RECOMBINATION AND ELECTRON ATTACHMENT IN THE F LAYERS OF THE IONOSPHERE

By Fred L. Mohler

ABSTRACT

Observational data for the ionosphere at Washington have been used as a basis for computations. The rate of recombination at night is roughly proportional to the square of the electron concentration, but the apparent recombination coefficient, α', tends to increase with decreasing electron concentration over the half period of a sunspot cycle. This fact and the observed variation of α' with height indicate that electrons disappear both by recombination and by negative-ion formation. The daily variation of electron concentration indicates that the F_2 level is far above the level where the rate of production of electrons is a maximum in midsummer and that the F_1 layer is near the level where the rate is a maximum. It is assumed that both layers come from the ionization of atomic oxygen.

If α' is a function of the pressure, there will be a maximum electron concentration at a pressure, p, given by the relation

$$\frac{p}{p_0} = \frac{\alpha}{\alpha'} f(\lambda),$$

where p_0 is the pressure at the F_1 level, α is the electronic-recombination coefficient, and λ is the ratio of negative ions to electrons. $f(\lambda)$ is 1, if λ is small, or a linear function of p. In midsummer, p is 4×10^{-8} mm of mercury. $p/p_0 = 0.027$ and $\alpha = 2 \times 10^{-12}$, in good agreement with the theory of recombination. A seasonal variation of p/p_0 can be explained, if $f(\lambda)$ is not always unity, as λ is very sensitive to temperature. The seasonal variation in electron concentration can be accounted for by the change in pressure. The pressure variation also accounts for the fact that F_2 changes much more than F_1 over a sunspot cycle. The effective collision area for electron attachment to oxygen atoms is 6.5×10^{-21} cm².

CONTENTS

I. INTRODUCTION

Phenomena of the ionosphere have been the subject of many theoretical investigations. The conventional theory is that electrons are produced by photoionization by solar radiation and disappear by recombination at a rate proportional to the square of the electron concentration. The different layers of ionization are usually ascribed to different absorption processes. This theory gives a very satisfactory explanation of the daily and annual variations of the E and F_1

layers, [1,2] but the F_2 layer varies in an apparently erratic manner that has never been adequately explained. This layer is characterized by a very slow rate of recombination, and Bradbury [3] has suggested that the F_2 maximum in electron concentration may come from the same ionization process that gives F_1 purely as a consequence of the slow recombination. Recombination in the ionosphere probably involves both spontaneous recombination of electrons and positive ions and negative-ion formation followed by ionic recombination, and the relative importance of the latter process will increase with increasing pressure. This paper reports an attempt to deduce the nature of the recombination processes from observational data on the F region.

II. OBSERVATIONAL DATA

Ionosphere characteristics are commonly published as plots of the critical radio penetration frequency and minimum virtual height
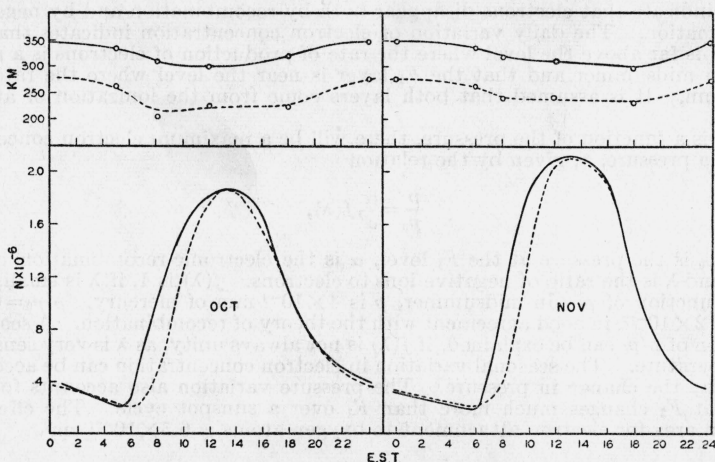

FIGURE 1.—*Mean values of electron concentration and true height of the F_2 layer for Washington, October and November 1938.*

Above, the full line is true height of the maximum, and the broken line is the height where N_e is half the maximum value. Below, the broken line is the theoretical curve for the conventional theory with $\alpha' = 0.8 \times 10^{-10}$ in October and 1.0×10^{-10} in November.

versus the time of day. Monthly mean values for several stations are published periodically. [4] The critical frequency depends on the number of free electrons per cubic centimeter, N_e, which is here computed by the equation

$$N_e = 0.0124 f^2, \qquad (1)$$

where f is the critical frequency in kilocycles for the ordinary wave. The question as to the proper coefficient in eq 1 is not important for this work.

The true height is not simply related to the virtual height, but methods [5] are now available for the computation of true height, and

[1] E. V. Appleton, Proc. Roy. Soc. (London) [A] 162, 451 (1937).
[2] E. O. Hulbert, Phys. Rev. 55, 639 (1939).
[3] Ter. Mag. and Atmos. Elec. 43, 55 (1938).
[4] National Bureau of Standards data for Washington, D. C., by Gilliland, Smith, and Kirby, appear monthly in the Proceedings of the Institute of Radio Engineers.
[5] F. H. Murray and J. B. Hoag, Phys. Rev. 51, 333 (1937).

N. Smith has made rather extensive computations of true heights as a function of frequency for the ionosphere at Washington during the past few years, and I am indebted to him for the opportunity to use some of this unpublished material.

A few months in 1938 have been selected as a basis for computations. Figures 1 and 2 give the number of electrons and true height as a function of the time of day for different months. This is for a period of maximum solar activity. In years of minimum solar activity the number of electrons in the F_2 layer was about one-fourth of the 1938 value, the daily curve broader and flatter.

Figure 3 is a plot of the vertical distribution of electrons above the E layer, as computed by Smith. The F_1 layer does not appear in October 1938 but is found in years of low solar activity.
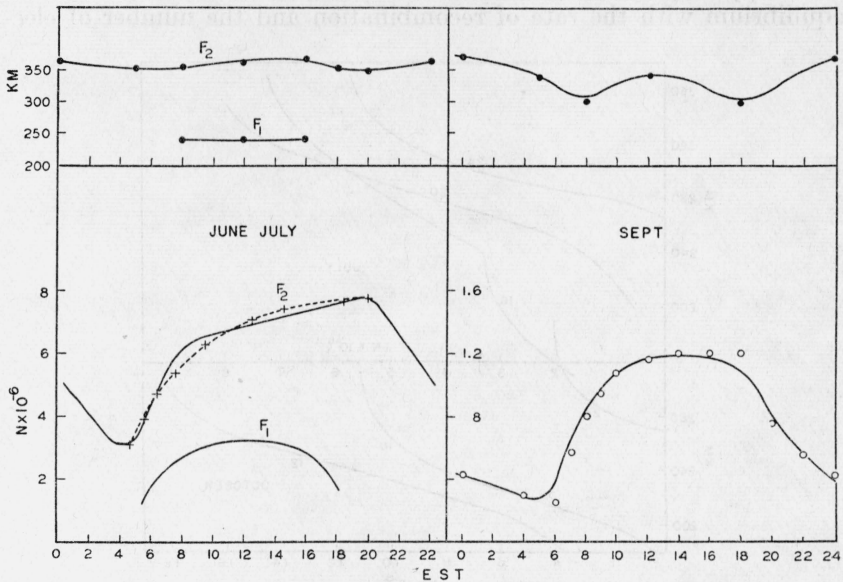

FIGURE 2.—*Mean values of electron concentration and true height for Washington, June, July, and September 1938.*

Above, true height of the maxima (F_1 is not well defined in September); below, full lines give observed values of N_e (two scales). The broken line and crosses are computed on the assumption that absorption is negligible and electrons disappear purely by electron attachment; circles, on the assumption of pure recombination with no absorption.

III. ELEMENTARY THEORY

If a is the atomic-absorption coefficient of the ionizing radiation, then the flux, J, of ionizing quanta per square centimeter per second is

$$J = J_0 e^{-Na},$$

where J_0 is the flux outside the atmosphere and N is the number of atoms in a square-centimeter column extending from the point where J is evaluated to the outside of the atmosphere.

The radiation is reduced to $1/e$ in a column of gas containing $1/a$ atoms per square centimeter and weighing M/a grams, where M is the weight of one atom. For vertical sunlight, M/a is the partial

pressure in grams per square centimeter, and $M/1.35a$ is the partial pressure in millimeters of mercury at the level where the radiation is reduced to $1/e$. The number of atoms per cubic centimeter at this pressure is $0.725 \times 10^{19} M/aT$, and the rate of production of electrons per cubic centimeter per second is

$$q = \frac{0.725 \times 10^{19} MJ_0}{T} e^{-1}, \tag{2}$$

and for any partial pressure, p,

$$q = \frac{0.725 \times 10^{19} MJ_0}{T} \frac{p}{p_1} e^{-\frac{p}{p_1}}, \tag{3}$$

where $p_1 = M/1.35a$. If the rate of production of electrons is in equilibrium with the rate of recombination and the number of elec-
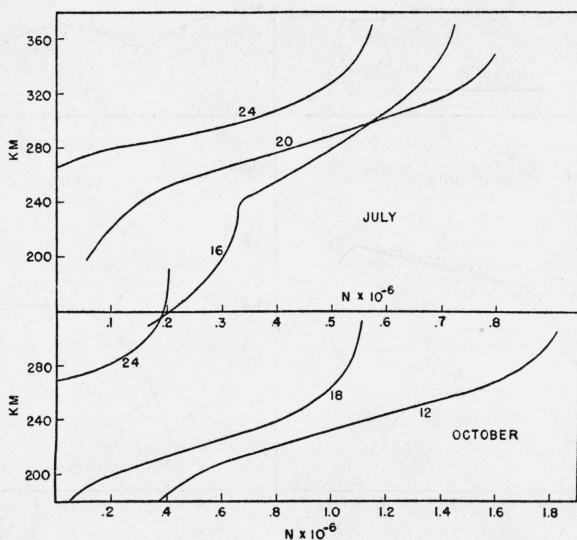

FIGURE 3.—*Electron concentration as a function of the height for Washington, July and October 1938 at the hours indicated on the curves.*

From calculations by N. Smith.

trons per cubic centimeter, N_e, is assumed equal to the number of positive ions,

$$q = \alpha N_e^2 \tag{4}$$

$$\left. \begin{array}{l} N_e = \frac{K^{1/2}}{\alpha^{1/2}} \frac{p^{1/2}}{p_1^{1/2}} e^{-\frac{p}{2p_1}} \\ K = 0.725 \times 10^{19} MJ_0/T \end{array} \right\} \tag{5}$$

For the case of oblique sunlight entering the atmosphere at a zenith angle, Z, the light is reduced to $1/e$ at a pressure $p_1 \cos Z$, and the maximum rate of production of ions is reduced by the factor $\cos Z$.

In an atmosphere of atoms of mass, M, the relation between pressure, p, and altitude, h, can be expressed

$$\left.\begin{array}{l} \dfrac{p_1}{p_2}=e^{(h_2-h_1)/H} \\ H=kT\times10^{-5}Mg \end{array}\right\}, \qquad (6)$$

where k is Boltzman's constant, g is the gravitational constant, and H is the height, in kilometers, in which the pressure is reduced to $1/e$ (commonly called the scale height).

It will be assumed in numerical computations that atomic oxygen gives rise to F-layer ionization. Wulf and Deming [6] have shown that the dissociation of oxygen must be nearly complete above 100 km and estimate the number of oxygen atoms per cubic centimeter at 100 km as 10^{12}. The dissociation of oxygen produces a sharply defined transition both in chemical composition and temperature near the 100-km level. If it is assumed that gases are in separate gravitational equilibrium above 100 km, then for atomic oxygen

$$H=T/18.8. \qquad (7)$$

The theoretical value of the atomic absorption coefficient of oxygen [7] at the photoelectric threshold, 910 A, is 1.25×10^{-17}, and p_1 for vertical sunlight is 1.56×10^{-6} mm.

It is generally considered that at the F_1 level there will be a large proportion of atomic oxygen negative ions, and ionic recombination may be important. The rate of absorption, q, gives the rate of production of positive ions, and if λ is the ratio of negative ions to electrons,

$$N_+=N_e+N_-=(1+\lambda)N_e, \qquad (8)$$

and for equilibrium between production of ions and recombination

$$q=\alpha N_e N_+ + \alpha_i N_- N_+$$
$$q=[(1+\lambda)\alpha+\lambda(1+\lambda)\alpha_i]N_e^2=\alpha'N_e^2, \qquad (9)$$

where α_i is the ionic recombination coefficient and α' the apparent coefficient for recombination. Appleton and Sayers [8] emphasize that since the daily and annual variation of the F_1 layer conforms to the simple recombination theory, α' must be a constant and λ must be independent of pressure at the F_1 level.

The rate of recombination in the F_2 layer is very much less than in the F_1 layer, so it is necessary to assume that λ decreases with the pressure above F_1. It commonly has been assumed that spontaneous recombination of electrons and positive ions will be predominant in the F_2 layer, because the pressure is very low. However, in contrast to the F_1 layer, the daily and annual variations of F_2 ionization give no evidence that α' is independent of pressure at this height.

[6] Ter. Mag. and Atmos. Elec. **43**, 283 (1938).
[7] D. R. Bates, R. A. Buckingham, H. S. W. Massey, and J. J. Unwin, Proc. Roy. Soc. (London) [A] **170**, 322 (1939).
[8] Union, Rad. Sci. Int. Proc., p. 272 (1938).

IV. RECOMBINATION AND ELECTRON ATTACHMENT

If electrons disappear by simple recombination during the night, then

$$\frac{dN_e}{dt} = -\alpha' N_e^2, \tag{10}$$

and the integral of this

$$\frac{1}{N_2} - \frac{1}{N_1} = \alpha'(t_2 - t_1), \tag{11}$$

where N_1 and N_2 are the number of electrons at times t_1 and t_2. Figure 4 gives plots of $1/N_e$ versus t for the data of figures 1 and 2. The
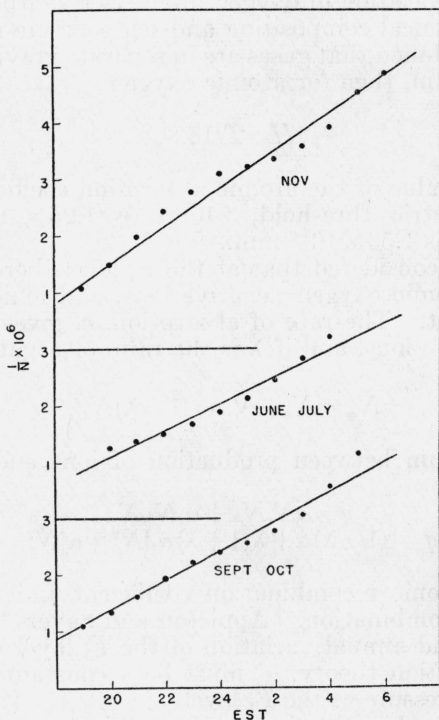

FIGURE 4.—*Plots of $1/N_e$ versus time from data of figures 1 and 2.*

Slopes of the lines give $\alpha' = 0.95 \times 10^{-10}$, 0.66×10^{-10}, and 0.72×10^{-10}, from top to bottom.

slopes of the straight lines give values of α', ranging from 0.66×10^{-10} to 0.95×10^{-10}.

Appleton [9] has pointed out that the rate of recombination during the daytime can be evaluated from pairs of values of N_e and of dN_e/dt at equal intervals before and after noon by the equation,

$$\left(\frac{dN_e}{dt}\right)_{a.m.} - \left(\frac{dN_e}{dt}\right)_{p.m.} = [(N_e^2)_{p.m.} - (N_e^2)_{a.m.}]\alpha', \tag{12}$$

[9] Proc. Roy. Soc. (London) [A] **162**, 451 (1937).

where subscripts a. m. and p. m. denote values at equal time intervals before and after noon. The October curve (fig. 1) gives a mean value of $\alpha' = 0.9 \times 10^{-10} \pm 0.2 \times 10^{-10}$, as compared with the nighttime value of 0.7×10^{-10}. Values based on sunrise and sunset values of the slopes and ordinates for 20 months in the period 1937–39 give $\alpha' = 0.9 \times 10^{-10} \pm 0.3 \times 10^{-10}$ and in the same period the mean nighttime value is about 0.7×10^{-10}. However, nighttime values for years of low solar activity (1934 and 1935) are very much larger than this, and the values of α' seem to be definitely correlated with the amount of ionization. Figure 5 is a plot of α' versus midnight values of $1/N_e$ for 30 months in the period 1934–39. Although the points are widely scattered, the plot indicates that α' is inversely proportional to N_e. This would suggest that electrons disappear by attachment rather
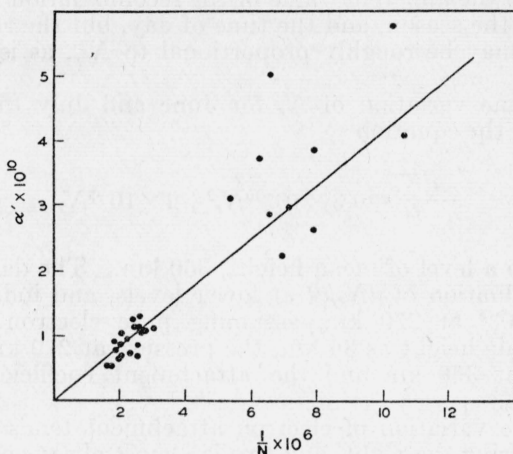

FIGURE 5.—*Values of the apparent recombination coefficient as a function of $1/N_e$ at midnight for years 1934 to 1939.*

than recombination. The time variation of electron concentration during the night would be

$$\frac{dN_e}{dt} = -\beta N_o N_e = -Bp N_e, \tag{13}$$

where N_o is the number of oxygen atoms per cubic centimeter; p, the partial pressure of oxygen atoms; β and B, constants. The integral of this is

$$\ln N_1 - \ln N_2 = Bp(t_2 - t_1). \tag{14}$$

Values for midnight and 4 a. m. for the 30 months considered above give values of Bp which are far from constant but show no systematic variation with N_e. The mean value is $Bp = 2.9 \pm 0.8 \times 10^{-5}$.

It seems impossible to admit, however, that electrons disappear purely by electron attachment, for this would not give a well-defined maximum in the vertical distribution of electrons, such as is observed, but rather a gradual exponential variation proportional to e^{-p}. It is of interest to investigate the possibility that electrons disappear

both by recombination and attachment. Then the nighttime variation would be

$$-\frac{dN_e}{dt} = \alpha N_e N_+ + Bp N_e,$$ (15)

and, by eq 8,

$$-\frac{dN_e}{dt} = \left[\alpha(1+\lambda) + \frac{Bp}{N_e}\right] N_e^2,$$ (16)

where λ is as before the ratio of negative ions to electrons.

The consequences of such a law are complicated, for the expression in brackets can be treated as a recombination coefficient which depends upon the electron concentration, the pressure, and possibly on the temperature, since λ may be very sensitive to temperature. This will make the apparent value of the recombination vary with the solar activity, the season, and the time of day, but the rate of change in ionization may be roughly proportional to N^2_e, as is found to be the case.

The nighttime variation of N_e for June and July (fig. 2) can be represented by the equation

$$-\frac{dN_e}{dt} = 0.3 \times 10^{-10} N_e^2 + 2 \times 10^{-5} N_e.$$ (17)

This applies to a level of mean height, 360 km. The data of figure 3 permit an evaluation of dN_e/dt at lower levels, and indicate a value of $Bp = 17 \times 10^{-5}$ at 270 km, assuming pure electron attachment. Taking the scale height as 36 km, the pressure at 270 km is 12 times the pressure at 360 km and the attachment coefficient 8.5 times as great.

The pressure variation of electron attachment tends to make the F layer rise during the night, and this is almost always observed from sunset to midnight. This pressure change complicates the problem of determining the rate of recombination and attachment. From midnight to dawn the height decreases slightly, and this is naturally ascribed to cooling of the air. However, the temperature changes introduce a further source of uncertainty in the computations. While curves of the type of figure 3 should give specific information as to the rate of recombination as a function of altitude, real or accidental variations make it impractical to evaluate the constants involved in eq 16.

V. DAYTIME VARIATION OF ELECTRON CONCENTRATION

The daily variation of N_e, on the basis of the simple recombination theory, has been evaluated by Millington [10] for conditions comparable to October and November 1938. The broken-line curves in figure 1 show these theoretical curves, and, except for a large discrepancy in the morning, the daily variation corresponds roughly to theory. The daily curves for September, June, and July rise more abruptly at sunrise, and the maximum is near sunset. The shape of the curves suggests that the ionizing radiation is not reduced appreciably by atmospheric absorption and that the F_2 level is far above the level

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[10] Proc. Phys. Soc. (London) 44, 580 (1932).

where the radiation is reduced to $1/e$. On the assumption that the F_2 level is at a constant pressure so low that absorption is negligible and that electrons disappear by attachment,

$$\frac{dN_e}{dt}=q-BpN_e=BpN_\infty-BpN_e, \tag{18}$$

where q is a constant from sunrise to sunset, and N_∞ is the equilibrium number of electrons reached after a sufficiently long time. The integral of this between times t_1 and t_2 is

$$Bp(t_2-t_1)=\ln\left(\frac{N_\infty-N_1}{N_\infty-N_2}\right). \tag{19}$$

Figure 2 includes a plot of this equation for June and July, taking N_1 as the observed value at dawn, $Bp=6\times10^{-3}$ and $N_\infty=0.8\times10^6$. The agreement is satisfactory, but it happens that the assumption of pure recombination gives a very similar curve. On the September curve of figure 2 the circles are computed on the assumption of pure recombination with no absorption, using the constants $\alpha'=0.7\times10^{-10}$ and $N_\infty=1.2\times10^6$. The curves clearly indicate that the atmospheric absorption is negligible, but they do not give conclusive evidence as to the law of recombination. The surprising conclusion is, that in the summer the F_2 layer is far above the level where radiation is reduced to $1/e$, while in the winter it is much closer to that level. From curves of Chapman [11] for ion production at different heights, it is estimated that if absorption is negligible within an hour of sunrise, then the F_2 level is more than 3 times the scale height, or over 100 km above the level where radiation is reduced to $1/e$. This rough estimate supports Bradbury's suggestion that F_1 and F_2 come from the same ionization process with the maximum rate of production of ions at the F_1 level.

VI. PRESSURE AT THE F_2 LEVEL

It is convenient to determine the pressure at which N_e is a maximum rather than the height. For midday conditions the number of electrons as a function of pressure can be expressed.

$$\alpha'N_e^2=\frac{Kp}{p_0}e^{-p/p_0} \tag{20}$$

$$\alpha'=\alpha(1+\lambda)+\frac{Bp}{N_e}, \tag{21}$$

where p_0 is the pressure at the level where radiation is reduced to $1/e$. As a simple working hypothesis, assume that λ is proportional to p ($\lambda=cp$). The condition that there be a maximum value of N_e at a pressure p is that $N_e^2 d\alpha'/dp$ is equal to the derivative of the right side of eq 20, N_e being taken as a constant.

$$\left(\alpha c+\frac{B}{N_e}\right)N_e^2=\frac{Ke^{-p/p_0}}{p_0}\left(1-\frac{p}{p_0}\right) \tag{22}$$

$$\alpha cp+\frac{Bp}{N_e}=\alpha'\left(1-\frac{p}{p_0}\right)$$

[11] Proc. Phys. Soc. (London) **43**, 26 (1931).

$$\frac{p}{p_o} = \frac{\alpha}{\alpha'},\tag{23}$$

where p is the pressure at the F_2 maximum, and p_0 is the pressure at the level where the radiation is reduced to $1/e$. This would indicate that if the F_2 level is far above p_0, then the effective recombination coefficient, α', is much greater than the electronic recombination coefficient. However, the large seasonal change of p/p_0 is not explained, for observed variations of α' are in the wrong direction. In general, if λ is not a linear function, p/p_0 will be a function of λ and, as λ is very sensitive to temperature, a seasonal variation can be understood. A physically simple assumption is that formation of negative ions by attachment and disappearance by recombination are in equilibrium.

$$\lambda(1+\lambda)\alpha_t N_e^2 = BpN_e\tag{24}$$

$$\frac{d\lambda}{dp} = \frac{B}{(1+2\lambda)\alpha_t Ne}\tag{25}$$

The substitution of this value of $d\lambda/dp$ in place of c in eq 22 gives, instead of eq 23, the relation

$$\frac{p}{p_0} = \frac{(1+\lambda)^2\alpha}{(1+2\lambda)\alpha'}\tag{26}$$

If λ is small (1 or less), eq 26 is nearly identical to eq 23, but, in contrast to eq 23, a seasonal variation in p/p_0 can here be ascribed to λ. There is no reason to believe that either equation is rigorous, but the derivations at least show, in a qualitative way, that there can be a maximum value of N_e far above p_0. It is not true, as has been suggested, [12] that electronic recombination is predominant at this maximum, but, on the contrary, it must be a small fraction of the apparent recombination coefficient, α', if p/p_0 is very small. It seems probable that the vertical variations of λ and $d\lambda/dp$ are subject to random variations and cannot be expressed as simple analytical functions. This would explain the large fluctuations in N_e and in the height of F_2, which are commonly but not always observed. However, Appleton's assumption that λ reaches a constant value at the F_1 level must be preserved for the reasons which he has given.

VII. NUMERICAL RESULTS

It will be assumed, following Bradbury's suggestion, that p_0 is at the F_1 level and that the ionization comes from atomic oxygen. Then the partial pressure for June and July noon is 1.48×10^{-6} mm at 240 km and (from section III) the effective temperature between 100 and 240 km is 680°K; the scale height, 36 km. This scale height will be used above 240 km for want of further data. In June and July the F_2 level is at 360 km, $p/p_0 = 0.027$, and $p = 4 \times 10^{-8}$ mm Hg. If it is assumed that λ is 1 or less, eq 23 is a good approximation, and on the basis $\alpha' = 0.8 \times 10^{-10}$, it follows that α, the coefficient of electronic recombination, is 2×10^{-12} (eq 26 indicates that α may be less).

[12] N. E. Bradbury, Ter. Mag. and Atmos. Elec. 43, 55 (1938).

A recent theoretical computation [13] of the recombination coefficient for atomic oxygen gives almost exactly this value; namely, 2.12×10^{-12} at 500°K. It would appear then that in this case λ must be small, and in the expression for α' electron attachment must be predominant. For October p/p_0 is larger and λ is evidently not negligible.

The measured rate of production of ions at the F_2 level for June and July is 47 per cubic centimeter per second. It follows from the above values of p and p_0 in eq 3 that the rate of production at $F_1(p=p_0)$ is 640 per cm³ per sec. This and the observed value of N_e give $\alpha'=5 \times 10^{-9}$ at F_1. An independent estimate of α' at F_1 can be made with the approximation that electron attachment is predominant. The value $Bp=6 \times 10^{-5}$ at $F_2(p=4 \times 10^{-8} \text{mm})$ gives $\alpha'=Bp/N_e=6.2 \times 10^{-9}$ at $p=1.48 \times 10^{-6}$ mm, in good agreement with the first value.

The outstanding anomaly of the F_2 layer has been the seasonal variation of N_e, but this can be entirely accounted for by the seasonal variation in pressure. The maximum rate of production of ions, $\alpha' N^2_e$, for October is 5.8 times the rate for July instead of 0.7 times the July value, as predicted by conventional theory. Since this rate is proportional to p exp. $(-p/p_0)$, then the pressure at F_2 is 7.3 times the July value. The observed difference in height is 70 km, and if the scale height is 36 km, this would correspond to a pressure ratio of 7.0.

While this pressure variation has been ascribed to a seasonal variation in λ, there is no basis for quantitative predictions. For temperature equilibrium between oxygen atoms, electrons, and ions, the ratio of ions to electrons would be given by Saha's equation with the electron affinity, 2.2 volts, in place of the ionization potential.

$$\frac{N_e N_o}{N_-}=\frac{N_o}{\lambda}=6.05 \times 10^{15} T^{3/2} e^{-2.2 \times 11600/T}, \tag{27}$$

where N_o is the number of oxygen atoms per cubic centimeter. At a partial pressure of 4×10^{-8} mm, λ would become unity at 960° K, and at this temperature a 10-percent change in T would give a tenfold change in λ. Oxygen ions exposed to sunlight cannot be considered to be in temperature equilibrium, and λ is probably much less than the value given by eq 27. The assumptions that λ is 1 or less at a pressure of 4×10^{-8} mm, and larger but variable at 7 times this pressure, are not incompatible with eq 27 though there is no good basis for numerical computations.

VIII. CONCLUSION

To summarize the results there is little doubt that the rate of recombination decreases rapidly with decreasing pressure above F_1 and a necessary consequence of this is that the maximum number of electrons is far above the level where the rate of production is a maximum. The analysis given here involves simplifying assumptions that may well be open to question, but several independent lines of evidence indicate that the maximum rate of production must be near the F_1 level so that one absorption process can account for both

[13] D. R. Bates, R. A. Buckingham, H. S. W. Massey, and J. J. Unwin, Proc. Roy. Soc. (London) [A] **170**, 322 (1939).

F layers. This avoids the assumption that the temperature above F_1 is extremely high and subject to enormous seasonal variations. A complication in the theory is that the height of F_2 and the electron concentration depend on the ratio of electrons to negative ions, which is extremely sensitive to temperature. Small changes in the vertical temperature gradient could produce large fluctuations in the F_2 layer, and it is possible that this can explain the apparently erratic variations in ionization that are characteristic of the F_2 layer.

One consequence of the theory is, that the variation of ionization with time and height will depend on the absolute intensity of the ionizing radiation, which varies over a wide range during a sunspot cycle. In periods of low solar activity, with low values of N_e, the electron attachment becomes relatively more important, the maximum rises to a lower pressure, and even in winter the F_1 layer appears as a separate maximum. N_e for the F_1 layer should vary as the square root of the intensity of the ionizing radiation. In the F_2 layer the relation between N_e and intensity is more complicated, but for summer conditions (electron attachment predominant) it will vary nearly as the first power of the intensity.[14] From July 1934 to July 1938 the F_1 ionizatoin increased by the factor 1.54, the F_2 ionization by the factor 2.34, which is almost exactly the square of 1.54.

The values of $Bp = 6 \times 10^{-5}$ at $p = 4 \times 10^{-8}$ mm and $T = 680°$ K lead to a value of the effective collision area, σ, for electron attachment to atomic oxygen of 6.5×10^{-21} cm^2. Massey[15] has published a rough theoretical estimate for this constant of 2.5×10^{-22} cm^2 at $680°$ K. This agreement is poor, but both values are subject to considerable uncertainty. As noted above, the computed value of the electronic recombination coefficient, 2×10^{-12}, is in accurate agreement with theory, though the uncertainty in this case also is large. The effective collision area for recombination at $680°$ K is 1.2×10^{-19} cm^2.

The author[16] measured the rate of recombination in low-pressure cesium and mercury discharges and obtained values of $\alpha = 2$ or 3×10^{-10}. Doubt was expressed as to whether this was the coefficient for spontaneous recombination, but the fact that α' for the F_2 layer is of the same magnitude has been quoted as evidence that α' was the electronic recombination coefficient. This is evidently not the case, and the ionosphere results seem to be consistent with the recombination theory.

WASHINGTON, June 8, 1940.

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[14] In a previous publication the author has considered that N^2_e was a measure of the ionizing intensity both for F_1 and F_2, but this is inconsistent with the present theory. See Science **90**, 137 (1939).

[15] Proc. Roy. Soc. (London) [A] **163**, 542 (1937).

[16] J. Research NBS **19**, 447 (1937) RP1037; **19**, 559 (1937), RP1045. There is a numerical error in the theoretical value of α used in the second paper.