 200 km will be enormously increased by the solar flash, by a factor of 10^5 perhaps, because the energy in the ionizing region below λ1000A is increased by this much during solar activity (see Table II). The number of high speed atoms will be greatly increased, but because of the greater intensity of the ionizing light these will be ionized very soon (see equation (1)), before they have had time to reach great heights. Being unable to shake off the entangling influence of

[19] Dobson, Proc. Roy Soc. **114,** 521 (1927); Buisson, Comptes Rendues **186,** 1229 (1928).
[20] Rayleigh, Proc. Roy. Soc. **119**, 11 (1928).

the earth's magnetic field the ions will be held in levels below, say, 2000 km. Therefore, the ionic distillation to polar latitudes, and hence the aurora intensity, will not increase by any such factor as 10^5, it may even decrease during the ultra-violet flash. After the half-hour flash begins to die down, the unusual flood of energy left in the high atmosphere in the form of heat ionization and excitation gives rise to an unusual number of high flying ions which stream to the polar regions and cause an unusual aurora display. At the same time there will be strong winds in levels 400 to 1000 km blowing mainly to the north and south, the east and west currents being relatively less because of the guiding effects of the magnetic field upon the ions. This results in an unusual tumbling in of ion pairs into the atmosphere of middle latitudes, and hence in auroras in these latitudes. This gives an explanation of the aurora displays at latitudes as low as 40° often seen in times of intense solar disturbance, the irregular flickering and shifting clouds and patterns of luminosity being exactly the type of display that one would expect to arise from windstorms in the high atmosphere.

The ultra-violet blast would be expected to cause changes in comets, much as it does in our own atmosphere, and we find that this actually happens. The complete investigation will appear in another paper. For, in nearly every instance the date on which a comet was observed to undergo an unusual change, such as breaking up of the nucleus, loss of tail, sudden increase in brightness, etc., was found to follow within a few days the date on which a strong magnetic storm occurred on the earth, provided the necessary condition was fulfilled that the earth and the comet were approximately on the same side of the sun. When the comet and the earth were on opposite sides of the sun, changes in the comet were found to occur between periods of terrestrial magnetic storms separated by one half a solar revolution. One might possibly expect changes in the appearance of Jupiter, Venus and the rings of Saturn to be connected with terrestrial magnetic storms.

12. *Data of magnetic storms.* The important facts of magnetic storms have been summarized by Chapman[21] in his extended analysis of the observations of many observatories of many storms. Certain data of interest in the present discussion are given in Figs. 3 and 4. The magnetic field variation is given by the variation in the horizontal field *HF*, the vertical field *VF* and the western declination *WD*, the angle through which the compass deviates to the west from its position on magnetically quiet days. The total magnetic variation at any station is made up of three parts, (1) a quiet day variation characteristic of the latitude of the station, etc., (2) a world wide storm variation and (3) a diurnal storm variation. The theory of the quiet day variation has been worked out by Gunn,[3] that of the storm is given in the following pages. The curves of Fig. 3 give the main facts of the average world wide storm for the temperate zone; the world wide storm occurs simultaneously (within a minute) over the whole earth; the abscissas of the curves are in hours from the beginning of the storm. The *HF* increases

[21] Chapman, Proc. Roy Soc. **A95,** 61 (1919); **A115,** 242 (1927).

rapidly to 50*y*, or 100*y* for a strong storm, ($y=10^{-5}$ gauss) in a half hour or so, decreases to negative values in several hours and finally ascends to zero in several days. The *VF* is at first negative then positive, the variations being on the whole small, less than 10*y*. The *WD* variation is small and irregular. The curves of Fig. 3 show that the *HF* values are slightly less, and the *VF* and *WD* values slightly greater, at the higher latitudes. The curves of the diurnal storm variations at various magnetic latitudes are given in Fig. 4, the abscissas being local solar time. These diurnal variations persist with lessening intensity for a day or more. The curves for latitudes 22, 51, 58 and 61 are taken directly from Chapman's paper, the curves for latitudes 70° are sketches which give the characteristic type of the variation within the aurora zone omitting many complexities and irregularities which are often observed in this region.

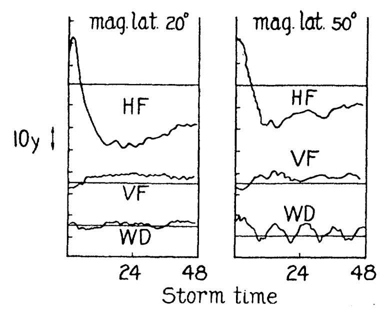

Fig. 3. World-wide storm variations of the components of the earth's magnetic field at various latitudes plotted against hours from the beginning of the storm.

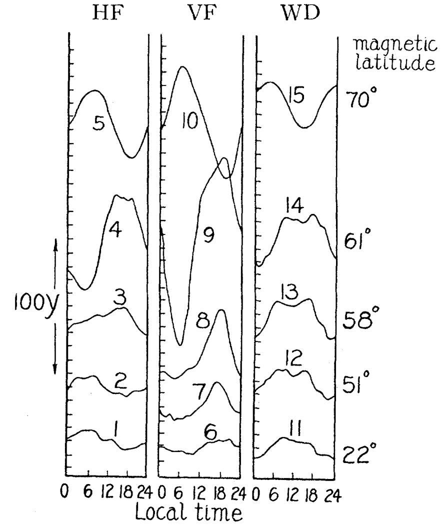

Fig. 4. Diurnal storm variations of the components of the earth's magnetic field at various altitudes plotted against local solar time.

13. *The theory of the world-wide magnetic storm.* From columns 5 and 6, Table I, it is seen that the heating effect of the solar ultra-violet flash expands the terrestrial atmosphere causing particles in the outer levels above 400 km to move upward 500 km or more, and, as shown in section 12, the ionizing effect of the flash is to produce large numbers of ions at fairly low levels between 1000 and 2000 km, say. In these regions where the molecular densities are 10^9 or less, and the temperatures are around 1500°K, the free paths are 10^6 cm, or more, and the radii of magnetic gyration 10^4 cm or less. It is the ions produced in these regions which give rise to the world-wide magnetic storm. If the energy of the flash which causes ionization is 10^3 erg cm^{-2} sec^{-1} (see Table II) and the ionization potentials of the atmospheric

atoms and molecules are around 20 volts (3.2×10^{-11} erg), there are 3×10^{13} ion pairs formed per second, or 10^{17} ion pairs in a half hour (1.8×10^{3} sec), in a 1 cm^2 column of the atmosphere. Some of these of course will disappear, by moving to lower levels, etc., so we take it that the number of long free path ions reaches a maximum value of 10^{16}, and then decreases when the flash begins to die down. These ions, no matter what their velocities are, under the combined action of the earth's gravitational and magnetic fields move at right angles to these two vectors with a velocity V, where approximately

$$V = mg/He, \tag{6}$$

the positive ions and negative electrons going in opposite directions. J. J. Thomson[22] worked out the case of an ion moving in crossed electric and magnetic fields, and it is only necessary to replace the electric force Xe in his first equation, page 87, by mg to get our equation (6). The approximation in (6) is due to the assumption, valid in the present instance, that the motion of the ion continue long enough so that periodic terms may be neglected; this in effect neglects (correctly) the kinks in the cycloidal path of the ion. At 1000 km above sea level $H = 0.3$ gauss and $g = 720$ cm sec^{-2}. With these values in (6) V is 3.9, 3.4 and 1 cm sec^{-1} for an oxygen, nitrogen and helium atom, respectively.

We note that V in (6) is independent of the random temperature velocities and is therefore a drift velocity parallel to the surface of the earth superimposed on the other velocities. Since the positive and negative electrons drift in opposite directions they form an electric current (or, rather, a pulse of current which dies down after the flash of light is over) flowing around the earth from west to east, the lines of current flow being roughly circles in planes perpendicular to the magnetic axis of the earth with centers on the axis. We may picture the positive ions as held in sort of a lattice by their own repulsive forces all moving around the earth, the positive lattice being congruent with a negative electron lattice (probably mostly negative ions on the dark side of the earth) which moves in the opposite direction, the two lattices being pushed by the gravitational magnetic forces which are operative mainly in the daylight regions. Each cm^3 of the atmosphere therefore remains approximately electrically neutral at all times.

The drift current around the earth is strong at the equator and weaker toward the poles, for at high latitudes, above the 40'th parallel (see Fig. 1) at a 1000 km level the magnetic force approaches verticalness and the ions slide down the magnetic line to low levels so quickly that they contribute but little to the drift current. Thus the drift current is in an equatorial belt roughly 5,000 km $= 5\times10^{8}$ cm wide, 10^{16} ions thick, and is at a distance 1000 to 2000 km from the earth's surface. With $V=1$, the current is $5\times10^{8}\times10^{16}\times1\times1.59\times10^{-20} = 10^{5}$ c.g.s.e.m.u. or 10^{6} amp. The current on the dark side of the earth is carried by the normal night-time ionization which is mainly in the levels below 300 km (the Kennelly-Heaviside layer), the total

[22] Thomson, "Conduction of Electricity through Gases," page 87 (1903).

number N of ion pairs in a 1 cm^2 column of the night atmosphere[2] being, say, 10^{15}. From Ohm's law the current i is related to the voltage E by $i=\sigma E$, σ being the conductivity. For an ionized gas $\sigma = Nef/2mu$, where f is the free path of the ions and u their velocity of temperature agitation. The formula neglects the effect of the earth's magnetic field, which is permissible for the night Kennelly-Heaviside layer where the molecular density is 10^{12} or more. With $N=10^{15}$, $f=10^2$ cm, $u=10^3$ cm sec^{-1} and $i=10^6$ amp, $\sigma=10^{16}$ c.g.s. e.m.u. and $E=10^{-9}$ volts. This shows that the night time conductivity of the ionized atmosphere is very high and is easily capable of carrying a 10^6 ampere current. To repeat, it is the mechanical gravitational drag of the long free path ions across the earth's magnetic field which gives rise to the effective voltage 10^{-9} volts.

The equatorial current pulse produces a magnetic field at the surface of the earth of 10^{-2} gauss, or $10^3 y$ (a long calculation, see Maxwell[23] for the method), which is in the direction from south to north and therefore increases the horizontal field HF, as is observed. The magnitude of the observed values is $10^2 y$ rather than $10^3 y$, for the first increase of the storm field (see Fig. 3). Due to the atmospheric current pulse, there is an opposing current induced in the earth, which prevents the storm field from reaching the value $10^3 y$. When the atmospheric pulse dies away, which may require several hours, the earth current finally reverses the storm field to negative values, which decrease to zero as the earth current in turn dies away. Thus the theory gives entire agreement with observation. The exact calculation of the induced effects leads far into eddy current theory; rough calculation indicates a reasonable earth resistance and damping constant. Into the calculation enters the time for the atmospheric current pulse to die away, a time which is made of two parts, (a) the time for an ion at 1500 km to crawl down a magnetic line to a 400 km level which is 6 to 14 hours, plus (b) the time for the ultraviolet flash to die away; only a study of the records can decide which of these times predominates in any particular case. Further, it is easily seen that the *HF* decreases at the higher latitudes and that the *VF* is small (theoretically zero) at the equator and increases with the latitude, as is observed. The simple theory described here indicates a zero value of WD for all latitudes, and at moderate latitudes *WD* is observed to be small, but at high latitudes WD fluctuates appreciably with a period around 12 hours. To explain this would require perhaps the careful consideration of many factors which have been neglected, such as the tilt of the magnetic axis, the induced earth currents, etc.

14. *The energy of the world-wide magnetic storm.* The energy of the world-wide storm is derived from the fall of the long free path ions from a storm level of about 1300 km to a quiet day level of 300 km, a fall of 10^8 cm. Each ion loses energy $mgh = 2.3\times10^{-23}\times900\times10^8 = 2\times10^{-12}$ ergs, for a nitrogen atomic ion. The total number of ion pairs in the daylight section of the current belt 5000 km wide and $\pi\times6400 = 20{,}000$ km long, with 10^{16} ions

[23] Maxwell, "Electricity and Magnetism," **2**, 307 (1873).

above each cm^2, is 10^{34}. Therefore the total energy of fall is $2\times10^{-12}\times10^{34}=2\times10^{22}$ erg. The observed value, or rather the value which Chapman[24] calculated from magnetic observations in a general manner, on the assumption that the storm was due to atmospheric currents, was 8.3×10^{22} erg. The agreement was of course to be expected, because the equatorial ion current produced the observed storm field $10^2\gamma$, and merely serves to bring out details of the present theory. Actually it was realized long ago that an equatorial atmospheric current would cause the world-wide storm, but no satisfactory origin of such a current or the details of the energy exchanges was proposed.

15. *The theory of the diurnal magnetic storm variations.* The first effect of the solar ultra-violet flash is to suppress the ion migration to polar regions, for although many fast moving atoms are produced, they are ionized so quickly that most of the ionization is confined to levels below 2000 km. As the flash dies down the polar ion migration becomes strong and then grows weaker with the dimming flash. Although the exact details are uncertain we may regard the dying away of the flash as the cooling of the 30,000° hot spot. The maximum energy shifts from λ911A to longer waves as the temperature falls. Therefore the energy in the ionizing spectrum region below λ1000 decreases more rapidly than the energy in the excitation region λ1000 to 2000, roughly. As the flash dies away the high flying ions are maintained in considerable number and the time of ionization is such as to bring them into polar regions. Therefore on the daylight side of the earth during a magnetic storm there is an unusual migration of ion pairs to the polar magnetic latitude 67°, a migration which increases during the morning, local time, reaching a maximum at noon, and which decreases again in the afternoon. Since 9 hours (see section 6) are required for the high flying ions to go from the equator to the polar zones, the flux of ion pairs arriving at any specified longitude on the 67° parallel is a maximum at about 21 hours, local time. The ion flux and hence the ion density, therefore increases all day, reaching a maximum at about 21 hours (9 P.M.), and decreases all night. In other words, the cloud of maximum ionization moves around the earth on the 67'th parallel remaining always roughly 9 hours behind the sun.

The ion cloud, which is at a level where the free paths of the ions are long compared to their radii of magnetic gyration, is a diamagnetic cloud, as shown by Gunn.[3] We may calculate its magnetic effects approximately by replacing it by a bar magnet *NS*, Fig. 5. The figure gives a cross section of the northern magnetic quadrant of the earth, the lines of the earth's permanent magnetic field being shown by the curves *a*. The ion cloud magnet lies along a curve *a* at magnetic latitude 67°, with its south magnetic pole fairly well concentrated and about 200 km above the earth's surface, and with its north magnetism spread out into the upper atmospheric regions. The field of this magnet is shown in curves *b*, Fig. 5; to this field should be added the field of the similar ion cloud in the southern polar zone, which is, however, practically negligible in the northern latitudes above the tropics.

[24] Chapman, Roy. Ast. Soc., Monthly Notices, **79,** 70 (1918).

The curves *b* yield at once diurnal storm variations in general agreement with observation. The increase or decrease, in the *HF* and *VF* values to a maximum or minimum at 7 to 10 P.M. is due to the fact that the magnet *NS*, Fig. 5, is nearest to the station at this time. The curves *b* indicate that at low latitudes *HF* should increase during the day and decrease at night; the observed curves 1 and 2, Fig. 4 show just the reverse of this, and we are not sure to which of the many simplications and omissions of the theory the discrepancy is to be attributed. At the higher latitudes, however, the theory is in exact agreement with observation, for curves *b*, Fig. 5, show that in latitudes below the auroral zone 65° the value of *HF* increases all day, in accord with curves 3 and 4, Fig. 4, and above the auroral zone it decreases all day, as in curve 5. It follows from curves *b*, Fig. 5, that the

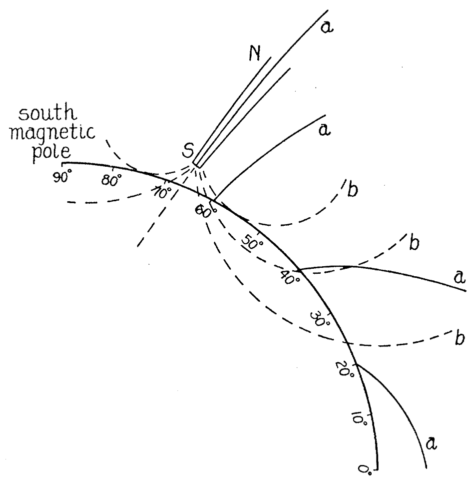

Fig. 5. Curves *a* are the permenant magnetic field lines of the earth's field. Curves *b* are the additional magnetic field lines due to the ionic cloud in the auroral zone during a magnetic storm. The cloud is roughly equivalent to the bar magnetic *NS*.

VF variation increases with the latitude, passes through a reversal at about 55°, and reaches high values in auroral latitudes, in exact accord with the observed curves 6 to 10, Fig. 4. Without giving obvious details it is seen that the *WD* at any station falls off during the day to a minimum in the early evening and then increases during the night. This agrees fairly well with the observations of curves 11 to 15, Fig. 4, with the exception of the afternoon humps of curves 12, 13 and 14. If the angle between the magnetic and geographic axes is taken into consideration, the theoretical *WD* curves get humps which vary with the longitude of the station. This is readily worked out with a pasteboard globe, plenty of pins and a strong geometrical imagination. We are uncertain whether the humps are to be attributed entirely to this, or perhaps also to some of the other simplifications introduced into the theory, or to the effect of induced earth currents.

Thus far the diurnal storm variations have been considered only qualitatively. To make quantative estimates we recall that in the Kennelly-Heaviside layer on a quiet day the maximum ion density may be as much as 10^9 or 10^{10} (reference 2, page 1033). Due to the unusual poleward ion migration during a magnetic storm we may expect a maximum ion density n as high as 10^{11} or 10^{12} at the 67° zone. For a magnetized long free path ion gas the intensity of magnetization I is given by $I = -3nkT/2H$, (reference 3, equation (16)), where T is the absolute temperature and k is the molecular gas constant 1.372×10^{-16} erg per degree Kelvin. With $n = 10^{11}$, $T = 1000$°K, $H = 0.5$ gauss, $I = 4.1 \times 10^{-2}$. From Poisson's equation the magnetic pole strength per unit area σ is $I/4\pi = 3.3 \times 10^{-3}$. Taking the end S of the magnet NS, Fig. 5, to be 300 km thick and 1000 km wide, the magnetic strength of S is $3.3 \times 10^{-3} \times 3 \times 10^{15} = 10^{13}$. At a distance 3000 km, neglecting the effect of the north pole N, Fig. 5, the field due to S is approximately 10^{-4} gauss or 10γ; or if we put $n = 10^{12}$ the field is 100γ. These are the orders of magnitude which are observed, and the conclusion is that quantitatively the present theory is acceptable.

16. *Earlier theories of auroras and magnetic storms.* The well-known theory of Birkeland, Störmer and Vegard[25] attributed the aurora to streams of charged particles emitted by the sun which under the influence of the magnetic field of the earth were diverted to polar regions. The theory has contained a number of difficulties, for example, if the charged particles are α-particles or ions of some sort they do not combine a sufficient penetrating power with a sufficient magnetic deflectibility to explain the height and structure of the aurora,[26] and if they are electrons their penetrating power may be too great.[27] No one, however, has been interested in stressing these difficulties as long as there was no other theory available. An explanation of magnetic storms by means of hypotheses of solar corpuscles, developed by Chapman[21] and modified by Lindemann,[28] was found inadequate to explain the diurnal effects.[21] It is too much to hope perhaps that the ultra-violet light theory as we have given it can stand without future modification. It is quite certain that charged coronal matter may reach the earth and may be active in causing auroral and magnetic effects. It seems, however, that in any outburst from the sun the energy emitted in the form of matter will be much less than that in the form of radiation, and therefore that terrestrial effects due to the radiation are greater than those due to the material stream. Furthermore, the ultra-violet radiation theory has been found adequate to explain the observed complicated distribtion of the phenomena over the surface of the earth without the many *ad hoc* hypotheses which would be necessary to a corpuscular theory.

Naval Research Laboratory,
Washington, D. C.
November 27, 1928.

[25] Müller-Pouillets, Lehrbuch der Physik, **5,** 484 (1928).
[26] Vegard, Phil. Mag. **46,** 211 (1923).
[27] Swann, Phil. Mag. **47,** 306 (1924).
[28] Lindemann, Phil. Mag. **38,** 669 (1919).