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IONIZATION IN THE UPPER ATMOSPHERE OF THE EARTH*

By E. O. Hulburt

Abstract

A theory of the ionization of the upper atmosphere of the earth by the ultra-violet light of the sun is developed based on known laws of pressures and constitution of the high atmosphere, ionic recombination, attachment of free electrons to neutral molecules, and diffusion of ions. It is concluded that the solar ultra-violet light is a necessary and sufficient cause of the Kennelly-Heaviside layer, and that hypotheses of other agencies of ionization, such as charged particles from the sun, penetrating radiation, etc., are uncalled for except perhaps in unusual cases. Assuming the solar ultra-violet energy to be that of a black body at 6000°K and using known, or estimated, absorption coefficients of the atmospheric gases for ultra-violet waves below λ1300A which cause photo-electric ionization, the electron curve for the sun overhead, i.e. for high noon in summer in the temperate zone, has a maximum of 3×10^5 electrons per cm^3 at a height of 190 km. Below this the ionization can not be calculated exactly, because of the lack of many facts which future laboratory experiments may supply, but a density of 10^4 to 10^5 electrons per cm^3, or 10^9 to 10^{10} ions per cm^3 (or a suitable mixture of ions and electrons) seems possible down to, say, 100 km. This ionization is shown to explain quantitatively many facts of wireless telegraphy, i.e., the skip distances, overhead absorption coefficients, limiting waves, ranges and the apparent heights reached by the waves. Taking into account the seasonal changes in the upper atmospheric pressures and the altitude of the sun, the electron layer for winter noon is found to have a maximum of 1.42×10^5 at a height 147 km, and the ionization below this is less than the summer values by a factor of 2 or so. After sunset the maximum ionization is found to decrease by a factor of about 6 in the small hours of the morning; below the maximum the decrease is greater. These seasonal and diurnal changes in the ionization are shown to be in agreement with the corresponding variations in wireless wave propagation phenomena.

The potential energy of the daytime ionization in a 1 cm^2 column of the atmosphere is found to be at least 1 erg and the assumption that less than 1% of this is liberated as light will account for the light of the night sky, or the *non-polar aurora*, as Rayleigh calls it. Due to diffusion of the ions along the lines of magnetic force the upper ionic spray of the ionized layer diffuses to the magnetic poles, concentrates there and causes the *aurora*. Calculation indicates that the *ozone* of the atmosphere is perhaps not directly connected with the foregoing ionization, but is formed by longer wave-lengths of ultra-violet light from λ1300 to 1800A.

THE more important agencies which may conceivably produce the ionization of the upper atmosphere of the earth are the ultra-violet light, α and β particles, all of solar origin, the penetrating radiation of cosmic origin, and the ionizing radiations from terrestrial sources. The last mentioned may perhaps be ruled out immediately because of the fact that the ionization in the lower atmospheric strata increases rapidly with the height for the first few kilometers.[1] The penetrating radiation apparently produces but

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* Published with the permission of the Navy Department. Read before the National Academy of Sciences, April 24, 1928.

[1] Hess, Phys. Zeits. **14,** 610 (1913).

few ions, about 1.4 per cm per sec, at the surface of the earth[2] and its ionization at the high levels may be expected to be entirely negligible. Hypotheses of α and β particles from the sun must be regarded as tentative in the extreme, and it is safe to say that no phenomena have yet been discovered which point unmistakably to the existence of such particles. There remains the ultra-violet light from the sun as deserving first consideration, and it is the purpose of this paper to examine the effects of its action in the atmosphere. The conclusion may be stated in advance that the ultra-violet light which may be expected reasonably from the sun produces electron and ion densities in the high atmosphere in agreement with the densities inferred from the data of wireless telegraphy. Further, because the question of the ionization of the high atmosphere is merely a part of the larger subject, the entire physics of the atmosphere, we obtain possibly a new glimpse into problems closely related to it, such as the aurora, the light of the night sky and the ozone. Only a glimpse, however, for many facts bearing on these fascinating questions are yet unknown. The possible effects of the various ionizing agencies have been considered by Swann,[3] Chapman and Milne,[4] Chapman,[5] Elias,[6] Lassen,[7] Benndorf[8] and others. In these investigations several factors such as the attachment of free electrons to oxygen molecules, the diffusion of the ions and electrons, etc., which have been considered important in the present investigation, were neglected entirely. New facts, particularly in the field of wireless telegraphy, and new calculations of the pressures in the upper atmosphere for day and night and for summer and winter have recently become available and have been used in the present calculations.

DATA OF WIRELESS TELEGRAPHY

Certain facts of skip distances and limiting waves of wireless telegraphy which are of interest in the present development have been furnished by Dr. A. H. Taylor of the Radio Division of this Laboratory. The skip distances for the north temperate zone for summer noon are 1000, 600, 300 and 200 miles for wave-lengths 16, 21, 32 and 40 meters, respectively. The corresponding skip distances for winter noon are 1350, 730, 400 and 200 miles. The values may be in error by a hundred miles or more because the skip distance varies in an erratic manner from time to time. The values agree well enough with earlier ones[9] which referred to daylight conditions averaged throughout the day and year. The change in the skip distance with the hour of the day is shown in Fig. 1 in which the abscissas are the times of day and the ordinates the relative values of the skip distance. The curves, which

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[2] Milliken and Cameron, Phys. Rev., **31**, 163, 1928; Hess, "Die elektrische Leitfähigheit der Atmosphäre und ihre Ursache," 1926.

[3] Swann, Terr. Mag. and Atmos. Elec. **21**, 1 (1916).

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

[5] Chapman, Ibid. **52**, 225 (1926).

[6] Elias, Zeit. f. Hochfreq. Technik **26**, 66 (1926),

[7] Lassem, Ibid. **28**, 109 and 139 (1926).

[8] Benndorf, Phys. Zeits. **27**, 687 (1926).

[9] Taylor and Hulburt, Phys. Rev. **27**, 189 (1926).

of course are not very accurate, are roughly the same for all the waves below 40 meters. In the early morning hours before dawn the curves have been given a jagged appearance to indicate that at these times the skip distances are so variable and erratic as to defy exact estimation.

The limiting wave-length, defined as the shortest wave which can be used for reliable long distance wireless communication, is 10.5 meters for summer noon, 17 meters for summer midnight, 14 meters for winter noon and 23 meters for winter midnight. The limiting wave is an erratic quantity, and the values, which are averages, are considered to be correct within meter or so.

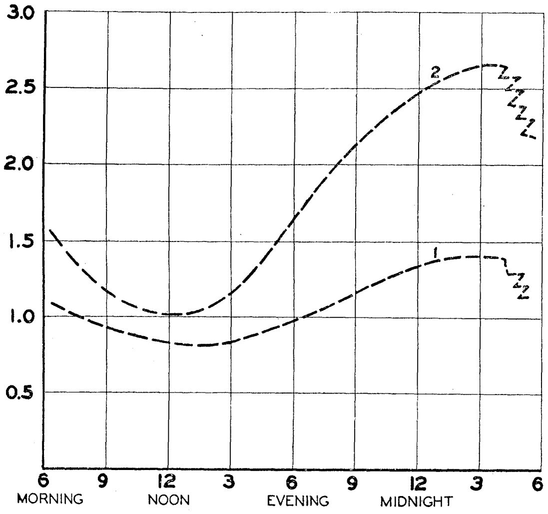

Fig. 1. Relative values of the skip distances of wireless waves below 40 meters in wave-length for temperate zone conditions as a function of the hour of the day, curve 1 for summer, curve 2 for winter.

A number of experimentors have determined the apparent heights above the earth reached by radio waves. Breit and Tuve[10] at Washington, D.C., U.S.A., found that 70 meter waves were reflected (refracted) back to earth at apparent heights from about 90 to 220 km in the daytime in the summer and autumn. Appleton and Barnett[11] determined the apparent heights to be 100 to 130 km for 400 meter waves on a June night in England. Recently Appleton[12] has observed that in the small hours of a winter night these waves seem to pierce their way to 300 or 400 km levels. Heising,[13] at New York City, found that 57 and 111 meter waves seemed to go to heights from 250 to 650 km before being turned back. These experiments were done on

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[10] Breit and Tuve, Phys. Rev. **28,** 554 (1926).

[11] Appleton and Barnet, Proc. Roy. Soc. **A113,** 450 (1926); **A109,** 621 (1925).

[12] Appleton, Nature, **120,** 330 (1927).

[13] Heising, Proc. Inst. Rad. Eng. **16,** 75 (1928).

winter nights. Hollingworth,[14] in England, concluded that the apparent heights reached by long waves, 6000 and 14,000 meters, in the day were 75 km in summer and 90 km in winter, the corresponding night values being 10 to 20 km greater. Taylor and Hulburt[9] calculated from the observed skip distances, averaged over the year for daylight conditions, for waves below 40 meters in length, that these waves reach heights between 120 and 240 km.

THE PRESSURES IN THE UPPER ATMOSPHERE

The constituent gases of the outer atmosphere and their partial pressures are taken as given completely in the recent paper of Maris.[15] This paper is a revision and an extension of the classical calculations of Humphreys,[16] Jeans[17] and others and provides tables of the partial pressures of the various gases for summer and winter and day and night. Although the question of the existence of hydrogen can hardly be said to be settled, we follow Chapman and Milne,[4] who have reviewed the evidence, and assume that there is no free hydrogen in the high atmosphere.

We shall need only the values of the total molecular density n (number of molecules per cm^3) and of the density n' of the oxygen molecules. It is convenient to express these as functions of z, the height above the earth in cms, by the relations

$$n = n_0 e^{-pz}, \tag{1}$$

and

$$n' = n_0' e^{-p'z}. \tag{2}$$

The values of p, p', n_0 and n_0' are given in Table I, n_0 and n_0' being the values of n and n' at $z = 60$ km. The equations with the constants of Table I are good approximations for z from 60 to 300 km for day conditions, at night above 200 km they cease to be very exact. For other heights Maris' tables must be used directly. It is well to mention, as Maris points out clearly enough, that the pressures at heights above 200 km are open to uncertainties of hundreds of percent, for they are based on assumptions of temperatures which may be widely in error.

TABLE I. *Constants of equations (1) and (2).*

	p	p'	n_0	n_0'
Summer day	0.872×10^{-6}	0.920×10^{-6}	9.92×10^{15}	2.08×10^{15}
Summer night	1.41×10^{-6}	1.50×10^{-6}	5.08×10^{15}	1.07×10^{15}
Winter day	1.21×10^{-6}	1.42×10^{-6}	5.58×10^{15}	1.15×10^{15}
Winter night	1.47×10^{-6}	1.56×10^{-6}	3.22×10^{15}	6.76×10^{14}

DISAPPEARANCE OF THE FREE ELECTRONS

There are three ways in which the free electrons of any region of the atmosphere may disappear, by diffusion into other regions, by combining with positive ions, and by attaching themselves to neutral molecules.

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[14] Hollingworth, Journal of Elec. Engrs. **64,** 579 (1926).

[15] Maris, to be published soon.

[16] Humphreys, "Physics of the Air," 1920.

[17] Jeans, "Dynamical Theory of Gases," 1925.

Diffusion. In considering the diffusion of the ions and electrons we assume that *each element of volume of the upper atmosphere is electrically neutral and remains so at all times.* It is true that in the lower atmosphere there is a gradient of electric potential and a vertical electric current, but in the light of the thunderstorm theory of C. T. R. Wilson[18] it seems probable that these effects do not extend to altitudes above, say, 40 km. The charged particles which are produced by the ultra-violet light in equal positive and negative amounts throughout each element of volume, diffuse about to attain if possible their equilibrium pressures. The diffusion of the electrons is considered to be governed entirely by the motions of the positive ions, for because of the electrostatic forces electrons may not stray from any region unless accompanied by equal numbers of positive ions, and, conversely, wherever the positive ions go equal numbers of electrons flock along with them.

The two hypotheses, (a) that all parts of the upper atmosphere are electrically neutral (or, in other words, that the fluctuations of excess charge are restricted to small volumes), and (b) that the profound electrical disturbances of the lower atmosphere around us do not extend to the high atmosphere, are very far reaching, and it must not be supposed, from the brief account that has been given, that their importance has been underestimated. If these hypotheses are untenable probably all the conclusions of the present paper must be modified. At best, I imagine, the hypotheses can only be regarded as approximately true.

If the density of particles of one kind is ρ_1 and of a second kind is ρ_2, and if ρ_1 is much less than ρ_2, the number N of particles of the first kind which move by diffusion across a cm^2 each second in the positive direction of the Z-axis is given[19] to a close approximation by $N=-0.41\gamma u\partial\rho_1/\partial z$ where γ is the mean free path of the first kind of particles, u their velocity of thermal agitation, and $\partial\rho_1/\partial z$ the departure of the pressure gradient along Z from the equilibrium gradient, i.e. the gradient for no diffusion. In the present case we have ions of density y diffusing among the gas molecules of density n, and (as we shall see) y is always less than $10^{-2}n$. There will be no diffusion of the ions if $y=Cn$, where C is a constant; in this case the slope of the ionic density curve is $dy/dz=Cdn/dz=-py$ (from (1)), and the ions may be said to be in uniform mixture equilibrium. If equilibrium does not exist there will be diffusion, and the rate of diffusion of the ions across a cm^2 is

$$N=-0.41\gamma u(-py-dy/dz). \qquad (3)$$

This formula also gives the diffusion of the electrons. With a temperature 219°K, $u=10^5$ cm sec^{-1} (actually u is 5.8×10^4, 6.3×10^4 and 1.7×10^5 for oxygen, nitrogen and helium ions, respectively). The mean free path of the ion $\gamma=1/2^{1/2}\pi n\sigma^2$, the molecular diameter σ being taken to be 3×10^{-8} cm. Formula (3) becomes

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[18] Wilson, Phil. Trans. Roy. Soc. **221,** 73 (1921); Proc. Phys. Soc. London **37,** 32D (1925); Nature **119,** 502 (1927).

[19] Jeans, "Dynamical Theory of Gases," Ch. XIV, 1904.

$$N=10^{19}(py+dy/dz)/n. \tag{4}$$

The rate of decrease of electrons (or ions) in a unit volume due to diffusion is

$$dN/dz=10^{19}(d^2y/dz^2+2pdy/dz+p^2y)/n. \tag{5}$$

Diffusion of the ions in the magnetic field of the earth. The magnetic field of the earth will have no appreciable influence upon the diffusion of the ions for gas pressures sufficiently high, i.e. above 10^{-8} atmospheres, but for lower pressures it reduces the diffusion across the field. For, an ion of mass m and elementary charge e moving with a velocity u transversely to a magnetic field H goes in a circle of radius r, where r is given by the relation $Heu=mu^2/r$. So that the straight line distance which a free ion can progress across the field can not be greater in order of magnitude than r. This does not disturb the diffusion formulas (4) and (5) as long as the free path γ is less than r, but for $\gamma>r$ we may replace γ of (3) by r as a rough approximation.

With $H=0.5$ gauss and with u corresponding to a temperature 219°K, r is 4×10^2 cm for oxygen and nitrogen molecular ions and 1.4×10^2 cm for helium ions. γ is 3×10^2, 2×10^3 and 10^4 cm at heights of 160, 180 and 200 km, respectively, on a summer day. Therefore, at about 180 km on a summer day and 140 km on a winter day the magnetic field reduces the diffusion of the ions across it by a factor of 5 from its value in the absence of the field, and at greater heights by a greater factor. The diffusion along the field is of course undistrubed by the field. In the present instance we are primarily interested in calculations for the temperate zone where the lines of magnetic force are at 45° or so with the vertical and we are content to neglect the effects of the field on the downward diffusion of the ions even at heights of 200 km (summer day). It seems certain, however, that a portion of the ions formed at greater heights are guided to the magnetic poles and accumulate there. The recognition of this has given a new theory of the origin of the aurora which is described in a subsequent paper.

Recombination of ions and electrons. A theory of the recombination of ions has been worked out by J. J. Thomson.[20] The essential idea of the theory was that an electron, or a negative ion, upon collision with a positive ion would combine with the ion only if the energy of recombination were dissipated in some way, as by the action of a neutral molecule. Therefore recombination involved a sort of three body collision, the energy of recombination going presumably into heat. The theory takes no cognizance of the possibility of recombination with the emission of radiation; this will be discussed later on. If ρ and ρ' are the densities of the positive and negative particles, respectively, the number of recombinations per second per cm^3 is

$$A\rho\rho'. \tag{6}$$

A general expression for A was derived by Thomson which, for pressures less than a centimeter of mercury, reduced to

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[20] J. J. Thomson, Phil. Mag. **47**, 337 (1924).

$$A=2\pi(u^2+u'^2)^{1/2}(2e^2/3kT)^3(1/\gamma+1/\gamma'),\qquad(7)$$

where u and u' are the velocities of thermal agitation of negative and positive ions, respectively, γ and γ' their free paths among the molecules of the gas, T is the absolute temperature and k the molecular gas constant 1.372×10^{-16} erg deg^{-1}. For free electrons and positive ions $\gamma=4/\pi n\sigma^2$ and $\gamma'=1/2^{1/2}\pi n\sigma^2$. The molecular diameter σ is 3×10^{-8} cm for the gases of the outer atmosphere. At the temperature 219°K $u=10^7$ cm sec^{-1} and u' is around 10^5. Putting these values in (7) gives $A=an$, where $a=3.82\times10^{-23}$, and as there are equal densities y of electrons and positive ions the rate of their recombination per cm^3 is from (6)

$$any^2=3.82\times10^{-23}ny^2.\qquad(8)$$

Similarly the rate of recombination per cm^3 of positive and negative ions, of oxygen or nitrogen is

$$a'ny^2=5.45\times10^{-25}ny^2.\qquad(9)$$

Thomson showed that the general formula for A agreed well with observations at pressures around an atmosphere. As a test at lower pressures (8) gives $an=1.22\times10^7$ for the recombination of electrons and positive ions in air at room temperature and a pressure of 0.2 mm of mercury, and Rumpf[21] obtained from experiment a value $an=0.35\times10^7$; the agreement is regarded as satisfactory.

The attachment of electrons to neutral molecules. At the present time a complete theory of the attachment of electrons to neutral molecules or atoms is not available. From the observations of Townsend and Bailey,[22] Thomson,[23] Loeb,[24] Wahlin[25] and others it seems that free electrons in thermal equilibrium at ordinary temperatures and pressures with molecules of the gases of the earth's atmosphere do not attach themselves to any of these molecules, thereby to form negative ions, except to oxygen molecules. Although there is some discussion[26] as to the exact value of the attachment coefficient for free electrons with oxygen molecules, the order of magnitude 10^5 is fairly well agreed to. This means that the electron makes 10^5 kinetic theory collisions with the oxygen molecules before it becomes attached to a molecule. We assume that this value is true for the low temperatures and pressures of the outer atmosphere. The number of free electrons which become attached to oxygen molecules per cm^3 per second is

$$uy/10^5\gamma,\qquad(10)$$

where u is the thermal velocity of the electrons and γ their mean free path among the oxygen molecules. Since $\gamma=4/\pi n'\sigma^2$ (n' is the density of the

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[21] Rumpf, Ann. d. Phys. u. Chem. **66**, 55 (1921).

[22] Townsend and Bailey, Phil. Mag. **43**, 875 (1921).

[23] Thomson, "Rays of Positive Electricity."

[24] Loeb, Phys. Rev. **17**, 89 (1921).

[25] Wahlin, Phys. Rev. **19**, 173 (1922).

[26] Bailey, Phil. Mag. **50**, 825 (1925); Brose, Phil. Mag. **50**, 536 (1925).

oxygen molecules, σ their diameter), $\sigma = 3 \times 10^8$ cm and $u = 10^7$ cm sec^{-1}, (10) becomes

$$bn'y = 7.1 \times 10^{-14} n'y. \tag{11}$$

(I have wondered about the correctness of arguments, such as the foregoing, which are based on average values. Better expressions, although perhaps not greatly different, might be expected to come out of Einstein's considerations of fluctuations.)

IONIZATION BY THE ULTRA-VIOLET LIGHT OF THE SUN

Let I_λ be the intensity of the sunlight of wave-length λ at a height z cms above the surface of the earth. If the direction of the light makes an angle ψ with the vertical, then

$$dI_\lambda = \beta_\lambda n I_\lambda dz / \cos \psi, \tag{12}$$

where β_λ is the molecular (or atomic) light absorption coefficient of the gas for light of wave-length λ. (12) is of course the usual definition of β_λ. Putting (1) into (12) and integrating gives

$$I_\lambda = E_\lambda \exp. \left(-\beta_\lambda n/p \cos \psi\right), \tag{13}$$

where E_λ is the intensity of light of wave-length λ for $z = \infty$, i.e. outside of the atmosphere.

Let $q_\lambda d\lambda$ be the number of ion pairs (i.e. electrons and positive ions) produced per cm^3 per sec by the light in the wave-length region λ to $\lambda + d\lambda$ and let W be the work of ionization of the gas molecule (or atom). Then

$$q_\lambda d\lambda = \left[\beta_\lambda n E_\lambda \exp. \left(-\beta_\lambda n/p \cos \psi\right) d\lambda\right]/W, \tag{14}$$

on the assumption that all of the absorbed energy causes ionization. The total electron production will be $\int q_\lambda d\lambda$, the integral to be taken over all regions of the spectrum which cause ionization. There will be a similar integral for each type of molecule or atom in the atmosphere and a more complete expression for the electron production would be represented by a sum of such integrals. However, too little is known about the photoelectric ionization of gases to permit a complete expression to be dealt with, and therefore we simplify (14) by dropping the subscript λ and write

$$q_z = \left[\beta n E \exp. \left(-\beta n/p \cos \psi\right)\right]/W, \tag{15}$$

where q_z denotes the number of ion pairs, or electrons, produced per cm^3 per sec at a height z. If the light is totally absorbed, or nearly so, in passing down to a height z, the total number of electrons q produced per sec in a 1 cm^2 column which extends from outside the atmosphere to z is

$$q = \int_z^\infty q_z dz = (E \cos \psi)/W. \tag{16}$$

On a simple photoelectric theory of ionization (Bohr's Theory) the light which causes ionization is in that region of the spectrum extending to shorter wave-lengths from the limit of the principal series. The atomic and molecular absorption coefficients in this region are just beginning to be hinted at in experiment and theory. Ditchburn[27] observed β to be 10^{-18} for potassium atoms and derived a value 10^{-16} for the molecule. Oppenheimer[28] calculated a value 2×10^{-17} for hydrogen-like atoms from a theory based on the new mechanics. For the absorption coefficients of the lines of the principal series values of 10^{-12} are mentioned. It seems that we are justified, as a working hypothesis, in taking β fairly high, equal to or greater than 2×10^{-17}, for that light which is most effective in causing photoelectric ionization. This means that the light will be nearly all absorbed in reaching a 190 km level on a summer day, for above this level there are $\int_{190}^{\infty} ndz = 6.6\times10^{16}$ molecules. The manner in which β varies with λ below the series limit is not known; Milne[29] finds theoretically that it decreases as λ^2 for hydrogenic atoms. For oxygen and nitrogen the processes of ionization of the molecules are not clearly understood. Apparently electron impacts generated by 17 volts or more (corresponding to λ725A or less) are necessary to make any sort of ionization in nitrogen.[30,31] For oxygen about 13 volts (λ950A) are needed to produce ionization, although it may be that by successive steps or cumulative action 10.8 volts (λ1140A) are effective.

If the distribution of energy in the spectrum of the sun be that of a black body at a temperature 6000°K, then with the value 1.35×10^6 erg cm^{-2} sec^{-1} for the solar constant the energy E in a band $5A$ wide at λ890A falling vertically down on the outer atmosphere of the earth is 4.5×10^{-3} erg cm^{-2} sec^{-1}. (It may be recalled that the energy at the earth's surface of moonlight is 1, of starlight is 3×10^{-3} and of the penetrating radiation is 3×10^{-4} erg cm^{-2} sec^{-1}.) At this wave-length the work of ionization W is 2.23×10^{-11} ergs and therefore from (7) E/W is 2×10^8 ion pairs. If the ionizing region of wave-lengths is at 1300A the width of the band is less than 0.1A in order for E/W to be 2×10^8, and for a region beginning at λ880A the band must extend to $\lambda=0$ for E/W to be 2×10^8.

The upshot of all this is; first, it is reasonable to assume that a large part of the ionization is caused by the short wave ultra-violet light, say, below λ1200, whose absorption coefficient in the gases of the outer atmosphere is high, greater than 2×10^{-17}, so that on a summer day most of the electrons are produced above the 200 km level; and second, it is reasonable to assume that the sun emits enough ultra-violet light in the proper region of the spectrum to produce 2×10^8 ion pairs in the upper atmosphere each second in a column 1 cm^2 extending from 200 km upward to interplanetary space.

The reason for assuming a rate of production of 2×10^8 ions pairs is that, as is shown later, this yields an ionization in agreement with the data of

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[27] Ditchburn, Proc. Roy. Soc. **A117**, 486 (1928).

[28] Oppenheimer, Zeits. f. Physik. **41**, 268 (1927).

[29] Milne, Phil. Mag. **47**, 209 (1924).

[30] Mohler, Nat. Res. Council Bul. **9**, 118 (1924).

[31] Hogness and Lunn, Phys. Rev. **27**, 732 (1926); **26**, 786 (1925).

wireless telegraphy. It must be emphasized, however, that after the laboratory has furnished certain facts of ionization of gases one should, taking the sun's ultra-violet intensity and the atmospheric pressures, etc., as known, be able to calculate the ionization of the upper atmosphere independently of any reference to the facts of wireless transmission. Or perhaps a better point of view is that the facts of wireless may eventually be used to give the distribution of sunlight energy in the extreme ultra-violet.

The electron layer formed by solar ultra-violet light absorbed above the 200 *km level on a summer day.* At any place in the atmosphere the change in the electron density y with the time t is equal to the difference between the rates of production and loss of the electrons. From (5), (8), (11) and (15) we obtain

$$dy/dt = q_z F(t) - 10^{19}(d^2y/dz^2 + 2p\,dy/dz + p^2y)/n - any^2 - bn'y, \tag{17}$$

where $F(t)$ is a periodic, or rather an intermittent, function of the time. It represents the variation of the sunlight throughout the day and its cessation at night. An exact solution of (17) is not attempted here, we pass immediately to approximations. In the daytime equilibrium of the electron density exists and $dy/dt = 0$. Considering now the case in which all the electrons and ions are produced above the 200 km level and none below this level, (17) for daytime equilibrium becomes

$$10^{19}(d^2y/dz^2 + 2p\,dy/dz + p^2y)/n + any^2 + bn'y = 0. \tag{18}$$

The y,z curve, i.e. the electron distribution curve, is obtained from (18) by approximate methods; its general shape can be seen from physical considerations. At high altitudes because of the low pressures which make for rapid diffusion and slow loss of the free electrons, the y,z curve will be closely that of uniform mixture equilibrium. Passing to lower altitudes the removal of the free electrons due to recombination and attachment increases very rapidly until the removal predominates over the supply due to diffusion. y therefore increases to a maximum, with z decreasing, and below the maximum falls rapidly to zero, as in curve 1, Fig. 2. More specifically, from some point a, curve 1, upward the curve follows the uniform mixture equation

$$y = y_a e^{-pz}, \tag{19}$$

which of course is nothing but (18) with all the terms to the right of the parenthesis put equal to zero. Below the point a the curve is drawn step by step from (18) with sufficient precision, by following the course of the first and second derivatives. It is possible to do this because dy/dz is positive below the maximum; hence d^2y/dz^2 is essentially negative and the curve is concave towards the Z-axis. The numerical values of the coefficients in (18) are such as to permit but little latitude in a proper choice of y, dy/dz and d^2y/dz^2 for each value of z in this region.

Turning to the calculations, $\psi = 17°$ for the temperate zone in summer (as at Washington, D. C.). $E/W = 2 \times 10^8$, as discussed in an earlier paragraph, and therefore from (16) $q = 1.92 \times 10^8$. The height z_m where y is a maximum is not known, so we try taking it at $z = 190$ km, as in curve 1, Fig. 2, the subscript m referring to the maximum point M. y_m, the value of y at M, is determined from the condition that the total recombination and attachment loss per second from z_m to infinity plus the diffusion downward at z_m is equal to q, or, from (4), (8) and (11),

$$\int_M^\infty any^2dz + \int_M^\infty bn'ydz + 10^{19}py_m/n_m = q, \tag{20}$$

n_m being the molecular density at M. The integrations in (20) were graphical (or, rather, a portion were), and several trials were necessary before y_m was found; it came out to be 3×10^5; the radius of curvature at M was 7.6 km (on the scale of Fig. 2), and the curve followed equation (19) from $z_a = 198$ km upwards, with $y_a = 2.93 \times 10^5$. The value of $\int_M^\infty any^2dz$ was 1.1×10^5, of $\int_M^\infty bn'ydz$ was 1.46×10^8 and of $10^{19}py_m/n_m$ was 4.55×10^7. Below the maximum the curve descended quickly to low values of y at a height of 186 ± 2 km.

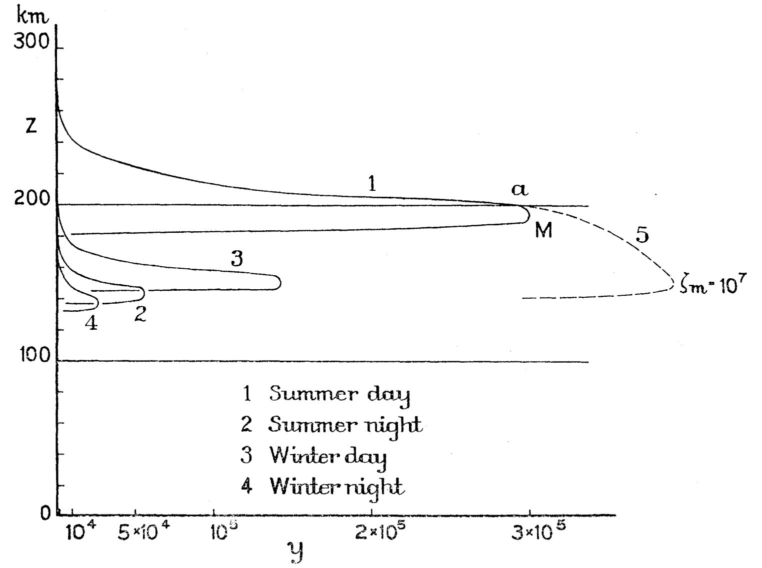

Fig. 2. Calculated ionization curves for the temperate zone resulting from the highly absorbed ultra-violet light of the sun. Curves 1, 2, 3 and 4 give the electron density y as a function of the height z above the earth for a summer day and night, and a winter day and night respectively. Curve 5 is the density ζ of the ions arising from the electrons of curve 1.

Below the maximum the curve must satisfy a relation similar to (20), namely, the total recombination and attachment loss per second must equal the diffusion across the maximum or,

$$\int_{186}^M any^2dz + \int_{186}^M bn'ydz = 10^{19}py_m/n_m \tag{21}$$

For curve 1, Fig. 2, this relation gave $4.5 \times 10^5 = 4.56 \times 10^5$, which was near enough. Curve 1, therefore, satisfied all the conditions and is the final solution for the distribution of those electrons which are produced at high levels. Furthermore, the curve is the only one which satisfies the conditions for a specified value of q. For, if the maximum was selected higher than 190 km, the diffusion across the maximum was greater than the total loss below the maximum, and if the maximum was taken below 190 km the reverse was true; this is of course to be expected from the physics of the case. The numerical calculations were made with sufficient care to determine the height 190 km within ±5 km.

If instead of using $q = 1.92 \times 10^8$ we take a different value, say ten times as great or ten times as small, the respective values of y_m are about 4×10^6 and 2×10^4, but the value of z_m remains practically unchanged at 190 km. *Therefore the height where the electron density is a maximum is* 190 *km* (*on a summer day*) *for those electrons which are produced at high altitudes* and is independent of assumptions about the intensity of the ultra-violet radiations from the sun. It depends upon the physical characteristics of the high atmosphere, as might be expected. Furthermore, the position of the maximum is not very sensitive to the numerical values of a and b in equation (18), changing by about 20 km when these are changed by an order of magnitude.

The rather clumsy method which has been used to unravel equation (18) is deservedly open to criticism; a small point in its favor is that it directs attention constantly to the essential physics of the case. An explicit mathematical solution of (18) would be more satisfactory, but graphical or approximate methods would still be necessary to the introduction of boundary conditions such as (20) and (21). As a matter of fact (18), when simplified a little by putting n' proportional to n, was solved as a series; the series although convergent, required the retention of a large number of terms, about 300, for its evaluation, and so was not useful. Dr. G. Breit very kindly showed that after several transformations a solution could be effected in Bessel's functions; this has not been used.

Agreement with the skip distances. The electron density increases very rapidly with the height, as shown by the portion of curve 1, Fig. 2, below the maximum. Therefore, the skip distances of the wireless waves may be calculated approximately as if the waves were sharply reflected at the height of 190 km, using the theory and method of the former paper.[9] The calculated values agree of course with the observed ones, since E/W has been put equal to 2×10^8 in order to secure this agreement.

The electron bank at night in summer. After nightfall the y,z curve is given by equation (17) with the $q_z F(t)$ term put equal to zero. An approximate solution is obtained by assuming that during the night y suffers a proportional decrease at every point of the daylight curve, curve 1, Fig. 2. Because of the cooling of the high atmosphere at night, the height for a given molecular density is lower at night than in the day, and therefore the entire night y,z curve is shifted downward about 50 km below the day curve in summer, the night curve maximum being at 140 km. The total loss of electrons per second due to recombination and attachment above the maximum of the daylight y,z curve is $\int_M^\infty (any^2+bn'y)dz=1.46\times 10^8$, which may be written $483y_m$, since y_m is 3×10^5. The loss per second due to diffusion across the maximum is $10^{19}py_m/n_m=4.55\times 10^7=152y_m$. The total number of electrons above the maximum is $5.76\times 10^{11}=1.95\times 10^6 y_m$. Then $dy_m/dt=(483+152)y_m/1.95\times 10^6$, which gives the value of y_m at any time t seconds to be $dy_m/dt=3\times 10^5$ exp. $(-3.25\times 10^{-4}t)$, the constant of integration having been determined from the condition that when $t=0$, $y=3\times 10^5$. With $t=8$ hours, y_m from this equation is 30. This is too small a value for it results in night skip distances greater than are observed. A decrement factor five times as small as 3.25×10^{-4} is required. The equation is then

$$y_m=3\times 10^5 \text{ exp. } (-6\times 10^{-5}t). \tag{22}$$

With $t=8$ hours, i.e. about midnight, (22) gives $y_m=5.6\times 10^4$. The summer night curve with this value of y_m is drawn in curve 2, Fig. 2. The skip distances calculated from this curve are twice the day values and are in accord with the observations given in Fig. 1.

The calculation of the decrease of the electrons at night has yielded a decrement factor, which, although apparently five times too great, is of the correct order of magnitude. We may regard this as an indication of the soundness of the theory. A more exact agreement is hardly to be expected in view of the approximate nature of the entire treatment and of the uncertainty in the numerical values of such quantities as the attachment and recombination coefficients. Perhaps the lateral diffusion due to winds, etc., of the ions from the sunlit to the dark areas is important here. As a matter of fact one could decrease the attachment coefficient, readjust things a bit, and obtain an exact, and perhaps misleading, agreement. Certainly the discrepancy can not be taken to suggest an agency, such as α or β particles from the sun, etc., which maintains the ionization during the night.

The electron layer in winter. For a winter day in the temperate zone (as at Washington, D.C.) the angle ψ which the rays of the sun at noon make with the vertical is 63°. With $E/W=2\times 10^8$ equation (16) gave $q=9.1\times 10^7$. The y,z curve was determined in the same way as was done for the summer day case. y_m came out to be 1.42×10^5 at $z_m=147$ km, and the y,z curve is plotted in curve 3, Fig. 2. The skip distances calculated from this were in agreement with the observed values.

The calculated decrease of the electrons at night was found to be too rapid, just as for the summer night, the decrement factor being again 3.25×10^{-4} which was five times too large. Upon dividing it by 5 the decrement equation became

$$y_m=1.42\times 10^5 \text{ exp } (-6\times 10^{-5}t). \tag{23}$$

With $t=8$ hours y_m from (23) was 2.6×10^4 at a height $z_m=135$ km; this y,z curve is plotted in curve 4, Fig. 2. It gave midnight skip distances 2.5 to 3 times the midday values, in entire accord with the data of Fig. 1.

The ion layer resulting from the electrons produced by the highly absorbed ultra-violet light of the sun. In the foregoing calculations of the electron layers we have supposed that there are 1.92×10^8 electrons and positive ions, for summer noon temperate zone conditions, produced per cm^2 per sec in the atmosphere above the 200 km level. These diffuse downward until, as the present theory puts it, at about 185 km there are no free electrons left at all. About 10^5 electrons each second (in a column 1 cm square) combine with the positive ions to form neutral molecules, and the remaining 1.92×10^8 attach themselves to oxygen molecules. Therefore the region above the 185 km level may be regarded as a source of about 2×10^8 negative oxygen molecular ions and 2×10^8 positive ions per cm per second. It is of interest now to follow the course of these ions in their excursions downward, and here we come upon so many gaps in experimental knowledge that speculation is the rule and hypotheses based on facts are the exception. We have thus far avoided specifying just what the positive ions are, but they are probably largely oxygen and nitrogen ions; possibly helium ions are less abundant because of the greater ionization potentials of helium; and there may be argon and other rare gas ions. Some of the oxygen and nitrogen positive ions may be atom ions and some molecular ions, in just what proportion it is impossible to say. No very satisfactory guess can be made as to what happens to the positive and negative ions after they are formed. A number of possibilities may be suggested: direct neutralization may occur, as by the encounter of, say, a negative oxygen and a positive nitrogen ion; the negative oxygen ion may lose its electron by a suitable encounter with a neutral molecule; ionic recombination with the emission of radiation may occur; oxides of nitrogen may be formed, ozone is formed, water vapor may be present and take part as a catalyst in all sorts of reactions; the presence of multiply ionized and excited atoms and molecules may be important; and to all this must be added the influence of the ultra-violet light from the sun of wave-length longer than, say, λ1000A, thus far left out of mention, which pours continually into the high atmosphere. No doubt in this maze of possibilities are to be found explanations of the light of the night sky, the aurora light, the presence of ozone in the high atmosphere, etc.

In spite of the many uncertainties we make an attempt at the calculation of the ion layer and assume that recombination of the positive and negative ions occurs according to the three body collision theory of J. J. Thomson, as expressed by equation (9). Denoting by ζ the density of the positive (or negative) ions, the general equation of the ζ, z curve is similar to (18), and is $10^{19}(d^2\zeta/dz^2+2p\,d\zeta/dz+p^2\zeta)/n+a'n\zeta^2=0$. A solution of this was obtained by the same approximate methods as were used for (18), and the ζ, z curve was found to have a maximum at about 150 km with ζ_m about 10^7, for a summer day. The curve is sketched in the dotted curve 5, Fig. 2. Below the maximum the curve fell rapidly, within a few km, to small values of ζ. The decrease in the ion bank at night was found to be given approximately by the equation $d\zeta_m/dt=-0.4\zeta_m{}^2-2.4\times 10^{-5}\zeta_m$, which showed that ζ_m decreased by an order of magnitude in 10^5 sec or 28 hours, a rather slow decrease. The equation was derived on the hypothesis that, as in the case of the electron layer, the source of ions was removed at nightfall. Actually in the ion case the source does not disappear with the sun, the electron layer itself being the source of the ions, and as it contains 5.76×10^{11} electrons it is able to maintain the daytime production rate of 2×10^{8} ions per sec for 2.9×10^{3} sec or 48 minutes. Therefore the decrease of ions at night is even a little slower than was calculated.

An ion layer, such as drawn in curve 5, Fig. 2, with ζ_m about 10^7 at a height of 150km is too weak to cause an appreciable refraction and absorption of wireless waves even as long as 1000 meters. Such effects, however, unquestionably exist, and we come to the conclusion, perhaps perfectly obvious, that something more is needed than the ionization thus far sketched out. This brings us to the next section.

The ionization below 190 *km on a summer day.* The ionization due to the highly absorbed ultra-violet light, although adequate to account for the skip distances of the wireless waves, is not capable of explaining many other effects, such as the downward reflection of 400 meter waves at heights around 100 km[11] and of 6000 meter waves at heights of 80 km[14], etc. More ionization in the region from 190 to 80 km, referring to summer day conditions, must exist than is indicated by the ion curve 5, Fig. 2. And, although this curve may underestimate greatly the ion density, because it is based on a recombination formula which may not be applicable, it seems reasonable to suppose that there is light which penetrates below 190 km and produces ions and electrons in regions down to 80 km perhaps. Just what light this might be is not certain, probably those wave-lengths near, but not too near, the principal series limits of the atmospheric gases; Hughes[32] inclines to the view that air, free of dust, etc., can only be ionized by wave-lengths shorter than λ1350A. Experiments [33,34,35] show that there is some sort of ultraviolet radiation, probably of wave-length less than λ1250A, which causes fluorescence, and perhaps we may infer ionization, at 4 cms in oxygen, nitrogen and air at atmospheric pressure. On a summer day the atmosphere above 80 km is equivalent to 40 cm, and above 100 km to 6 cm, of air at sea-level pressures. Furthermore, the energy from the sun in the region from λ880 to 1234A is 4.2 erg cm^{-2} sec^{-1}. This is much greater than the energy 4.5×10^{-3} erg cm^{-2} sec^{-1} which was used for the curves of Fig. 2, and although possibly less efficient might be expected to cause considerable ionization.

But here we are nearly at the end of our rope as far as direct calculations from photoelectric effects are concerned; it seems hardly worth while at this time to assume absorption coefficients and intensities of various wavelengths of light and work out explicit curves of ionization in the region below 190 km. We are content with merely the preliminary step, that is, to point out what ionization will be in accord with wireless and other data, and

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[32] Hughes, Report on Photo-electricity, Nat. Res. Council Bul. **2**, 86 (1921).

[33] Hopfield, Phys. Rev. **20**, 573 (1922).

[34] Oldenburg, Zeits. f. Physik **38**, 370 (1926).

[35] Wynn Williams, Phil. Mag. **1**, 353 (1926).

to mention that as far as can be seen now the sunlight is quite capable of making this ionization.

There are required 40 electrons per cm^3 or 2×10^6 ions (nitrogen or oxygen) for normal incidence, and lesser numbers for grazing angles of incidence, to give the downward reflection at heights of 80 or 100 km observed for the long waves.[14] Between the 100 and 200 km levels about 10^4 to 10^5 electrons or 10^9 to 10^{10} ions (or a suitable mixture of electrons and ions) are necessary to explain the various apparent heights reached by the waves in the pulse experiments of Breit and Tuve[10]. The apparent heights above 200 km observed by Appleton[12] and by Heising[13] in certain cases are not regarded as meaning that the waves are returned from any such overhead heights above the earth. These effects seem more readily attributable perhaps to multiple reflections, delayed group velocities over the ray path, etc., and in addition, in the case of Heising, who used a high powered transmitter, to round-the-world signals, to signals reflected from the magnetic pole ion cap, etc. A density of 10^9 or 10^{10} ions in regions where the molecular density may be as low as 10^{12} seems at first sight to be rather high. But perhaps not so, in view of the undoubted efficacy of ultra-violet light in causing ionization and the slow recombinations of the ions at low pressures.

An ionic density of 5×10^9 ions per cm^3 at a level of 110 to 130 km, or 5×10^4 electrons at 130 to 150 km, or a proper combination of ions and electrons at these heights (and fewer numbers at lower heights) will give values of the overhead absorption coefficients of wireless waves in agreement with those observed. The absorption coefficient κ of an electromagnetic wave transversing an ionized gas has been shown, in the notation of a former paper,[36] to be $\kappa=\pi CG/(1/\lambda^2+G^2)$, for propagation in the absence of a magnetic field. For waves below 1000 meters this reduces approximately in the present notation to

$$\kappa=2.1\times 10^{-32} n y \lambda^2 \tag{24}$$

for electrons, and to

$$\kappa=2.0\times 10^{-38} n \zeta \lambda^2 \tag{25}$$

for ions. From these relations it is seen that 1 electron is equivalent to 10^6 ions as far as absorption is concerned, and at 140 km with $n=4.4\times 10^{12}$ and $y=5\times 10^4$, from (24) $\kappa=1.2\times 10^{-7}$ for 50 meter waves, which means that the intensity is reduced to $1/e$ of its value in going 40 km through the medium. This seems to be about the right value,[36] for only a portion of the ray path lies in the region of absorption. An ion density of $\zeta=10^9$ at $z=120$ km, where $n=2.57\times 10^{13}$ gives about the same absorption.

Calculations based on the recombination and diffusion formulas indicate that ionic densities of 10^9 or 10^{10} in the region from 100 to 190 km (summer day, or 80 to 150 km for a winter day) may be expected to decrease by an order of magnitude or so at night, thereby causing a marked diminution of the overhead absorption, particularly of certain wave-length regions of

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[36] Hulburt, Phys. Rev. **29**, 706 (1927).

the wireless waves. However, it is not necessary to enter into further detail to indicate that this sort of ionization may cause an absorption and a refraction of the wireless waves which varies with the wave-length in such a manner as to account in general for the diurnal and seasonal variations of the wireless wave propagation phenomena. This has already been blocked out to some extent in the earlier paper,[36] and, indeed, the idea is now common property of many writers on the subject.[37] Eckersley[38] has suggested that the skip distance is to be attributed to the overhead absorption of the ray and not to the electron limitation hypothesis of the present and earlier[9] papers, but has not put his suggestion into a sufficiently quantitative form to enable it to be tested. Besides, the Radio Division of this Laboratory has experimental evidence (Taylor and Young, Proc. Inst. Rad. Eng., May, 1928), which is regarded as unfavorable to the suggestion.

Finally it may be remarked that the addition of, say, 10^5 electrons or 6×10^9 ions at 150 km to the summer day ionization of curve 1, Fig. 2, lessens the calculated skip distances by only 10 or 20%. Therefore the electron curves of Fig. 2 may be regarded as workable approximations at the present time, although they will undoubtedly require some modification in the future. The possible presence of appreciable numbers of ions amid the electrons may account for Meissner's[39] failure to observe any marked critical behavior of wireless waves in the region of 214 meters, as might be expected, although not necessarily, for an ionization predominately electronic.[9] And yet many polarization experiments, and particularly the recent ones of Appleton[40] and of Hollingworth and Naismith[41] indicate double refractions suggestive of electrons and not of ions.

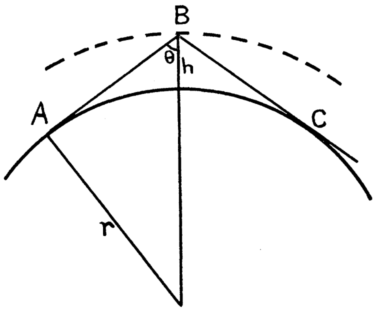

Fig. 3. The limiting ray ABC for sharp reflection from the Kennelly-Heaviside layer.

Limiting waves. A calculation of the limiting wireless wave λ_s for the electron layers of Fig. 2 gives values of λ_s somewhat greater than are observed. For example, referring to Fig. 3, ABC is the limiting ray path and θ is therefore the critical, or Snell, angle of reflection from the electron layer. The refractive index μ of the layer for any state of polarization is very closely for the short waves[9] $\mu^2=1-ye^2\lambda_s^2/\pi m$. Since $\mu=\sin\,\theta$ (Snell's law) and $\sin\,\theta=r/(r+h)$, r being the radius of the earth and h the height of the reflecting layer above the earth, we have

$$1-ye^2\lambda_s^2/\pi m=[r/(r+h)]^2. \tag{26}$$

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[37] Pederson, Book on Wireless wave Propagation reviewed in the Proc. Inst. Rad. Eng. **16,** 219 (1928).

[38] Eckersley, Journ. Inst. Elect. Eng. **65**, 600 (1927).

[39] Meissner, Elek. Nachr. Techn. **3**, 321 (1926).

[40] Appleton, Proc. Roy. Soc. **A117,** 576 (1928).

[41] Hollingworth and Naismith, Nature **121,** 170 (1928).

Using the summer noon values $h=190$ km and $y=3\times10^5$ we get $\lambda_s=14$ meters. The observed value is 10.5 meters. Similarly with the electron layers of Fig. 2, we find for summer night, winter noon and winter night that λ_s is 24, 18 and 28 meters, respectively, whereas the observed values are 17, 14 and 23 meters.

Upon putting at 150 km an ionized layer of 10^5 electrons or 6×10^9 ions in addition to the 3×10^5 electron layer at 190 km for summer noon, λ_s comes out to be 12 meters. By spreading out the ionization a little in the region below 190 km it is possible to get exact agreement with the observed value 10.5 meters for the summer day case; and similarly for the summer night and winter day and night cases.

Brief summary of the conclusions regarding ionization. Roughly we may say that for summer day conditions in the temperate zone an ionization consisting of about 10^4 electrons or 10^9 ions (or a proper mixture of ions and electrons) at 100 km, increasing to about 5×10^4 electrons or 10^9 to 10^{10} ions at 150 km and 3×10^5 electrons at 190 km, will account quantitatively for many facts of wireless telegraphy, namely, the skip distances, limiting wavelengths, apparent heights reached by the waves, overhead absorptions, and ranges. The calculated seasonal and diurnal variations of this ionization give agreement with the corresponding variations in the wireless wave phenomena. Furthermore, this ionization is in keeping, as far as can be seen, with that to be expected from the action of the ultra-violet light of the sun in the atmosphere. It may therefore be concluded that hypotheses of other ionizing agencies such as charged particles from the sun, penetrating radiations, etc., are quite unnecessary, except possibly (but not probably) to explain secondary or unusual effects such as are indicated in the recent correlations of sunspots and wireless transmission.[42]

Non-polar aurora. There is no evident connection of the negative oxygen ions, formed by the attachment of electrons to neutral molecules, with the night sky light and with the ozone of the upper atmosphere. Except that the green line of the night sky and of the aurora is attributed[43] to the oxygen molecule nothing definite can be said. We may, however, without specifying the exact process* conceive the night sky light, or the "non-polar aurora" as Rayleigh[44] calls it, to come from the solar energy which is stored in the high atmosphere in the form of ionized or excited atoms, and which presumably may be liberated in the form of recombination, or other types of, spectra. This of course is exactly Rayleigh's idea of the night-time "phosphorescence" of the high atmosphere.[45] The recombination formula (7) assumes that all the energy of recombination goes into heat and makes no provision for recombination with the emission of radiation. A complete theory must do this. However, in the present case the amount of radiation

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* Cario's recent note, Journ. Frank. Inst. 205, 515 (1928), indicates that the process may be a complex one.

[42] Pickard, Proc. Inst. Rad. Eng. **15,** 1004 (1927).

[43] Cario, Zeits. f. Physik **42,** 15 (1927).

[44] Rayleigh, Proc. Roy. Soc. **A109,** 428 (1925).

[45] Rayleigh, Proc. Roy. Soc. **A109,** 136 (1924).

turns out to be so small as to leave undisturbed the calculations based on (7). The non-polar aurora energy has not been measured, but may be estimated to be 10^{-7} erg cm^{-2} sec^{-1}, or 10^4 quanta cm^{-2} sec^{-1} of green light, at the earth's surface. Taking the total number of electron and positive ion pairs in a 1 cm^2 column of the atmosphere to be 10^{11} as in curve 1, Fig. 2, (there may be many more ion pairs below this curve) and supposing the energy of recombination of each pair is 1.6×10^{-11} ergs (10 volts), there is 1.6 erg stored up, a low estimate. If this energy is shed down as non-polar aurora light at the rate of 10^{-7} erg sec^{-1} only 3×10^{-3} erg are used in 3×10^4 sec or 9 hours. Therefore only a small fraction, less than 1%, of the solar energy stored in the atmosphere as ionization will suffice to maintain the non-polar aurora all night.

Ozone. The energy of formation of ozone is 2.38×10^{-12} erg per molecule, and according to Fabry[46] there are 3.2 mm or 10^{19} molecules of ozone in a 1 cm^2 column of the atmosphere. These persist all night, or at least a sufficient number of them do, to cut off by their absorption stellar spectra at λ2900A; this is also the ultra-violet limit of the sun's spectrum.

Although the process of the formation of ozone by ultra-violet light is not known, let us suppose that the ozone comes somehow from the negative oxygen ions resulting from the attachment of the free electrons which required in summer 4.5×10^{-3} erg cm^{-2} sec^{-1} of the highly absorbed ultra-violet light for their production. The number of ozone molecules formed per sec is, then, $4.5\times10^{-3}\div2.2\times10^{-12}=2\times10^9$, and to produce the 10^{19} molecules observed would take 5×10^9 sec or 150 years, if there were no losses. This seems too long a time; our supposition is therefore untenable, and we turn to other ways of accounting for the ozone. Experiment shows that light in the great oxygen absorption band from λ1300 to 1850A produces ozone, and in this spectral region the sun gives, by calculation, 100 erg cm^{-2} sec^{-1}. This energy would produce $100\div2.2\times10^{-12}=4.5\times10^{13}$ molecules of ozone per sec, and in 2×10^5 sec or 2.3 days the 10^{19} molecules would be made; this seems reasonable. We can go no farther, however, for aside from the fact that light in the ozone absorption band from λ2300 to 2900A causes ozone to revert to oxygen, nothing is known about the life of the ozone molecule or its manner of decomposition. And whether the formation and breaking up of ozone has anything to do with ionization is quite obscure. Oxides of nitrogen, as well as ozone, are formed by the action of ultra-violet light on air, and what part these may play in the physics (or the chemistry) of the atmosphere is entirely dark.

Brief summary of the atmospheric absorption of the ultra-violet light of the sun. In conclusion, a complete theory of the absorption of sunlight in the atmosphere must not be content with showing that some of the light is sufficient to cause the observed ionization, but must account for what happens to all of the light. In Table II are collected various facts and suggestions which have been mentioned in earlier paragraphs. The first column gives the wave-length region in angstrom units, the second column

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[46] Fabry, Proc. Phys. Soc. London **39**, 1 (1926).

TABLE II. *The Energy of the sun's ultra-violet light in various regions of the spectrum which is absorbed by the atmosphere of the earth, and the effects produced.*

Spectral region in angstrom units	Solar energy erg cm^{-2} sec^{-1}	Description
0 to 880	4.5×10^{-3}	Highly absorbed; produces the high lying electron and ion layer, at 190 km in summer and 150 km in winter. A portion of the upper spray of this layer diffuses to the magnetic poles and causes the aurora.
800 to 1250	4	Absorbed and produces ions at lower levels, 190 to 100 km in summer, and 150 to 80 km in winter. The potential energy of some of this ionization, and of the higher lying ionization, may be released at night to cause the non polar aurora.
1250 to 1800	10^2	Absorbed by oxygen and produces ozone. Production of ionization doubtful.
1800 to 2300	8.5×10^3	Not known exactly what absorbs this, but oxygen, ozone, oxides of nitrogen, carbon dioxide, water vapor, etc., may contribute. Production of ionization doubtful.
2300 to 2900	3.7×10^4	Absorbed by ozone and may cause some of the ozone to revert to oxygen. Production of ionization doubtful.

the solar energy in this region falling per cm^2 per sec on the atmosphere of the earth calculated on the assumption that the sun radiates as a black body at 6000°K, and the third column gives a description of the effects which the light may produce. The table is of course highly tentative, the description has been written down in the interests of simplicity, whereas a true and complete description will be in all probability immensely more complex.

NAVAL RESEARCH LABORATORY,
WASHINGTON, D. C.,
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