The collision frequency of electrons in the ionosphere

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ABSTRACT

Theoretical analysis shows that the electron collision frequency in the ionosphere depends on the neutral particle concentration in Regions D and E and on the electron concentration in Region F. Any atmospheric model above the E layer cannot, therefore, be based on the electron collision frequency with neutral particles.

1. INTRODUCTION

Several methods have been used for measuring the collision frequency of electrons in ionospheric regions. The observational determination of collision frequency is possible because the theory of the phenomenon of wave interaction in the lower ionospheric regions necessarily involves consideration of electron collisions with atmospheric molecules, and because the values of the reflection coefficient obtained for waves reflected from the upper ionospheric regions can be explained on the assumption that absorption occurs in the lower layers, or near the critical frequency.

The published observational values vary widely (GERSON, 1951). The discrepancies cannot be attributed entirely to some naturally occurring variations. The degree of dispersion in the collision frequency measurements depends on the difficulties of the measurements. Furthermore, the data representing mean values are very often considered at various levels. For example, values of the electron collision frequency varying from $\nu_e = 10^5 \sec^{-1}$ to $\nu_e = 10^4 \sec^{-1}$ have been quoted for the E layer.

BEST and RATCLIFFE (1938), considering an E layer with a constant scale height, have obtained from absorption measurements a value of $H\nu_m$ (H = constant scale height, ν_m = collision frequency at the maximum of electron density) = $3 \cdot 5 \times 10^{10}$ cm-sec^{-1}. This result approximately corresponds to an *equivalent* height of 130 km. Using $H = 9$ km, they find $\nu_m = 3 \cdot 9 \times 10^4 \sec^{-1}$. Comparing their result with the value (BEST and RATCLIFFE, 1938) given by FARMER, who used the group retardation method and obtained a mean value of $10^4 \sec^{-1}$ at a height of 130 km, they conclude that a value of about $2 \times 10^4 \sec^{-1}$ cannot be far wrong at 130 km. MARTYN and PULLEY (1936) adopted a scale height of 9 km and used a mean value of $\nu = 3 \times 10^5 \sec^{-1}$ for Region E. This value of the collision frequency, which was deduced by MARTYN (1935) and BAILEY and MARTYN (1935), corresponds to a pressure of 10^{-3} mm of mercury and must be applied at a height below 100 km. It does not correspond to the maximum of the E layer, but represents datum for the lower portion of this layer.

A general study of the absorption measurements on different frequencies made at Slough and Freiburg, by RAWER, BIBL and ARGENCE (RAWER, 1951; BIBL and RAWER, 1951; RAWER, BIBL and ARGENCE, 1952) leads to the separation of the contributions due to Regions E and D. Assuming a parabolic E layer and

an exponential variation of the collision frequency, these authors found a median value of 7×10^3 sec^{-1} at a level of about 125 km. Thus, this value is lower than the other determinations. It may be noted that, assuming round figures, APPLETON (1939) has quoted 10^4 sec^{-1} at a height of 120 km.

The results obtained from investigations of ionospheric cross modulation lead to values of the collision frequency which are of interest in connection with the study of Region D. For instance, SHAW (1951) gives a value of $1 \cdot 4 \times 10^6$ sec^{-1} for the collision frequency at a height of 92 km. This figure is obtained from the product νG where G is the energy loss factor and is found from laboratory measurements (HUXLEY and ZAAZOU, 1949) to be equal to $1 \cdot 3 \times 10^3$. The deduced height utilized is of the region of cross modulation and represents an equivalent height. An estimated height correction, by SHAW (1951), would be of the order of $-2 \cdot 5$ km. In particular, three of his results are considered:

28th April 1949	$G\nu/2\pi = 307,$	$\nu = 1 \cdot 48 \times 10^6$ sec$^{-1},$	$z = 91 \cdot 7$ km
5th June 1949	552	$2 \cdot 66 \times 10^6$	$86 \cdot 1$
21st June 1949	612	$2 \cdot 96 \times 10^6$	$86 \cdot 5$

HUXLEY, in different publications [1950a, b] has discussed the electron collision frequencies obtained by ionospheric cross modulation and especially the value of the parameter G. Three values have been generally used: $G = 2 \cdot 6 \times 10^{-3}$ (BAILEY and MARTYN, 1935; BAILEY, 1937; RATCLIFFE and SHAW, 1948), $G = 1 \cdot 3 \times 10^{-3}$ (HUXLEY and ZAAZOU, 1949) and $G = 2 \cdot 2 \times 10^{-3}$ (CROMPTON and SUTTON)*. A round figure should be 2×10^{-3}. Adopting $G = 1 \cdot 3 \times 10^{-3}$, HUXLEY (1950) has found $\nu = 1 \cdot 2 \times 10^6$ sec^{-1} at 85 km. The height is determined from the collision cross-section of molecules, $5 \cdot 8 \times 10^{-16}$ cm^2, a 210°K temperature and the pressure given by rocket soundings (BEST, HAVENS and LAGOW, 1947). More recently HUXLEY (1950a), taking a mean value of $G\nu = 1 \cdot 7 \times 10^3$ and assuming a rounded value of $G = 2 \times 10^{-3}$, obtained $\nu = 8 \cdot 5 \times 10^5$ sec^{-1} at a height of 86 km. These results yield lower values than those obtained by SHAW (1951). For example, at 86 km the ratio is 1/3.

BRIGGS (1951) has used a method based on observations of the reflection coefficient of the abnormal E layer. The collision frequency of electrons is calculated assuming that the abnormal E layer consists of a thin horizontally stratified layer with some exponential density-height variation. Values between $3 \cdot 9 \times 10^4$ sec^{-1} at 111 km (one value) and 2×10^4 sec^{-1} at 135 km (one value), passing through values of about $1 \cdot 7 \times 10^4$ sec^{-1} at $117 \cdot 5$ km (two values) are given by this method.

Another result has been deduced by FINDLAY (1951) who has observed the change of phase path of radio waves returned from the E layer during radio fadeouts on frequencies near 2 Mc/s. He has obtained values of ν between 2×10^5 and 6×10^5 sec^{-1} with a mean value of $\bar{\nu} = (4 \cdot 43 \pm 0 \cdot 20) \times 10^5$ sec^{-1}. Using an empirical formula due to BRIGGS, he obtained the associated height value of 101 ± 2 km which seems too high for the radio fade-out phenomenon involved. In fact, BRIGGS' formula, which seems to be based on SHAW's and BEST's and RATCLIFFE's data, would give the following values of ν: at 90 km, $\nu = 1 \cdot 8 \times 10^6$

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* cf. HUXLEY (1950b)

$\sec^{-1}$; at 100 km, $\nu = 5\cdot1 \times 10^5 \sec^{-1}$; and at 120 km, $\nu = 4\cdot2 \times 10^4 \sec^{-1}$, which are larger than the values found by RAWER and computed by HUXLEY.

Considerable uncertainty is introduced in the discussion of the collision frequencies in the F region if we try to use some quoted experimental value for the F_1 daytime layer. Thus, we shall neglect the values of electron collision frequency for this layer, and consider only the data for Region F_2; and particularly the nighttime data. The maximum value which may be considered (GERSON, 1951) is $\nu = 3 \times 10^3 \sec^{-1}$, and a mean value for the F_2 daytime layer may be not more than $10^3 \sec^{-1}$. This corresponds to the round figure given by APPLETON (1939) for Region F; approximately between 250 km and 300 km.

After the observations made by FARMER and RATCLIFFE (1935) and the other results (GERSON, 1951), it is important to consider a recent publication by RAWER, BIBL and ARGENCE (1952) in which the nighttime observations of the F_2 layer during November, 1949–April, 1950 and February, 1951 lead to a very low value, $\nu = 2 \times 10^2 \sec^{-1}$, for the collision frequency of electrons. If all the observational results are considered as correct, they indicate that a variation of the collision frequency occurs between day and night not only due to a variation of height, but also in the collision processes.

Thus, as we study the electron collision frequency distribution in the high atmosphere, we must keep the observational data in mind, considering that the highest values mentioned above are probably incorrect and that $\nu = 10^4 \sec^{-1}$ must be considered as an acceptable (upper) value for the maximum of the E layer and $\nu = 10^3 \sec^{-1}$ is a high acceptable value for Region F.

2. COLLISION BETWEEN A NEUTRAL MOLECULE AND AN ELECTRON

1. CHAPMAN and COWLING (1939) and COWLING (1945) have given formulas to determine collision frequencies. In the velocity distribution method, the effective collision interval τ_{12} for molecules of mass m_1 and mass m_2 is

$$\tau_{12} = \frac{m_1 m_2 (n_1 + n_2)}{(n_1 m_1 + n_2 m_2) kT} D \tag{1}$$

where D is the ordinary coefficient of mutual diffusion of the two kinds of molecules in the absence of other gases, n_1 and n_2 are the particle number densities (numbers of molecules present per cm^3), k is BOLTZMANN's constant, and T is the absolute temperature. To a certain degree of approximation, D is, for rigid elastic spheres,

$$D = \frac{3}{16(n_1 + n_2)\sigma_{12}^2} \left[\frac{2kT(m_1 + m_2)}{\pi m_1 m_2} \right]^{1/2} \tag{2}$$

where σ is the so-called collision distance.

From (1) and (2), the collision frequency ν_{12} for a molecule of type 1 with molecules of type 2 is

$$\nu_{12} = \frac{16}{3} \frac{n_1 m_1 + n_2 m_2}{m_1 + m_2} \pi \sigma_{12}^2 \left[\frac{(m_1 + m_2)kT}{2\pi m_1 m_2} \right]^{1/2} \tag{3}$$

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For collisions between an electron of mass m_e and neutral particles of mass m with number density n, (3) becomes

$$\nu_{e,\,n} = \frac{4}{3}\, n\pi\sigma^2 \left(\frac{8kT}{\pi m_e}\right)^{1/2} \tag{4}$$

because $m_1 \rightleftharpoons m \gg m_2 \equiv m_e$.

Thus, the collision frequency of an electron with neutral particles is determined if we can find the effective collision distance.

2. It is not easy to obtain an exact value for the collision distance of low velocity electrons in the ionosphere. The constant kinetic cross-section ($Q = \pi\sigma^2$) does not represent the effective cross-section and the quantal cross-section may also yield some uncertainty according to the approximations involved. From the experimental point of view, results are not given at low electron speeds and the data can only be obtained by extrapolation.

Fisk (1936) has compared the theoretical results for O_2 and N_2 that he has obtained using a quantal method with experimental cross-section curves. At electron velocities greater than 1 eV, his values can agree with the experimental data; but for electron velocities approximating those of the ionosphere, the experimentally observed values are somewhat larger. In fact, no exact comparison is possible because the experimental study becomes less precise at low electron speeds.

Fisk's results expressed in atomic units are (Q in atomic units; 1 atomic unit $= 2\cdot8 \times 10^{-17}$ cm^2)

Electron energy	Theory		Experimental results	
in eV	N_2	O_2	N_2	O_2
0	25	15	—	—
0·7	17*	12*	30	19
1	30	13	35	22

These data indicate that the effective collision cross-sections for very slow electrons are generally of the order of 20 atomic units, but values between 25 and 15 atomic units are not excluded. In fact, a cross-section of 45 atomic units for molecular nitrogen, corresponding to an effective collision distance of 2×10^{-8} cm, refers to electrons with velocities not less than 1 eV. Cowling (1945) has used a value of 2×10^{-8} cm for the collision distance, but he notes that it depends on an extrapolation from experimental velocities much greater than those in the thermal range.

If we consider an effective cross-section of 25 atomic units or $7\cdot0 \times 10^{-16}$ cm^2, we adopt an effective collision distance of $1\cdot5 \times 10^{-8}$ cm. By choosing this value as the collision distance for an N_2 molecule with respect to a very slow electron, we use a value less than the collision radius obtained by viscosity or diffusion measurements. A corresponding value for O_2 with 16 atomic units or $4\cdot5 \times 10^{-16}$ cm^2 would be $1\cdot2 \times 10^{-8}$ cm. In air, with an approximate ratio of number densities of N_2 and O_2 equal to 4/1, the effective cross-section becomes $6\cdot5 \times 10^{-16}$ cm^2.

* Approximate minima.

It appears that the problem of the collision cross-section of atomic oxygen with respect to an electron is different, according to the critical survey made by GERSON (1951). Using the predicted value, and not the resonance value which is certainly too great, BATES and MASSEY (1947) have found at 250°K a round value of 4×10^{-10} sec^{-1} as the collision frequency per oxygen atom. Such a value is 23 times less than the collision frequency per nitrogen molecule and thus is negligible*.

With the numerical values adopted for the collision cross-section, the equation (4) becomes for air ($N_2 + O_2$)

$$\nu_{e,\,m} = 5{\cdot}4 \times 10^{-10} n(M) T^{1/2} \qquad (5)$$

where $n(M)$ is the total number of molecules per cc.

If P is the total pressure in mm of mercury, (5) may be written

$$\nu_{e,\,m} = 5{\cdot}22 \times 10^{9} P T^{-1/2} \qquad (6)$$

When oxygen is dissociated, $n(N_2) = \dfrac{2}{3} n(M)$, and instead of (5) and (6), we obtain

$$\nu_{e,\,m} = 3{\cdot}87 \times 10^{-10} n(M) T^{1/2} \qquad (7)$$

and

$$\nu_{e,\,m} = 3{\cdot}74 \times 10^{9} P T^{-1/2} \qquad (8)$$

3. In order to determine the numerical values of the electron collision frequencies in the lower ionosphere, we may use the rocket data (HAVENS et al., 1952) giving the pressures, in mm of Hg, at ten kilometer increments and round figures for the temperatures at the same levels. The computed pressures, temperatures and collision frequencies are given in Table 1.

Table 1. Electron collision frequencies

Height (km)	Pressure (mm of Hg)	Temperature ($O_2 + N_2$)	Temperature ($O + N_2$)	Collision frequency sec^{-1} ($O_2 + N_2$)	Collision frequency sec^{-1} ($O + N_2$)
60	$2{\cdot}23 \times 10^{-1}$	268		$7{\cdot}1 \times 10^{7}$	
70	$5{\cdot}77 \times 10^{-2}$	220		$2{\cdot}0 \times 10^{7}$	
80	$1{\cdot}08 \times 10^{-2}$	181	151	$4{\cdot}2 \times 10^{6}$	$3{\cdot}3 \times 10^{6}$
90	$1{\cdot}90 \times 10^{-3}$	197	164	$7{\cdot}0 \times 10^{5}$	$5{\cdot}5 \times 10^{5}$
100	$4{\cdot}06 \times 10^{-4}$		191		$1{\cdot}1 \times 10^{5}$
110	$1{\cdot}05 \times 10^{-4}$		218		$2{\cdot}7 \times 10^{4}$
120	$3{\cdot}50 \times 10^{-5}$		271		$8{\cdot}0 \times 10^{3}$
130	$1{\cdot}41 \times 10^{-5}$		324		$2{\cdot}9 \times 10^{3}$
140	$6{\cdot}51 \times 10^{-6}$		377		$1{\cdot}3 \times 10^{3}$
150	$3{\cdot}34 \times 10^{-6}$		430		$6{\cdot}0 \times 10^{2}$
160	$1{\cdot}85 \times 10^{-6}$		482		$3{\cdot}2 \times 10^{2}$
170	$1{\cdot}09 \times 10^{-6}$		534		$1{\cdot}8 \times 10^{2}$
180	$6{\cdot}79 \times 10^{-7}$		586		$1{\cdot}0 \times 10^{2}$

* Another determination of the elastic cross-section of oxygen atoms for slow electrons has been carried out by YAMANOUCHI [24]. The cross-section obtained is $24{\cdot}1 \times 10^{-16}$ cm^2. With such a value, the atmospheric ($N_2 + O$) collision frequency with respect to an electron should be increased by a factor of $2{\cdot}7$.

The collision frequencies at heights lower than 90 km have been computed with the help of equation (6), and above 80 km with the help of (8). If, at 90 km, the dissociation of O_2 is not complete, an intermediate value between 6 and $7 \times 10^5 \sec^{-1}$ may be used. A plot of these results appears as the solid lines in Figs. 1 and 2. As may be seen by referring to these Figures, the net result of these computations is that many observational values are too high.
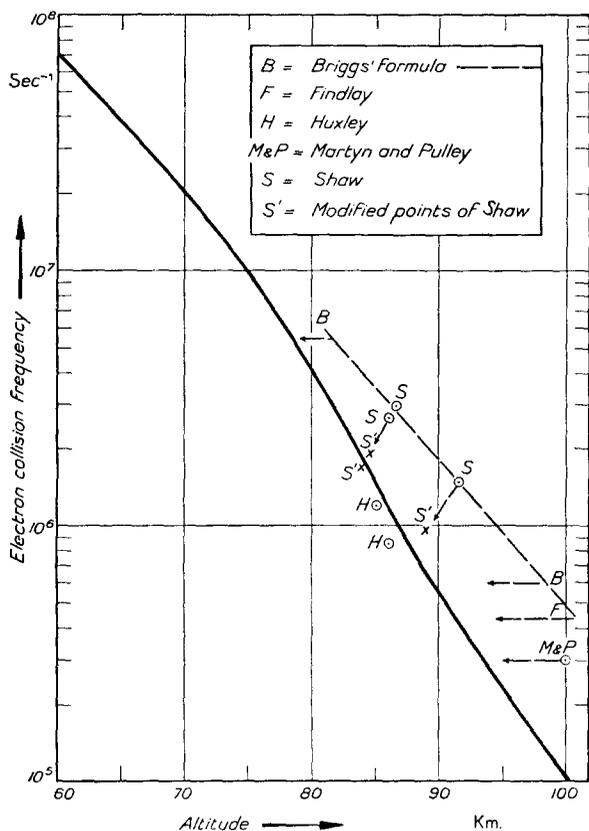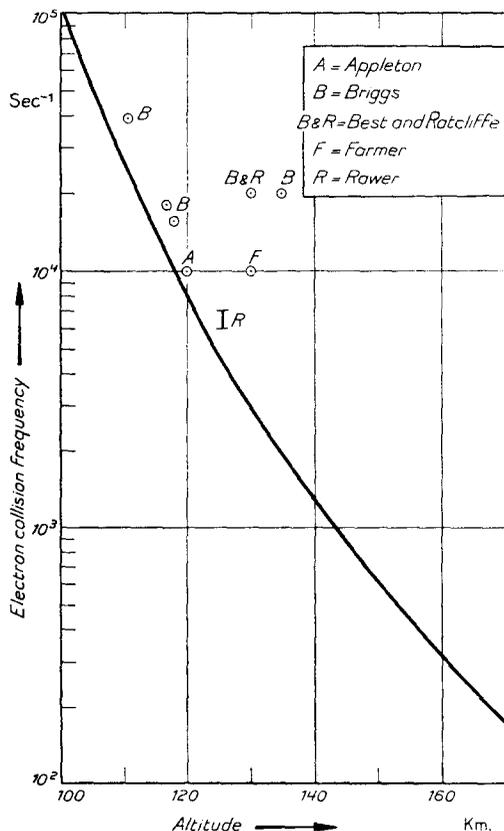

Fig. 1

Fig. 2

FINDLAY's investigations (1951) on fade-outs at a frequency near 2 Mc/s, which resulted in a mean value of $\nu = 4 \times 10^5 \sec^{-1}$, correspond to a maximum height of $90 - 91$ km. With the extreme values of $\nu = 6 \times 10^{-5} \sec^{-1}$ and $2 \times 10^5 \sec^{-1}$ obtained by FINDLAY we may say that the maximum of fade-out producing ionization occurs at heights lower than 95 km.

Considering that the levels given by SHAW (1951) correspond to equivalent heights which may be transformed into actual heights (SHAW, 1951) by subtracting not less than 2 or 2·5 km and also that G, the energy loss factor, is, in round figures, 2×10^{-3}, SHAW's data adequately describes the variation of ν with height obtained by our theoretical determination.

If we consider BRIGGS' observational data (1951), the collision frequencies at 111, 117, and 118 km follow the theoretical curve approximately, but a value of

2×10^4 sec^{-1} at 135 km is certainly too high. BRIGGS' formula (1951) appears to be based on SHAW's data ($1 \cdot 6 \times 10^6$ sec^{-1} at 90 km) and on high values at 130 km. It must be changed in order to follow the more recent investigations.

Finally, having transformed some observational data by the means indicated, it is possible to obtain a consistent set of values which follow the computed curve between 80 and 130 km as indicated in Figs. 1 and 2.

4. If the collision frequency depends only on the number density of the neutral particles, we must assume that, at the level of Region F, the pressure and the temperature are very high. But this hypothesis, which has been generally considered, cannot be applied, for at 180 km the collision frequency is only 10^2 sec^{-1}. Thus, the immediate conclusion cannot be avoided that the electron collision frequency in Region F does not result from the collision with neutral particles* and must be due to another type of collision.

This conclusion is important because the former deductions about the structure of the higher ionosphere (formation of layers) are based on a number density of neutral particles connected with a collision frequency due to neutral particles. In fact, it is not correct to use the collision frequency in order to obtain information regarding the pressure or the particle concentration above the E layer. Furthermore, the origin of Region F cannot be explained as occurring at the level of the maximum of photo-ionization if the absorption coefficients of atomic oxygen which are used are correct, and the problem of the formation of the upper ionospheric regions (F_1 and F_2) cannot be considered in an ionization equilibrium with a constant recombination coefficient.

3. COLLISION BETWEEN CHARGED PARTICLES

1. We follow CHAPMAN and COWLING (1939) again in order to determine the collision frequency between charged particles. The effective collision interval for charged molecules of mass m_1 and m_2 is still found by (1); but now the diffusion coefficient D for charged particles is (to the first approximation)

$$D = \frac{3}{16} \frac{1}{n_1 + n_2} \left[\frac{2kT(m_1 + m_2)}{\pi m_1 m_2} \right]^{1/2} \left(\frac{2kT}{e^2} \right)^2 \frac{1}{A_1(2)} \tag{9}$$

where e denotes the electric charge as used in the following equation for the force P between pairs of particles having charge e_1 and e_2,

$$P = \frac{e_1 e_2}{r^2},$$

and $A_1(2)$ denotes a slowly varying function of T and n_e which will be given later.

In terms of (1) and (9), the collision frequency between positive and negative particles of charge e is

$$\nu_{+-} = \frac{4}{3} \frac{\pi e^4}{(2\pi k^3 T^3)^{1/2}} \frac{n_1 m_1 + n_2 m_2}{(m_1 m_2)^{1/2} (m_1 + m_2)^{1/2}} A_1(2) \tag{10}$$

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* MITRA (1948) found excellent agreement between his theoretical determination and an adopted value of $\nu = 2 \times 10^3$ sec^{-1} at 250 km. He uses a value of 1060 atomic units for the cross-section of atomic oxygen at 1000°K. If the E layer is considered, atomic oxygen would be more effective and the collision frequency deduced would be too high.

If we consider the collision frequency of positive ions with respect to an electron, we may use the following conditions:

$$m_1 \equiv m_+ \gg m_e \equiv m_2$$

and

$$n_+ = n_- + n_e \equiv (1 + u)n_e$$

where $n_-/n_e = u$ is the ratio of negative ion (n_-) and electron concentrations if the gas as a whole is assumed to be electrically neutral. Then, the general expression (10) can be written

$$\nu_{e,\,+} = \frac{4}{3} \frac{\pi e^4}{(2\pi m_e k^3 T^3)^{1/2}} A_1(2)\,(1 + u)n_e \tag{11}$$

which is the collision frequency of an electron with positive ions which all have the same mass m_+. Note that the value of u, the ratio of the negative ions to electrons, determines the importance of the attachment process. If the number of negative ions is negligible $u \ll 1$, $n_+ = n_e$, and the electron collision frequency is proportional to the electron concentration.

2. The nature of $A_1(2)$ must be known in order to perform an actual calculation of the collision frequency. This slowly varying function of temperature and density may take different forms depending upon the assumed mean collision distance.

The expression given by CHAPMAN and COWLING (1939) is, to the first approximation,

$$A_1(2) = \log_e(1 + v^2{}_{01}) \tag{12}$$

where

$$v_{01} = \frac{4dkT}{e^2} \tag{13}$$

with d = mean distance between "pairs of neighbouring molecules."

If we define d as being equal to $(2n_e)^{-1/3}$,

$$A_1(2) = \log_e\left[1 + \left(\frac{4kT}{e^2(2n_e)^{1/3}}\right)^2\right] \tag{14}$$

and if

$$1 \ll \frac{4kT}{e^2(2n_e)^{1/3}} \tag{15}$$

the correction term $A_1(2)$ is

$$A_1(2) = 2 \log_e \frac{4kT}{e^2(2n_e)^{1/3}} \tag{16}$$

If we define d as being equal to DEBYE's distance

$$d = \left(\frac{kT}{8\pi e^2 n_e}\right)^{1/2}$$

the correction term must be written

$$A_1(2) = \log_e\left[1 + \left\{\frac{4}{\pi^{1/2}e^3 n_e^{1/2}}\left(\frac{kT}{2}\right)^{3/2}\right\}^2\right] \tag{17}$$

and with the condition (15)

$$A_1(2) = 2 \log_e \frac{4}{\pi^{1/2} e^3 n_e^{1/2}} \left(\frac{kT}{2} \right)^{3/2} \tag{18}$$

If we define d as being equal to $e^2/h\nu$, where ν is the radiation frequency and h is PLANCK's constant, (13) becomes

$$\nu_{01} = \frac{4kT}{h\nu} \tag{19}$$

and the correction term is

$$A_1(2) = \log_e \left[1 + \left(\frac{4kT'}{h\nu} \right)^2 \right] \tag{20}$$

When the wave length of the radiation emitted in a free-free transition (positive ion and electron collision) is very short, $A_1(2)$ represents GAUNT's factor.

3. For the calculation of free-free emissions in interstellar space and in the sun, various authors have used formulas such as (16), but it should be noted that the difference between numerical results depends on the correction terms used (DENISSE, 1950). For example, at $T = 10^6$°K and $n_e = 10^9$ cm^{-3}, we obtain, respectively, by (16) and (18) $A_1(2) = 28\cdot9$ and $39\cdot4$; at 1000°K and $n_e = 10^6$, $A_1(2) = 19\cdot7$ and $25\cdot6$. Thus, their ratio equals about $\frac{3}{4}$.

Considering that, under certain conditions, the cut-off distance d equals the DEBYE distance (COHEN et al., 1950), we adopt the formula (18) which gives the greatest numerical value. Nevertheless, we must keep in mind that the results given by the two formulas (16) and (18) are approximately of the same order.

Other expressions (GERSON, 1951) have also been introduced for ion-electron collisions. MAJUMDAR (1937) and GINSBURG (1944) have derived collision frequency expressions which are identical with the (11) relationship provided their correction terms are so adopted that they give agreement with the preceding values. RAY (1938) and PANDE (1947) have claimed that the ratio between collision probabilities of neutral particles and ions with electrons cannot be as high as the value obtained by MAJUMDAR. This criticism is not justified.

4. In order to determine the numerical values of the electron collision frequencies in the upper ionosphere, we use the formulas (11) and (18). We obtain a collision frequency

$$\nu_{e,\,+} = \left[34 + 8\cdot36 \log_{10} \frac{T^{3/2}}{n_e^{1/2}} \right] n_e T^{-3/2} \tag{21}$$

which depends on the temperature and electron concentration. Results of a computation with this last formula, which are given in Table 2, indicate a strong, very sensitive dependence on the temperature.

It is, of course, to be expected that the electron collision frequency will be variable (for the same electron concentration) according to the actual height obtained from observational data. Fig. 3 shows the electron collision frequency as a function of the temperature for various electron concentrations between

Table 2. *Electron collision frequencies (with positive ions)*

T \ n_e	5×10^4	10^5	5×10^5	10^6	2×10^6
200°K	$7 \cdot 7 \times 10^2$	$1 \cdot 5 \times 10^3$	$6 \cdot 9 \times 10^3$	$1 \cdot 3 \times 10^4$	$2 \cdot 6 \times 10^4$
500	$2 \cdot 2 \times 10^2$	$4 \cdot 2 \times 10^2$	$2 \cdot 0 \times 10^3$	$3 \cdot 8 \times 10^3$	$7 \cdot 4 \times 10^3$
750	$1 \cdot 2 \times 10^2$	$2 \cdot 4 \times 10^2$	$1 \cdot 1 \times 10^3$	$2 \cdot 2 \times 10^3$	$4 \cdot 3 \times 10^3$
1000	$8 \cdot 2 \times 10^1$	$1 \cdot 6 \times 10^2$	$7 \cdot 7 \times 10^2$	$1 \cdot 5 \times 10^3$	$2 \cdot 9 \times 10^3$
1500	$4 \cdot 7 \times 10^1$	$9 \cdot 1 \times 10^1$	$4 \cdot 3 \times 10^2$	$8 \cdot 4 \times 10^2$	$1 \cdot 6 \times 10^3$

5×10^4 and 2×10^6 cm^{-3}. The temperature effect is so very important that it is perhaps possible to determine limits for the temperature in the ionosphere if the actual height is known. From another point of view, considering a constant
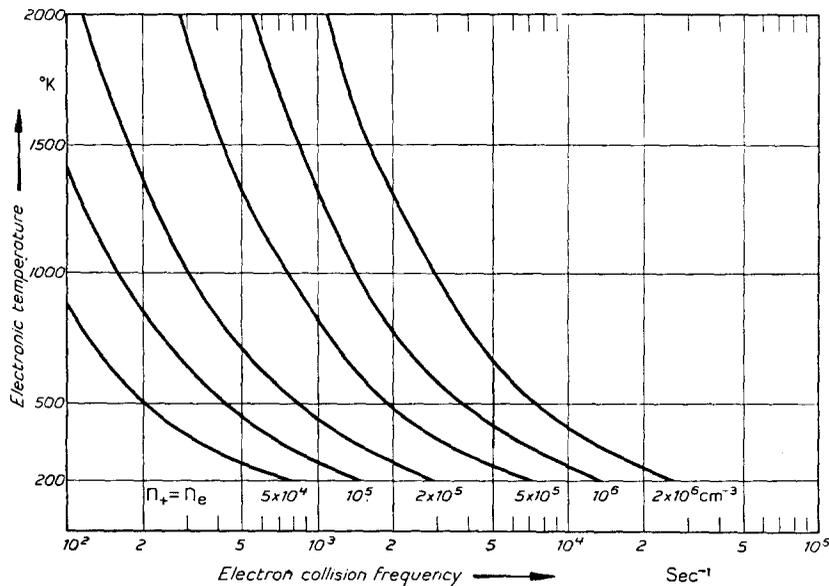

Fig. 3

temperature (Fig. 4), we can see the variation of the electron collision frequency with the electron concentration. It is evident that the diurnal variation of the electron collision frequency must be very important.

It is, therefore, reasonable to conclude that the absorption of radio waves in the F layers is due to collisions between electrons and positive ions since the collision frequency between positive ions and electrons, as calculated here, gives various values which can agree with the observed values (GERSON, 1951; RAWER et al., 1952; APPLETON, 1939; FARMER and RATCLIFFE, 1935) in Region F. Furthermore, any conclusion about the concentration of neutral particles cannot be obtained from an electron collision frequency above the E layer, because the electron collision frequency with neutral particles is negligible compared with this collision frequency with positive ions.

It should be noted that the electron collision frequency with positive ions would be effective at lower heights than the E layer if the positive ion concentrations were very great. For example, positive ion concentrations from 10^6 cm^{-3} to 2×10^8 cm^{-3} (at 2000°K) give electron collision frequencies of about one hundredth of these figures. If we adopt 2×10^8 positive ions per cm^3 at about 90 km (SEDDON, 1952), the electron collision frequency with positive ions is 2×10^6 sec^{-1}, which is, therefore, four times greater than the collision frequency with neutral particles. Furthermore, with such a preponderance of heavy ions, the phenomena of wave
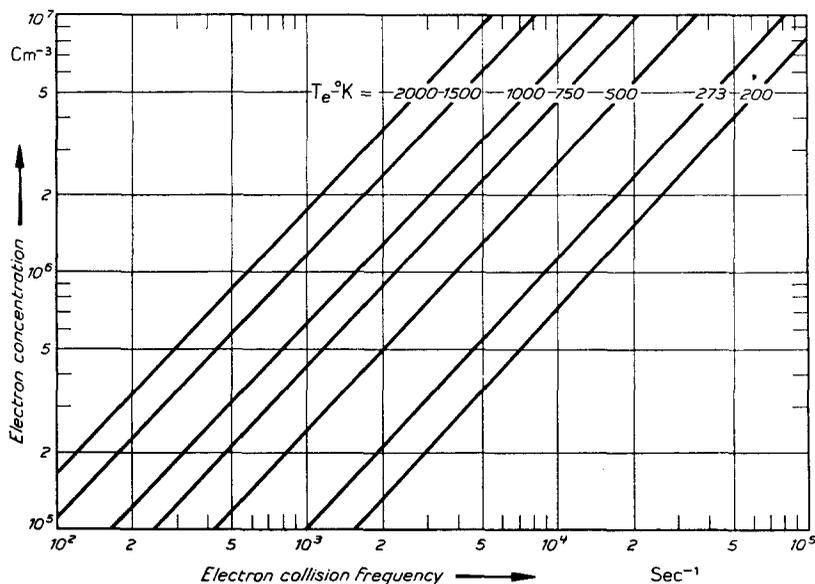

Fig. 4

propagation should be affected. Nevertheless, the last theoretical investigation of BATES and MASSEY (1952) failed to reveal any mechanism which could give a contribution of positive ions in Region D.

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