Photoelectric Ionization in the Ionosphere

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The ionization equilibrium in the various atmospheric gases is calculated from the Saha theory on the assumption that the spectral energy curve of sunlight for ultraviolet frequencies above the limits of the principal series is that of a black body at 6000°K. A calculated region of ionization due mainly to oxygen and partly to nitrogen is found at about 200 km with maximum electron density 1.6×10^6, in agreement with F_2 observation in winter temperate latitudes. The assumption of an expansion of the high atmosphere under the sun, with resulting winds and diffusion, leads to a partly quantitative explanation of the observed seasonal changes in F_2, and to a qualitative explanation of F_1. In the case of E region the equations do not indicate what radiation causes the ionization nor what gases are ionized. This may be due to the omission in the theory of the possibility of ionization by frequencies below the series limits. Calculation suggests that E ionization is mainly ionic resulting from two processes, the first being the formation by the ionizing radiation of positive ions and free electrons, and the second being the formation of negative ions by the attachment of the electrons to oxygen molecules.

IN the early stage of ionospheric research two theoretical papers appeared which reached similar conclusions, namely, that the upper atmospheric ionization could reasonably be attributed to the ultraviolet light of the sun. In one paper[1] the recombination of electrons was calculated from the Saha theory of photoelectric equilibrium and in the other paper[2] from oxygen attachment and the three-body encounter theory of Sir J. J. Thomson. Experimental knowledge of the ionosphere has been greatly increased by the investigations[3] of the National Bureau of Standards, the Department of Terrestrial Magnetism of the Carnegie Institution and the Bell Telephone Laboratories, with observing stations at Washington, D. C., U. S. A., New York, N. Y., U. S. A., Huancayo, Peru, and Watheroo, Western Australia. Additional experimental data have become available concerning the attachment of free electrons to oxygen molecules. In the following paragraphs the photoelectric theory is worked out in detail and is compared with experiment with greater rigor than has been possible hitherto. The conclusion is reached that F_2 arises from the ionization of oxygen and nitrogen and that F_1 may be due to the modification of F_2 by winds and expansion of the atmosphere. No quantitative explanation of the origin of the E region emerges from the equations.

Certain important facts of the ionosphere may be briefly stated. We deal only with the more prominent regions of ionization and present numerical data averaged over at least a month, thereby eliminating from discussion daily, or other short time, irregularities and disturbances in the ionosphere. During the years of sunspot minimum 1933 and 1934 for the sun overhead the equivalent electron density y for E, F_1 and F_2 was about 1.5, 3 and 6×10^5 at virtual heights of about 100, 200 and 400 km, respectively. The ionization below, between and above these apparent levels is not known except that the values at the levels are not exceeded. On the assumption, as yet unchallenged, that the upper atmosphere is approximately electrically neutral, the densities of positively and negatively charged particles are equal. With increased sunspots in 1935, 1936 and 1937 y for all regions experienced a general augmentation. At Washington in 1937 the summer noon values of y were about 2, 4 and 8×10^5 for E, F_1 and F_2, respectively; the winter noon value for F_2 was 2×10^6. During daylight hours not too near sunrise and sunset y of E varied with the zenith angle ζ of the sun closely according to

$$y=y_0(\cos\zeta)^{\frac{1}{2}}, \quad (1)$$

where y_0 is the value of y for $\zeta=0°$, i.e., the sun overhead.[3, 4] In the case of F_1 y obeyed (1) only

[1] Pannekoek, Proc. K. Akad. Amsterdam **29**, 1165 (1926).
[2] Hulburt, Phys. Rev. **31**, 1018 (1928).
[3] Gilliland, Kirby, Smith and Reyner, Nat. Bur. Stand. J. Research **18**, 645 (1937); Berkner, Wells and Seaton, Terr. Mag. and Atmos. Elect. **41**, 173 (1936); Schafer and Goodall, Proc. Inst. Rad. Eng. **23**, 1670 (1935); each paper being the latest of a series.
[4] Hulburt, Phys. Rev. **46**, 822 (1934); Terr. Mag. **40**, 193 (1935).

approximately. For F_2 y departed considerably from (1) but a reasonable theory[4] based on expansion of the atmosphere, winds and the rotation of the earth was proposed to account for the departures.

Observations of the magnetic double refraction of radio echoes returned from the ionosphere indicate that F, F_1 and F_2 are predominately electronic as far as the refraction of radio waves is concerned. In the case of E the double refraction is rarely observed. The fact is open to two interpretations, (1) that E is always predominately electronic and that the nonappearance of the extraordinary component is due to absorption, (2) that E is usually predominately ionic, hence yielding no extraordinary component within the accessible radio spectrum, but may at times be electronic. The two views are equally acceptable to the echo experiments. (2) is preferable to E layer theory, as explained later, and to theories of terrestrial magnetic variations.[5]

From measurements[3] at various latitudes and hours of the day in 1933 and 1934 the virtual heights of E were about 100, 120, and 140 km, and of F_1 were about 210, 230 and 240 km, for $\zeta=0°$, 60° and 70° to 80°, respectively. F_1 does not usualy appear in winter temperate latitudes. The virtual heights of F_2 were, within 30 km, 400, 380, 330, 280, 260 and 250 km for $\zeta=0°$, 20°, 40°, 60°, 80° and 90°, respectively. At night F_2 and F_1 coalesce to form a single F layer which remains at a virtual height of 250 to 300 km during the nocturnal hours. There were no important changes in the virtual heights during the years of increasing sunspots 1935, 1936 and 1937.

In general the virtual heights are always greater than the true heights, and the virtual height curve may give a very deceiving impression of the true distribution of ionization above sea level. For example, Murray and Hoag[6] have worked out a method for determining within limits the true heights from the virtual heights. When the method was applied to the Washington ionosphere observations of August 31, 1933, it turned out that whereas the virtual height of F_2 increased with decreasing ζ, the true height decreased with decreasing ζ. Thus, although F_2 appeared to rise during the morning to a midday maximum height and to descend in the afternoon, it actually descended during the morning to a midday minimum height and rose again in the afternoon.

[5] Hulbert, Rev. Mod. Phys. **9**, 44 (1937).
[6] Murray and Hoag, Phys. Rev. **51**, 333 (1937).

We use the tables of Maris[7] of the densities of the various gases of the atmosphere to great heights based on a day temperature of 360°K above 80 km with complete mixing from sea level to about 110 km and isothermal equilibrium above 110 km. The density n of the molecules or atoms of each gas is expressed as a function of the height z by

$$n=n_0\epsilon^{-pz}, \tag{2}$$

where z is measured from the level where $n=n_0$.

$$p=mg/kt, \tag{3}$$

m being the mass of the gas particle, g the acceleration due to gravity at the height z, $k=1.372\times10^{-16}$ the Boltzman constant and t the temperature Kelvin. For $z=140$ km n is 3.45×10^{12}, 9.29×10^{11}, 4.20×10^{10}, 4.42×10^{8}, 4.29×10^{8} and 1.77×10^{7}, and above 140 km p is 0.810, 0.925, 1.12, 2.36 and 0.116×10^{-6}, for molecular nitrogen, molecular oxygen, argon, krypton and helium, respectively. For atomic nitrogen and oxygen p is 0.405 and 0.462×10^{-6}, respectively. From these values the average percentages by volume of the gases in the atmosphere from 200 to 280 km are about 88, 10 and 1 for nitrogen, oxygen and argon, respectively; the proportion of helium increases from about 0.1 at 200 km to 30 percent at 300 km. Above 300 km helium predominates if the extrapolation to such high levels is valid. Hydrogen and water vapor are left out of consideration on the basis that if they were present hydrogen lines should appear in spectra of the night sky and the aurorae; no such lines are observed. However, the presence or absence of hydrogen and water vapor in the high atmosphere can not be said to be settled at the present time.

It is assumed that the atmospheric gases are ionized by the absorption of solar ultraviolet light of frequencies above ν_0, where $h\nu_0=\chi$, χ being the ionizing energy. If $i_\nu d\nu$ is the intensity of the ionizing sunlight in the range from ν to $\nu+d\nu$ and β_ν the molecular or atomic absorption

[7] Maris, Terr. Mag. **33**, 233 (1928); **34**, 45 (1929).

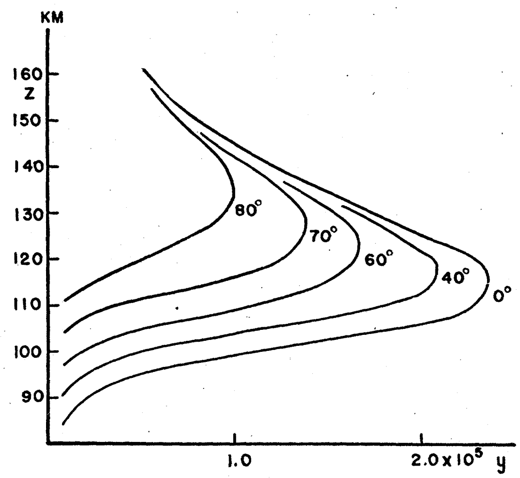

FIG. 1. Ionization curves calculated from (6).

coefficient of the gas, the rate cm^{-3} of absorption of energy is $n\beta_\nu i_\nu d\nu$. If one assumes that all of the absorbed energy causes ionization one finds that the number $q_\nu d\nu$ cm^{-3} $sec.^{-1}$ of electron ion pairs produced is

$$q_\nu d\nu = n\beta_\nu i_\nu d\nu/\chi. \tag{4}$$

The total ionization production is equal to $\int q_\nu d\nu$ taken over all regions of the spectrum which cause ionization. An exact evaluation of the integral is unprofitable at present and sufficient accuracy is secured by dealing with average values. Therefore we drop the subscript ν, denoting the intensity of the total ionizing light by i and the average absorption coefficient by β. (4) becomes

$$q = n\beta i/\chi. \tag{4.1}$$

Recombination of electrons and positive ions is assumed to take place at the rate of

$$\alpha y^2, \tag{4.2}$$

where α is the recombination coefficient and y the electron density. For equilibrium $q=\alpha y^2$ and from (4.1)

$$y^2 = n\beta i/\alpha\chi. \tag{4.3}$$

Let i be the intensity at a height z in the terrestrial atmosphere and ζ the zenith angle of the sun. Then

$$di = n\beta i\, dz/\cos\zeta. \tag{4.4}$$

On substituting (2) into (4.4) and integrating one obtains

$$i = i_0\epsilon^{-\beta n/p \cos\zeta}, \tag{5}$$

where i_0 is the intensity outside of the atmosphere. From (4.3) and (5).

$$y^2 = (n\beta i_0/\alpha\chi)\epsilon^{-\beta n/p \cos\zeta}. \tag{6}$$

This is the general expression for the ionization in any region for equilibrium conditions. Equilibrium requires that for a sufficient period of time the sun be approximately stationary with reference to the earth, the atmosphere be free from winds and mass motions and there be no diffusion of the ionization. None of these conditions are exactly true but some may be approximately true. Further, (5) and hence (6) is derived on the assumptions that the earth is flat and that the rays of ionizing light traverse the atmosphere in straight lines. For $\zeta < 80°$ the errors arising from the assumptions are less than 15 percent, but as ζ nears 90° the errors may be large.

With arbitrary values of the constants β, i_0, α and χ the y, z curves calculated from (6), (2) and (3) are plotted in Fig. 1 for various values of ζ. From (6) y reaches a maximum value given by

$$y = [(p i_0 \cos\zeta)/(\epsilon\alpha\chi)]^{\frac{1}{2}}, \tag{7}$$

ϵ being the Naperian base. Eq. (7) is of the same form as (1) and therefore is in agreement with observation insofar as (1) represents facts.

The virtual height z' of a radio ray passing vertically into a region of ionization is given by

$$z' = \int dz/\mu, \tag{8}$$

where μ is the refractive index of the region at a height z and the integral is taken along the ray. Because of the magnetic field of the earth the ionosphere is doubly refracting and for the ordinary component

$$\mu^2 = 1 - ye^2c^2/\pi m f^2, \tag{9}$$

where f is the frequency of the radio wave, e and m refer to the electron, and c is the velocity of light. C.g.s.e.m. units are used throughout this paper.

In Fig. 2 are plotted the values of z' from (8) and (9) corresponding to the y, z curves of Fig. 1. If the curves of Figs. 1 and 2 were worked out for values of z 100 km higher, they would be little changed; in such a case, for example, z'

for $\zeta = 80°$ would be about 35 km above z' for $\zeta = 0°$, as in Fig. 2. The variations of z' with latitude and time of day given by the f, z' curves of Fig. 2 agree fairly well with observation in the case of E region and moderately well in the case of F_1 region. This agreement together with that of (7) constitutes the main evidence in favor of the supposition that E and F_1 are largely due to photoelectric effects of sunlight, and that the effects reach approximate equilibrium in a time short in comparison with possible modifications due to the relative motions of earth and sun, and to diffusion and winds in the upper atmosphere. Ionosphere changes[3] during eclipses of the sun offer corroborative evidence.

In order to work out quantitatively by means of (6) the ionization in the various gases of the atmosphere, we proceed to explicit formulation of i_0, β and α. We consider first the intensity i_0. The spectral energy curve of solar radiation is assumed to be that of a black body at temperature $t_1 = 6000°K$. The total energy cm^{-2} radiated in the frequency range from ∞ to ν_0 is

$$\int_{\infty}^{\nu_0} (8\pi h\nu^3/c^2)(\epsilon^{a\nu}-1)^{-1}d\nu, \qquad (10)$$

where $a = h/kt_1$. Integration of (10) yields approximately

$$(8\pi h/c^2)(\nu_0^3/a + 3\nu_0^2/a^2 + 6\nu_0/a^3 + 6/a^4)e^{-a\nu_0}. \qquad (10.1)$$

For ν_0 in the ultraviolet the first term only of (10.1) may be retained without causing an error greater than 15 percent. Then the solar energy i_0 erg cm^{-2} $sec.^{-1}$ falling vertically on the top of the atmosphere is

$$i_0 = f(8\pi\nu_0^3 kt_1/c^2)\epsilon^{-h\nu_0/kt_1}, \qquad (11)$$

where $f = 1/184{,}000$ is the fraction of the total sphere subtended at the earth by the sun.

The absorption coefficient β for light in the continuum below the series limit usually used is that deduced by Kramers[8] from classical electromagnetic theory assuming a special law of electron capture. Kramers' theory gives, neglecting terms of unit order,

$$\beta = \frac{16\pi^2}{3(3)^{\frac{1}{2}}}\frac{Z^2e^6c^5}{h}\frac{h\nu_0}{(h\nu)^3}, \qquad (12)$$

where Z is the atomic number. β has values only for $\nu \geqq \nu_0$. (12) was derived for atoms but may be used approximately for molecules. From quantum theory Gaunt[9] derived a slightly different expression. There appear to be no direct experimental tests of (12) in the optical range; the formula can scarcely claim an accuracy better than an order of magnitude. Rosseland[10] has commented, "One sometimes has the feeling that the applicability of this formula has been strained beyond the breaking point." For He, A, N and O the first ionization potential is 24.46, 15.69, 14.48 and 13.55 volts,[11] and at ν_0 from (12) β is 4.75×10^{-18}, 9.46×10^{-16}, 1.69×10^{-16} and 2.52×10^{-16}, respectively.

The recombination coefficient α is derived from the Saha theory[12] of the ionization of a gas in photoelectric, thermodynamic equilibrium with radiation. The reaction isobar of a gas at temperature t_1 ionized by and in equilibrium with radiation at temperature t_1 is

$$x^2P/(1-x^2) = (2\pi mh^{-2})^{3/2}(kt_1)^{5/2}\epsilon^{-h\nu_0/kt_1}, \qquad (13)$$

where x is the fraction of atoms ionized and P is the total pressure. For a gas at temperature t and radiation at a temperature t_1, Pannekoek[1] showed that the right-hand side of (13) must be multiplied by $t^{\frac{3}{2}}/2t_1^{\frac{3}{2}}$. Then noting that $P = nkt$ and $x = y/n \ll 1$, (13) becomes

$$y^2 = n2^{\frac{1}{2}}(\pi mkh^{-2})^{\frac{3}{2}}t_1 t^{\frac{1}{2}}\epsilon^{-h\nu_0/kt} \equiv nA, \qquad (13.1)$$

which is of the same form as (4.3). Comparison

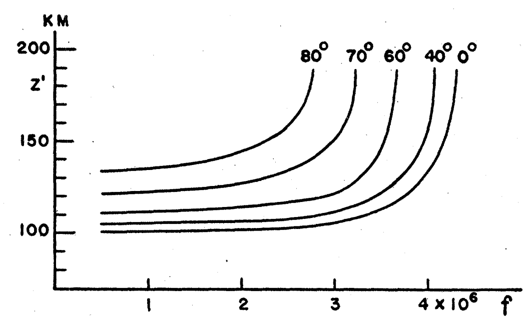

FIG. 2. Virtual height curves corresponding to the curves of Fig. 1.

[8] Kramers, Phil. Mag. **46**, 836 (1923).

[9] Gaunt, Phil. Trans. Roy. Soc. **229A**, 163 (1929–1930), also gives a critical discussion of the opacity formulae of Milne, Eddington, Oppenheimer and Rosseland.

[10] Rosseland, *Theoretical Astrophysics*, (1936) p. 194.

[11] Bacher and Goudsmit, *Atomic Energy States* (1932).

[12] Saha, Phil. Mag. **40**, 472 (1920); Woltjer, ibid. **47**, 209 (1924); Fowler, ibid. **45**, 1 (1923).

of (13.1) and (4.3) gives $\alpha=\beta i_0/A\chi$. Substitution of β from (12), i_0 from (11) and A from (13.1) leads to

$$\alpha=32\pi(2\pi m/27k)^{\frac{1}{2}}(Z^2e^6c^3/m^2)(\nu_0{}^3/h\nu^3t^{\frac{1}{2}}). \quad (14)$$

If some other formula for β than (12) were used a value of α different from (14) would result. Since α has been derived directly from β it contains the errors and uncertainties of β. The substitution of ν_0 for ν in (14) and the introduction of numerical values yield an average value of α in the continuum near to and ending with ν_0,

$$\alpha=1.02\times10^{-11}Z^2/t^{\frac{1}{2}}. \quad (14.1)$$

For $t=360$°K, α is 3.4×10^{-11} and 2.6×10^{-11} for atomic oxygen and nitrogen, respectively.

Mohler[13] has recently determined α to be 2×10^{-10} for mercury vapor at pressures below 10^{-1} mm and an electron temperature of about 2000°K, and 3×10^{-10} for caesium vapor at a pressure below 10^{-2} mm and temperature 1200°K. The corresponding values from (14.1) are 1.5 $\times10^{-9}$ and 8.9×10^{-11}. The agreement is perhaps as good as could be expected in view of the fact that (14) contains no correction due to screening of the nuclear charge Z or additional terms to include effects of line absorption at frequencies below ν_0.

The three-body collision theory of Sir J. J. Thomson[14] led to a recombination rate αy^2 in agreement with (4.2), and yielded an expression for α which for pressures below 10^{-2} atmosphere

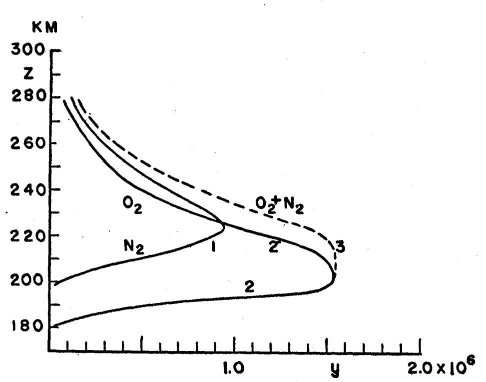

FIG. 3. Theoretical ionization curves for winter noon.

[13] Mohler, Phys. Rev. **51**, 1008 (1937).
[14] Thomson, Phil. Mag. **47**, 337 (1924).

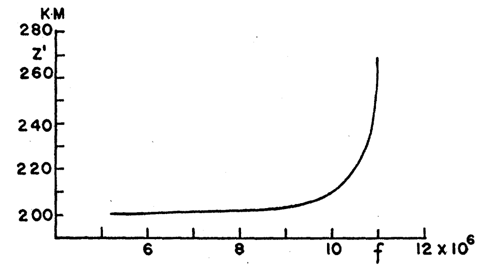

FIG. 4. Virtual height curve corresponding to curve 2, Fig. 3.

reduced to

$$\alpha=2\pi(u^2+u'^2)^{\frac{1}{2}}(2e^2/3kt)^3(1/\gamma+1/\gamma'), \quad (15)$$

where u and u' are the velocities of thermal agitation of negative and positive particles, respectively, and γ and γ' their free paths among the molecules of the gas. For $t=360$°K (15) becomes

$$\alpha=\tau n, \quad (15.1)$$

where τ is 1.6×10^{-23} for electrons and positive ions and 2.4×10^{-25} for positive and negative ions. Eq. (15) was derived on the assumption that a positively and negatively charged particle combine only upon simultaneous encounter with a third body, as a neutral atom or molecule, which absorbs the energy of recombination. The formula does not include the possibility of recombination by "direct encounter" of the charged particles. Loeb[15] pointed out that this effect will add a term to (15) which may be important at low pressures; however, lack of potential barrier data precluded exact evaluation of the term. Since α of (15.1) varies with the molecular density it is greater than α of (14) for $n>10^{12}$ or $z<150$ km. Therefore the ionization equilibrium in F region is controlled by (14) and in E region by (15).

According to laboratory experiment free electrons become attached to oxygen molecules to form relatively stable negative ions; they do not become attached appreciably to the other particles of the high atmosphere. The rate of attachment is

$$by. \quad (16)$$

The attachment is usually stated in terms of h, the probability of electron capture at a collision. Then

$$b=uh/\gamma, \quad (16.1)$$

[15] Loeb, Phys. Rev. **51**, 1110 (1937); **52**, 40 and 136 (1937).

where u is the temperature velocity of the electron and γ the free path among the oxygen molecules. From Bradbury's[16] measurements h increased rapidly with the decrease of electron energy for energies below 1 electron volt. At 0.2 electron volt, the lowest energy at which observations were made, corresponding to a temperature of 770°K, h was 2.5×10^{-4}. This in (16.1) with $t=360$°K gives $b=2\times10^{-12}\ n'$, where n' is the density of oxygen molecules, which is nearly two orders of magnitude above the value of the former paper[2] based on earlier experimental data.

Now (16) with $b=2\times10^{-12}n'$ gives a loss of electrons much more rapid than that due to the recombination of (14) or (15) and therefore would be expected to control the ionization equilibrium. However for F_1 and F_2 regions (16) gives very low values of y, a very rapid decrease of y at night, and leads to $y=y_0\cos\zeta$ instead of to (1). These results conflict with observation and force the conclusion that (16) does not hold in the F regions, either because all the oxygen there is atomic, or because for some unknown reason the laboratory value is not applicable to the conditions at great heights. As discussed later similar difficulties with (16) in E region are not so acute.

The atmospheric ionization is now calculated by means of (6) with i_0, β and α given by (11), (12) and (14), respectively. Assume that for winter midday in temperate latitudes the temperature t of the high atmosphere is 360°K and ζ is 60°. Assume that oxygen and nitrogen are molecular and that the values of β and α derived from atomic constants are true for molecules. The y, z curve from (6) for N_2 is drawn in curve 1, Fig. 3. For O_2 the values of y given by (6) were reduced by $\frac{1}{8}$ because of the reduction of i_0 for O_2 due to the absorption by nitrogen of frequencies below the series limit 850A; the reduced y, z values for O_2 are plotted in curve 2, Fig. 3. Similar calculations for He, A and Kr yielded regions of ionization with maximum values of y of 0.06, 1.3 and 4.8×10^5 at heights of 55, 172 and 140 km, respectively. However, these regions probably do not exist in theory, for the light which causes them is totally extinguished by

[16] Bradbury, Phys. Rev. **44**, 883 (1933).

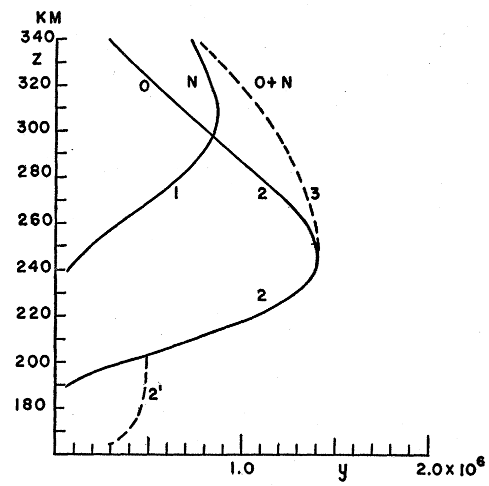

FIG. 5. Theoretical ionization curves for summer noon.

superincumbent oxygen and nitrogen, if the variation of β with ν indicated by (12) is anywhere near correct. Therefore, the total ionization is the summation of curves 1 and 2, Fig. 3, obtained approximately by taking the square root of the sum of the squares of the abscissas of curves 1 and 2. This gives curve 3, Fig. 3, with a maximum $y=1.55\times10^6$ in fair agreement with the Washington winter noon values for F_2 which have increased from about 0.5×10^6 in 1934 to 2×10^6 in 1937. The f, z' curve corresponding to curve 2 (or 3), Fig. 3, is drawn in Fig. 4 and indicates a virtual height of 205 km. This value is increased by effects of ionization below 180 km, and would appear to be in accord with the observed virtual heights 230 to 270 km. Calculation shows that diffusion[2] of the ionization in a vertical direction will not modify the y, z curves of Fig. 3 very much and therefore will not disturb the conclusion just stated.

For noon in the tropics and in summer temperate latitudes we give numerical expression to the expansion hypothesis[4] and assume that above 200 km oxygen and nitrogen are atomic and that the temperature is 500°K. The y, z curves, determined on these assumptions, from (6) for $\zeta=0°$, are shown in curves 1 and 2, Fig. 5, for O and N, and the curve of total ionization in curve 3. The maximum value 1.4×10^6 of curve 3 is somewhat above the summer noon values for F_2 at Washington, Watheroo (Australia) and Huancayo (Peru), which were about

0.5, 0.6 and 0.9×10^6 in 1934, 1935 and 1936, respectively. The f, z' curve, given in curve 2, Fig. 6, corresponding to curve 2, Fig. 5, indicates a virtual height of 220 km, which is below the observed values of 300 to 400 km for $\zeta < 25°$. Furthermore, the curves of Fig. 5 do not account for F_1 region. However, a relatively minor bulge in lower part of curve 2, Fig. 5, will yield F_1. In illustration, the bulge 2′ gives rise to an f, z' curve shown in curve 2′, Fig. 6, which is similar to the observed curves, the lower branch referring to F_1 and the upper to F_2. In the main, the several discrepancies between observation and theory would seem to be reasonably attributable to effects of diffusion and winds which have not been included in the theoretical calculations. Such effects follow necessarily from the expansion hypothesis, for expansion of the atmospheric reaches under the sun must give rise to winds blowing in all directions away from the subsolar regions. Spreading of the ionization in vertical and horizontal directions by winds and diffusion will reduce the calculated values of y, increase the virtual heights, and might produce the F_1 bulge in the y, z curves.

The foregoing calculations have been based on the assumption of upper atmospheric temperatures of 360° and 500°K for winter and summer days, respectively. The conclusions do not depend critically on the assumption but would hold equally well for a lower selection of temperatures, say, 260° and 400°K. Appleton's[17] extension of the expansion hypothesis[4] to indicate summer noon temperatures of at least 1200°K appears extreme and uncalled for by the experimental facts.

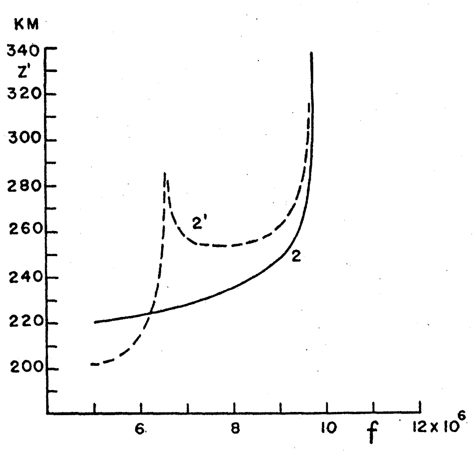

FIG. 6. Virtual height curves corresponding to curves 2 and 2′, Fig. 5.

[17] Appleton, Nature **136**, 52 (1935).

If the degradation of y in the night is assumed to be due to recombination unaffected by other factors, an assumption open to discussion, we may write

$$dy = -\alpha y^2 dt,$$

or

$$y = 1/(1/y_0 + \alpha t), \tag{17}$$

where y_0 is the value at sunset and y the value t seconds later. For F region at Washington in December, 1936, the average value of y_0 at sunset, or 5 P.M., was 1.25×10^6 and at 11 P.M. y was 0.25×10^6. With $\alpha = 3.4 \times 10^{-11}$, calculated from (14) for oxygen, and with $t = 6$ hours (17) gives $y = 0.59 \times 10^6$, which is larger than the observed value. Similar calculations with the data of other times and places gave similar results, namely, that the recombination coefficient α of (14) was of the correct order of magnitude but was too small by a factor of 2 to 4. Therefore (14) yields agreement with F region observation which, although not precise, is perhaps unexpectedly good.

The theory provides no explanation of the E region ionization since no light in the continuum above ν_0 can reach E levels in effective amount, if the absorption coefficients given by (12) are correct. For example, the total number of molecules in a vertical column of the atmosphere above 100 km is 1.8×10^{20}, which is equivalent to 6.4 cm of air at N.T.P. Accordingly, in order for the ionization to reach 100 km levels β cannot be much greater than 10^{-20}; this is several orders of magnitude below β of (12). The fact that y of E conforms closely with (1) indeed more closely than y of any other region of ionization, is strong evidence that E is caused by a moderately penetrating solar radiation which approximately travels in straight lines into the terrestrial atmosphere and is absorbed exponentially. The radiation might be ultraviolet light, x-rays or particles of zero average charge; the first seems the most probable, the light being of frequency less than ν_0, as the lines of the principal series.

The high value of the attachment of electrons to oxygen molecules gives support to the view[18] that in E region a twofold reaction occurs, namely, the ionizing radiation first produces positive ions and free electrons and the free electrons become rapidly attached to form negative oxygen ions. If the ratio of the rate of electron attachment to the rate of ionic recombination were sufficiently great the ionization of E region would be predominately ionic, rather than electronic as far as the refraction of radio waves is concerned, the disappearance of ions would be by the recombination formula (15.1), and y of E would agree with (1) and hence with observation. Numerically, however, the ratio of b/α should be about 3 times greater than the value given by (15.1) and (16.1). This would occur either if α of (15.1) were a little less, or if Bradbury's[16] curve of h against electron energy continued to increase with decreasing energy in the domain below 0.2 electron volts. Further experimental knowledge of attachment and recombination coefficients might contribute to the question in an important manner.

[18] Hulburt, Phys. Rev. **34**, 1167 (1929); **35**, 240 (1930).

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Emission of Neutrons from Argon, Chlorine, Aluminum and Some Heavier Elements Under Alpha-Particle Bombardment

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The emission of neutrons from chlorine, argon, scandium, titanium, manganese and iron under alpha-particle bombardment was established. The yield from argon is considerable and enabled a measurement of the energy of the neutrons to be made: the majority are associated with a group of energy change -5.6 ± 1.0 Mev, but two groups must be present. The excitation curve for these neutrons was plotted for alpha-particle energies between 3.5 and 9.0 Mev and varies smoothly in agreement with penetration through a barrier of radius 7.6×10^{-13} cm. This smooth variation means that the total neutron yield does not change rapidly as a new group is excited, from which it is deduced that observations on single groups would show apparent resonance effects. The excitation curve for chlorine fits a theoretically derived function for a nuclear radius of 6.0×10^{-13} cm and a similarly plotted curve for aluminum agrees with a radius of 5.8×10^{-13} cm. These last elements have radii approximately fitting the formula $R=R_0A^{\frac{1}{3}}$ with $R_0=1.94\times10^{-13}$, while argon has a radius which is definitely too large to fit the above relation. This abnormally large radius is linked with the large neutron content of the argon nucleus.

INTRODUCTION

THE use of a boron trifluoride filled ionization chamber surrounded by paraffin is so sensitive a neutron detector that neutron emission can be detected even with weak alpha-particle sources. Using an arrangement of this kind we have subjected a number of elements to bombardment by Th C′ alpha-particles and looked for the emission of neutrons. It was found that a slight yield could be detected from scandium, titanium, manganese and iron, indicating that the absorption of an alpha-particle with emission of a neutron is a general occurrence in this section of the periodic table. The yields from these elements were, however, roughly equal to the background of the detecting apparatus and therefore not suitable for detailed study. On the other hand argon and chlorine were found to give considerable yields of neutrons (in the case of argon the yield is second only to that from beryllium if Th C′ alpha-particles are used) and the nature of the neutron yield from these two elements was therefore further studied. An estimate of the energy of a neutron group was made for argon and excitation curves for both elements plotted. As a check an excitation curve for the neutrons from aluminum was also determined: from these three excitation curves values for the nuclear radii of the three elements can be found. A preliminary report of the experiments on argon and chlorine appeared early in 1937.[1]

[1] E. Pollard, H. L. Schultz and G. Brubaker, Phys. Rev. **51**, 140 (1937).