MEMOIRS

OF THE

Commonwealth Solar Observatory

MOUNT STROMLO, CANBERRA, AUSTRALIA.

MEMOIR No. 7.

(Second Number of Volume II.)

THE CONDUCTION OF ELECTRICITY IN THE LOWEST LEVELS OF THE ATMOSPHERE

BY

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March, 1939.

By Authority:
L. F. JOHNSTON, Commonwealth Government Printer, Canberra.
(Printed in Australia.)

1334.

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ABSTRACT.

A series of experiments has been carried out to measure the relations between certain atmospheric electric elements in the lowest 100 cm. of the atmosphere. The experiments were performed in an underground laboratory so as to obtain a good approximation to infinite plane conditions.

The measurements showed that—

(1) The Wilson air-earth current apparatus, when exposed at ground level to the normal fine weather field, gives a value for the conductivity which, on the average, equals, to within a few per cent., the positive conductivity measured by an aspiration type of apparatus drawing air from ground level.

(2) When the Wilson apparatus is exposed to natural reversed fields its indications are, to within a few per cent., equal to the negative conductivity measured by the aspiration apparatus.

(3) The positive conductivity, mainly due to small ions, decreases with increase of height, the decrease being relatively rapid in the lowest 25 cm.

(4) The negative conductivity, above 12.5 cm., shows a slight increase with increase of height.

(5) The total conductivity measured by the aspiration apparatus between 12.5 cm. and 100 cm. is approximately equal to that measured by the Wilson apparatus at ground level.

(6) The potential gradient does not undergo any large variation with height.

(7) There is present close to the ground a small positive space charge, amounting in these observations, to about 1000 e/cm^3.

(8) The rate of ionisation, measured in a vessel provided with a cellophane window, is appreciably less at 100 cm. than at ground level.

From the foregoing results it would appear that—

(1) The Wilson apparatus (when properly exposed) measures the total air-earth current irrespective of the sign of the potential gradient.

(2) The air-earth current is mainly a conduction current. Diffusion currents, if present at all, are not relatively great.

(3) The space charge carried by the small ions is very small and is quite insufficient to account for any significant variation of the potential gradient between the surface and 100 cm.

(4) The space charge carried by the large ions, whilst greater than that carried by the small ions, is still not sufficiently big to account for variations of more than a few per cent. between the gradient at the surface and at 1 metre.

(5) The space charge observations may be taken as supporting, within the limits of experimental error, the result obtained by direct measurement, viz., that the gradient at the surface is essentially the same as that measured at 100 cm.

THE CONDUCTION OF ELECTRICITY IN THE LOWEST LEVELS OF THE ATMOSPHERE.

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1. INTRODUCTION.

The estimation of the fine weather air-earth current is effected either directly, using apparatus of the Wilson plate type, or indirectly, as a product of the potential gradient by the sum of the unipolar conductivities. Measurements of the former type give directly a current i_w and a field strength F_w from which may be calculated a conductivity λ_w such that

$$i_w = F_w \lambda_w$$

With estimations of the indirect type, a measurement of field strength, F_m is combined with measurements by aspiration apparatus of positive and negative conductivity, $\lambda_{1(a)}$ and $\lambda_{2(a)}$. For these measurements the air is usually drawn from a point shielded from the earth's field and 1–2 metres above the surface. The current i_c is then calculated on the assumption that

$$i_c = F_m \left(\lambda_{1(a)} + \lambda_{2(a)}\right)$$

Comparison of the values of i_w at Kew with the values of i_c obtained at various other places indicates the possibility that i_c is about twice as great as i_w. No measurements of i_c were hitherto available for Kew.

The work of Watson (1929) and later of Scrase (1934) demonstrated that with suitable precautions as to the exposure of apparatus the Wilson readings of field strength are essentially the same as the readings obtained by a stretched wire apparatus over the range 0–1 metre, i.e., that within the limits of observational error $F_w = F_m$.

Further, these results gave an indication that λ_w did not vary largely with the height in the range 0–1½ metre. This latter result was not so clear cut as the former, for the observed effect of test plate level on conductivity could not be disentangled completely from the distortion of the field due to the introduction of the apparatus. Also Lautner (1928) showed that on the Zugspitze the conductivity measured by a Wilson apparatus with a vertical plate let into a first floor window agreed with measurements of positive conductivity made two years previously at the same site using a Gerdien apparatus, the intake of which projected about a metre from the wall of the building.

The combination of these results led to a suggestion by Dr. F. J. W. Whipple (1930) that the effective conductivity of the air, which really determined the true air-earth current i, was equal to $\lambda_{1(a)}$ the contribution due to $\lambda_{2(a)}$ being nullified by the transport of electricity due to eddy motion in the atmosphere and thus $i = F\lambda_{1(a)}$. In this specification F = field strength, the distinction between F_w and F_m being abandoned.

J. J. Nolan and P. J. Nolan (1937) have recently attacked this problem. Working at Glencree they confirmed that $F_w = F_m$ (F_m being measured by a water dropper with a jet 24 cm. from the ground) and further showed that, as an average state of affairs, to within about 10 per cent.

$$\lambda_w = \lambda_{1(a)} + \lambda_{2(a)}$$

Thus they conclude it would be unsafe to accept the suggestion that $i = F\lambda_{1(a)}$.

Now if it be assumed that $\lambda_w = \lambda_{1(0)}$ (the true positive conductivity of the air at ground level) and that $\lambda_{1(a)}$ and $\lambda_{2(a)}$ represent the conductivities in the open at the height of the mouth of the aspirator, then the Glencree observations indicate a change of conductivity with height. As the Glencree observations, quite properly for their purpose, were made in accordance with the current practice of drawing the air for the aspiration apparatus through a wall of a building, without making any correction to the infinite plane conditions, the above deduction as to the variation of conductivity with height may not be correct when transferred to such conditions. Accordingly it appeared desirable to determine the relation between conductivity and height over an infinite plane; making use of the exposure facilities provided by the underground laboratory at Kew Observatory.

The original programme of the work resolved itself into two main portions, viz.—

(1) The comparison of λ_w with $\lambda_{1(a)}$, both conductivities being measured under the same conditions of exposure at ground level.

(2) The comparison of λ_w measured at ground level with $\lambda_{1(a)}$ and $\lambda_{2(a)}$ measured at different levels in the range 0 to 1 m.

Later it became desirable to investigate—

(3) The variation of potential with height (three stretched wires being used simultaneously).

(4) The concentration of positive and negative large ions at the ground.

(5) The variation of the rate of production of ions with height.

2. CONDUCTIVITY AT GROUND LEVEL.

The conductivity at ground level was measured simultaneously by a Wilson apparatus and by an aspiration apparatus. As it was desired to expose the two instruments under as far as possible identical conditions, use was made of the underground laboratory at Kew Observatory (Scrase (1934)). The Wilson apparatus was that employed for the routine daily measurements at Kew Observatory, the test plate being mounted flush with the roof of the underground laboratory (see Fig. 1). Two aspiration instruments were also placed underground adjoining the Wilson apparatus and arranged at such a level that their intakes were flush with the roof. In Fig. 1 the positions of the intakes are indicated by projecting cardboard tubes used in a later stage of the investigation. The two aspiration instruments were originally Ebert ion counters by Gunther and Tegetmeyer. One had been modified by P. A. Sheppard, (1932) in such a fashion as to employ the advantages of the sensitivity of the charging method of measurement without the usual attendant errors due to the turning back of ions by the collecting field. In place of the Swann method which was used by Sheppard and which requires additional insulators, a scheme devised by J. J. Nolan and P. J. Nolan (1935) was adopted for the present investigation. In this latter method the outer electrode of the ion collecting condenser is earthed, and the inner electrode, together with the electrometer case, is initially brought to a potential of sign opposite to that of the conductivity being measured. For measuring the current a Lindemann electrometer was employed, usually at a sensitivity of about 100 divisions per volt. The electrometer plate potentials were applied from a potentiometer system (Fig. 2) which rendered it possible to bring into coincidence the mechanical and electrostatic null points of the electrometer. The dimensions of the apparatus, with a collecting potential of 4.5 volts and an air flow of 1,000 cm^3. per second, gave for the fastest ion completely caught, a limiting mobility of 2.8 cm./sec./volt/cm. The results were reduced by a method previously described (Hogg (1936)) which is independent of the electrometer capacity thus enabling small alterations of the electrometer sensitivity to be made without the necessity of employing a new reduction factor.

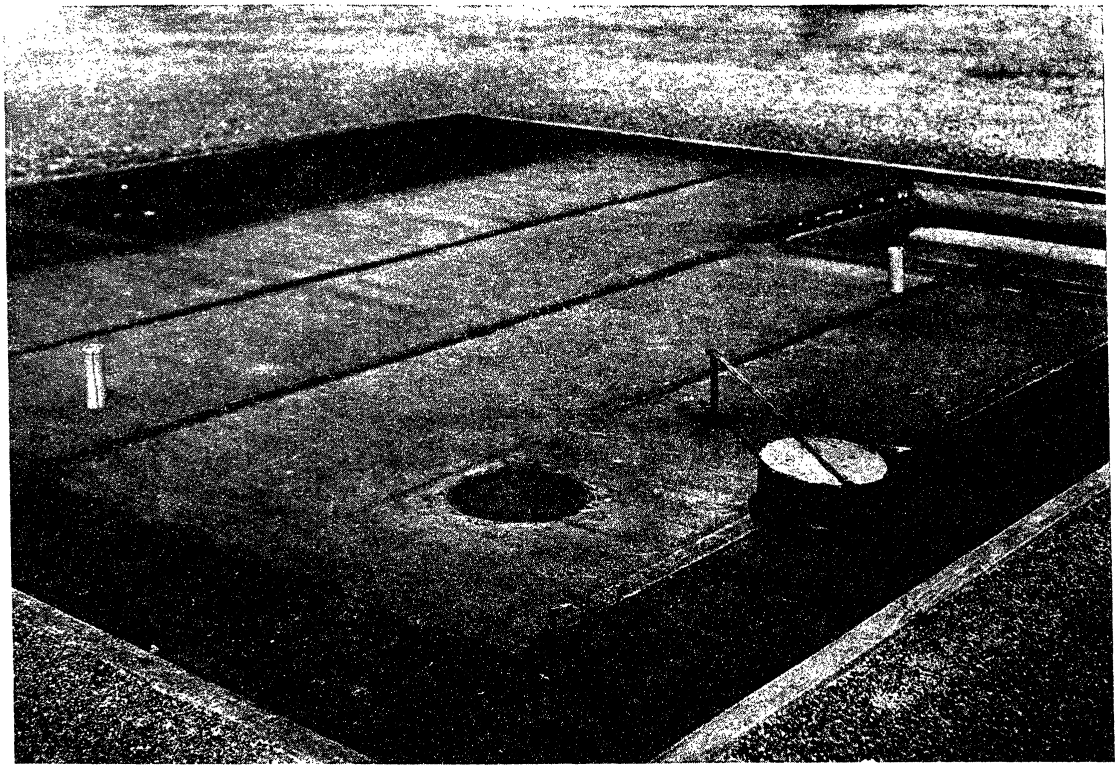

Fig. 1.—The underground laboratory at Kew Observatory. The photograph shows the apparatus set up for Series II. of the space charge measurements. The two larger tubes were connected to the aspiration conductivity instruments whilst the glass tube, visible with difficulty on the right, was attached to the large ion apparatus. The test plate of the Wilson apparatus is seen uncovered in the lower centre.

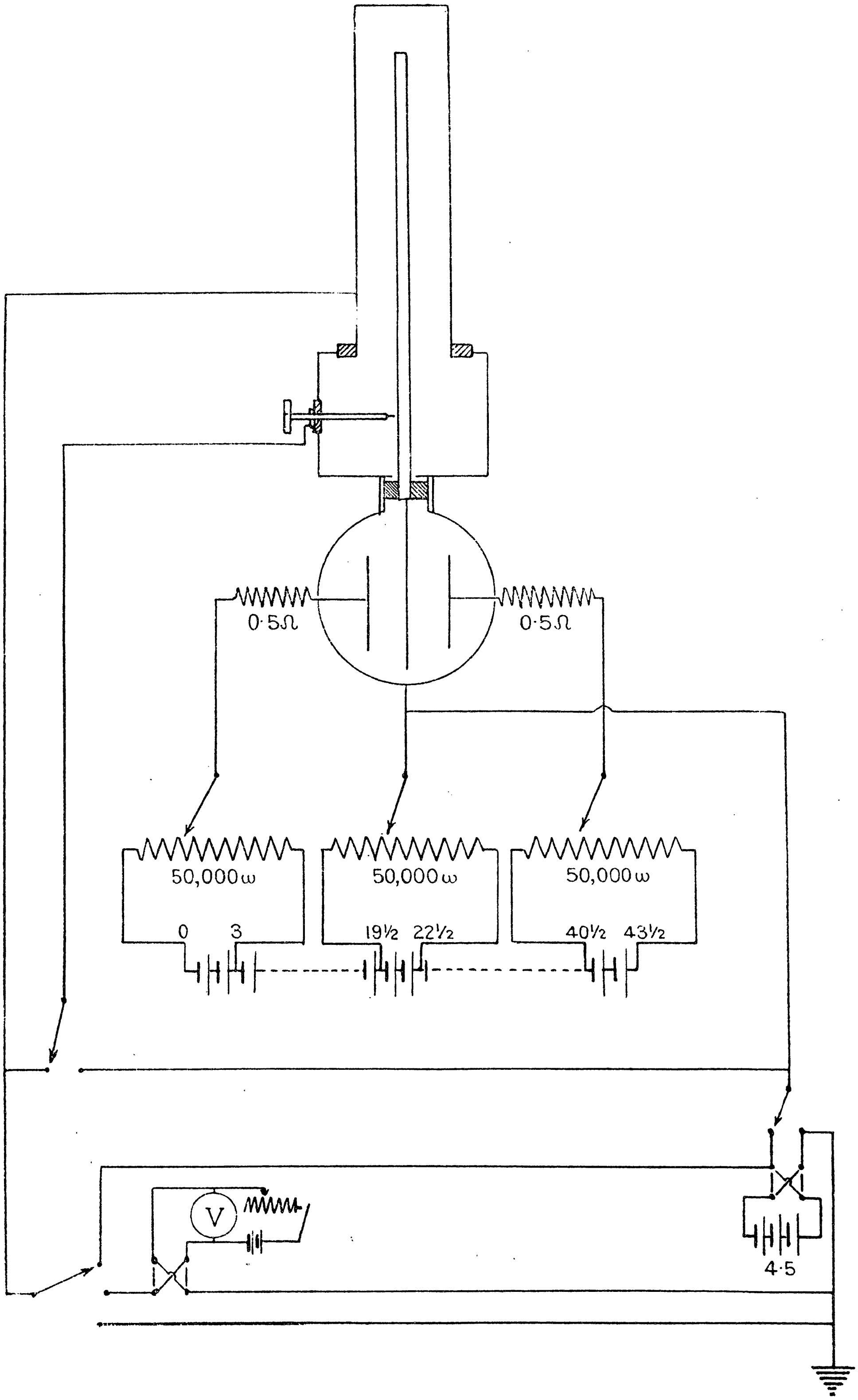

Fig. 2.—Circuit diagram of the aspiration apparatus for the measurement of conductivity.

A portion of the conductivity measured by the Wilson apparatus is due to charged nuclei. With town air this portion may be relatively large. It is not practicable to eliminate the effect of these nuclei in the Wilson apparatus, and in any case for the purpose of obtaining the air-earth current it is this effective conductivity, rather than the small ion conductivity, which must be taken into account. For the range of field strengths employed the current voltage characteristics for both the Wilson and the aspiration instruments may be regarded as linear. Thus each of the instruments will be affected to the same extent by the precipitation of charged nuclei. Accordingly no corrections are necessary on this account.

Two aspiration instruments, denoted I and II, were employed and the positive conductivities measured by these were compared separately with the results of simultaneous measurements by the Wilson apparatus. The results are shown in the dot diagrams (Fig. 3) each dot representing an individual comparison. The straight lines in the diagrams represent the ideal graphs which would have been obtained if the pairs of apparatus being investigated gave identical results. The ratio Wilson/Aspiration I amounted to 1.04 as a mean of 50 observations on twelve days (Fig. 3*a*), whilst the ratio Wilson/Aspiration II was 1.02 for 50 observations spread over seven days (Fig. 3*b*). Most of the comparisons with Aspiration I were made by two observers, one using the aspiration apparatus, the other the Wilson, whilst with Aspiration II both instruments were operated by the same observer. Comparisons were also made when the test plate of the Wilson apparatus was covered by an aluminium sheet 90 cm. square, supported on insulating blocks at a distance of 10 cm. above the test plate and charged to such a potential as to give a field approximating to that of the earth. A series of preliminary experiments with different voltages on this aluminium plate was carried out using a second Wilson apparatus as a control. It was found that the measured conductivity was independent of the field strength over a moderate range. The comparison under these conditions gave a ratio Wilson/Aspiration I of 1.01 (80 observations on three days), (Fig. 3*c*). This method of using the Wilson apparatus for a conductivity measurement is in one way preferable to that using the natural field for, in the latter case, the field strength generally fluctuates during an observation, and thus there is some uncertainty as to the exact average strength of the field which has been used for collecting the ions. On the other hand, the presence of the covering plate may tend to impede the air motion over the Wilson plate proper and this effect may be responsible for the relatively great scatter of some of the points in Fig. 3*c*.

Thus, in the three series of experiments, the Wilson apparatus mounted at ground level gave readings of conductivity some two or three per cent. greater than the unipolar positive conductivity measured by the aspiration apparatus with its intake at ground level. It should be borne in mind that, whilst the Wilson apparatus measures the conductivity essentially at ground level, the aspiration apparatus draws its air from points a little above the ground, where, as is later shown, the positive conductivity is less. With these considerations in mind it is convenient to denote the positive conductivity measured with the aspiration apparatus "at ground level" by λ_{+0}, and the negative by

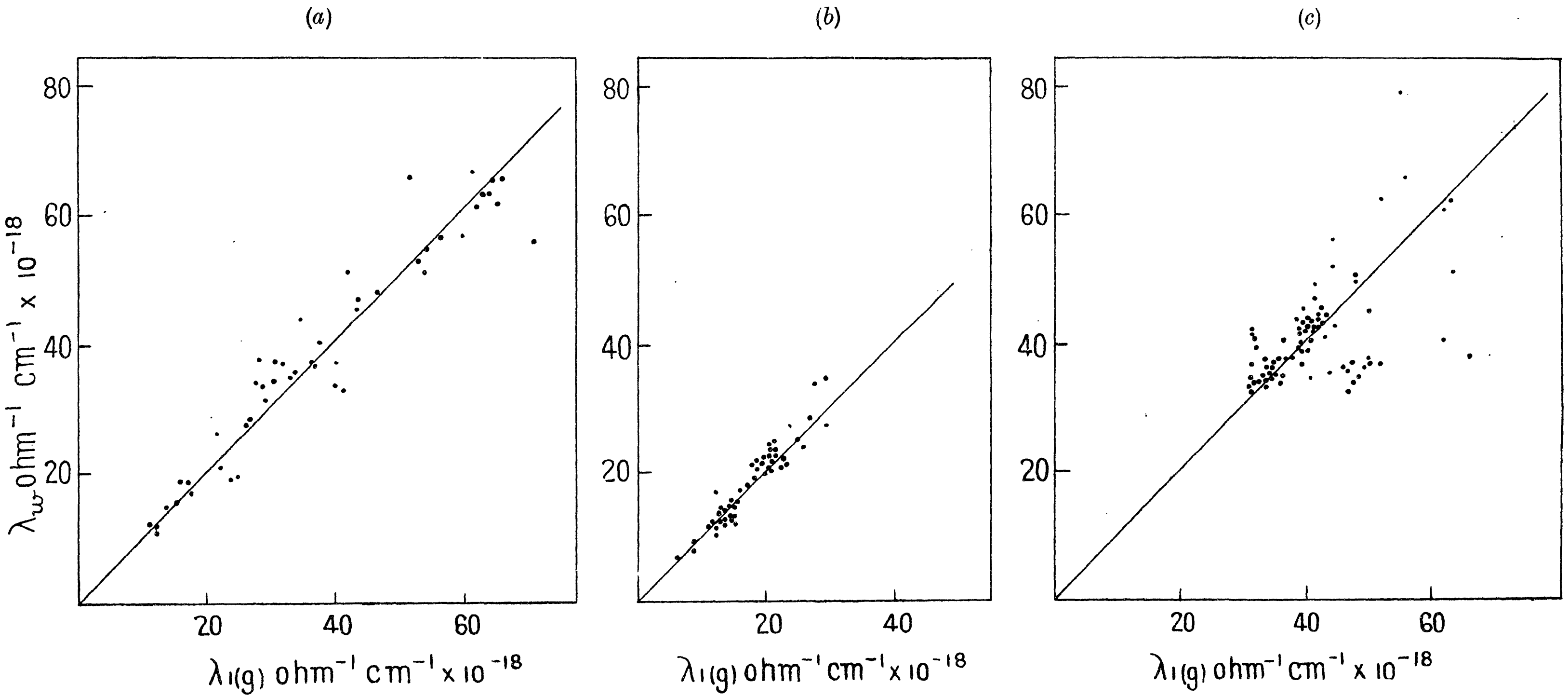

Fig. 3.—Comparison of the conductivity measured by the Wilson apparatus at ground level (λ_w) with positive conductivity measured by the aspiration apparatus at ground level ($\lambda_{1(g)}$). (*a*) Wilson (natural field) and aspiration I.; (*b*) Wilson (natural field) and aspiration II.; (*c*) Wilson (artificial field) and aspiration I.

$\lambda_{2(g)}$. The true conductivities actually existing at the surface of the ground may then be represented by $\lambda_{1(o)}$ and $\lambda_{2(o)}$. The observations make it appear likely that with positive gradients a close approximation is—

$$\lambda_w = \lambda_{1(g)} = \lambda_{1(o)}.$$

Accordingly, in the sequel the distinction between these three quantities will be abandoned sometimes, and when necessary it will be assumed that $\lambda_{1(o)}$ may be measured by either the Wilson or the aspiration apparatus.

Occasionally at Kew there occurs a period of negative gradient sustained over a few hours without any specially disturbed meteorological conditions being apparent. It was possible to take advantage of such a period (7.5.38) to compare the negative conductivity measured by the Wilson with that measured by the aspiration apparatus. An average of 10 readings extending over a period of 1½ hours gave Wilson/Aspiration I =1.04, hence it may be assumed that under conditions of negative potential gradient, at ground level—

$$\lambda_w = \lambda_{2(g)} = \lambda_{2(o)}.$$

It should not be assumed, however, that with positive gradients $\lambda_{2(g)}$ is equal to $\lambda_{2(o)}$.

3. THE VARIATION OF CONDUCTIVITY WITH HEIGHT.

A. The Method of Observation.

The variation of positive conductivity with height was investigated by observations on air drawn from different levels with an aspiration apparatus compared with simultaneous control observations made at ground level with a Wilson apparatus. As before the experiments were carried out in the underground laboratory. Air from the desired height was drawn into the aspiration apparatus through a vertical cardboard tube slipped over the earthed outer electrode (Fig. 1). To reduce the disturbance of the earth's field due to the introduction of the tube the top of the latter was surrounded by a narrow metal band which was charged to a potential appropriate to its height. The potential required was determined by the Wilson apparatus just prior to the conductivity observation. Bearing in mind the results of earlier observations at Kew, (Scrase (1934)), in showing that the potential gradient did not vary appreciably in the metre nearest the ground, it was argued that the approximately uniform potential drop which would be established down the cardboard tube would not be very different from that existing in the atmosphere and thus that the introduction of the tube should not in itself appreciably affect the distribution of the ions in its vicinity.

Amongst possible sources of error in this method of working are—

(*a*) changes in the distribution of ions external to the tube on account of changes in the earth's field during the course of an experiment.

(*b*) changes in the distribution of ions due to the velocity of the air current entering the tube.

(*c*) absorption or combination of ions in their passage along the tube.

(*d*) precipitation of ions in the tube owing to stray internal transverse fields produced on account of irregularities in the conductivity of the internal surface of the tube.

(*e*) a turning back of the negative ions by the field at the mouth of the tube.

(*a*) To investigate (*a*) comparisons were made between results obtained when the band around the top of the tube was earthed and when it was charged to near atmospheric potential. Using a 50 cm. tube it was found that with earthed top the positive conductivity was about 10 per cent. greater than when the top of the tube was at air potential whilst the negative conductivity was reduced by as much as 40 per cent. It was concluded that during a single experiment the field changes, usually less than 10 per cent., would be insufficient to have any marked effect on the result and in a series of experiments the effects of the fluctuations would most likely cancel out statistically.

(*b*) The effect of (*b*) has been mentioned in the previous section as an explanation of the measured λ_{m} being slightly greater than $\lambda_{1(g)}$. The effect would not be large except at those levels where the ion content is changing rapidly with height.

(*c*) Absorption effects (*c*) were investigated by aspirating air from the ground level directly into one apparatus and also through a cardboard tube one metre long into a second. Results showed that with a tube one metre long the air lost about 6 per cent. of both positive and negative ions. With a tube 40 cms. long a decrease of 4 per cent. was observed. A uniform correction of +0.06 per cent. per cm. of tube was applied throughout on this account.

(*d*) To investigate (*d*), the losses due to stray internal fields, a cardboard tube 80 cm. long was arranged vertically with its top end flush with the ground and its lower end slipped over the metal cylinder of an aspiration apparatus, in the underground laboratory. The tube was earthed at the top and the bottom whilst a metal band at its centre was charged to + or −180 volts, thus giving gradients along the tube comparable numerically with the atmospheric potential gradient. The apparent changes of conductivity brought about by varying the potential of the centre of the tube were measured as follows :—

	λ_1	λ_2
Centre of tube positive	−46% ..	+1%
Centre of tube negative	0% ..	−50%

Differences in the apparent conductivity brought about by charging the centre of the tube might arise through :—

(i) distortion of the external field near the mouth of the tube.

(ii) stray internal fields produced by irregularities in the conductivity of the material of the tube.

In the former case apparent alterations in conductivity would be produced by ions being repelled from, or drawn into the mouth of the tube. In the latter case ions already inside the tube would be drawn to some part or parts of the tube wall. External field effects would be expected to vary with the sign of the potential applied to the centre of the tube. Any internal field effects would be observed for both kinds of ions with either sign of potential. Referring to the above results it is seen that, when the fields in the upper portion of the tube did not oppose the entrance of ions, there was practically no difference between the results obtained with the tube charged and with the tube earthed. Thus it may be concluded that effects due to any stray internal fields may be neglected.

(*e*) The turning back of the ions by the field at the mouth of an ion counter is a well-known error in the observation of ion concentrations. It was expected that this effect, which in the present observations concerns only negative ions, would be absent because, whilst the upward velocity of a negative ion in the earth's field was estimated as varying from $2\frac{1}{2}$ to 10 cm./sec., the average downward velocity of air in the aspirator tube was 100 cm./sec. When certain discrepancies appeared in the results it was realized that whilst the average velocity of air down the aspirator tube was greater than the upward velocity of negative ions in the earth's field a proportion of the entering air would approach the tube with a velocity whose downward component would be less than the ionic velocity. This reduction in velocity would be due to a change in the cross sectional area of the stream of air approaching the tube together with the effect of the upwardly directed portions of atmospheric eddies. The turning back may be considerably intensified if the top of the tube happens to be at a potential lower than that which is appropriate to its height, for in this instance, the atmospheric potential gradient around the top of the tube is increased. This error was allowed for by a method involving an analysis of the observations as described later.

B. RESULTS.

In the earlier experiments, for which only one aspiration apparatus was available, a comparison was made of the positive conductivity at a height z (denoted by $\lambda_{1(z)}$) with the positive conductivity (λ_w) measured simultaneously at ground level. Later, when a second aspiration apparatus became available, measurements of the negative conductivity at height z (denoted by $\lambda_{2(z)}$) were also made simultaneously with the above observations. The earlier measurements, Table 1, which were made in November, 1937, were obtained by using a Wilson apparatus with artificial field for the measurements at ground level, and an aspiration apparatus for the measurements at z cm. In this Table F is the atmospheric potential gradient measured for part of these observations by a

Table I.

z cm.	10	20	30	50	66	80	90
$\lambda_{1(z)}/\lambda_w$ (*obsd.*)	0.85	0.71	0.65	0.62	0.66	0.62	0.53
$\lambda_{1(z)}/\lambda_w$ (*corrd.*)	0.80	0.78	0.63	0.58	0.55	0.54	0.53
$\lambda_w \times 10^{18} ohm^{-1} cm^{-1}$	10	21	18	20	16	24	29
F v/cm.	5.20	4.55	3.68	5.97	4.32	3.32	3.55
Observations	20	35	19	20	20	19	26

Wilson apparatus at ground level, and for the remainder by a collector on a vertical rod attached to a Wulf bifilar electrometer (Dines (1935)). The later measurements were obtained by using a Wilson apparatus with natural field at ground level simultaneously with two aspirators, one for $\lambda_{1(z)}$, the other for $\lambda_{2(z)}$. The results (Table II) were obtained for the higher levels in January and February 1938, and for the 12.5 cm. level in May, 1938.

Table II.

z cm.	12.5	25	50	100
1. $\lambda_{1(z)}/\lambda_w$ (*obsd.*)	0.60	0.60	0.45	0.46
2. $\lambda_{2(z)}/\lambda_w$ (*obsd.*)	0.40	0.31	0.34	0.37
3. $\lambda_w \times 10^{18} ohm^{-1} cm^{-1}$	54	19	28	22
4. F *v/cm.*	2.14	4.55	3.88	4.09
5. $\lambda_{1(z)}/\lambda_w$ (*corrd.*)	0.69	0.62	0.54	0.50
6. $\lambda_{2(z)}/\lambda_w$ (*corrd.*)	0.43	0.37	0.39	0.43
7. $(\lambda_{1(z)} + \lambda_{2(z)})/\lambda_w$ (*corrd.*)	1.12	0.99	0.93	0.93
Observations	110	72	86	90

In Tables I and II the quantities marked "*obsd.*" were made up of direct observational results corrected only for the absorption of ions in the tube.

To obtain a proper picture of the variation of λ_1 with z it was necessary to ascertain whether the ratio $\lambda_{1(z)}/\lambda_w$ was dependent on variables other than z and which, on the average, did not remain constant for the observations at the different levels. An analysis of the observations summarized in Table II showed that the value of $\lambda_{1(z)}/\lambda_w$ was dependent on F (see Fig. 4). The points in Fig. 4 were obtained by arranging the $\lambda_{1(z)}/\lambda_w$ values for each level in four approximately equal groups according to the magnitude of the associated value of F. For each of the four levels a straight line was drawn, account being taken not only of the points for each level but also of the lie of the lines for adjoining levels. The results of Table I were analysed similarly but the variation of F in this series was too small to show any relationship. The increase of $\lambda_{1(z)}/\lambda_w$ with F may be related to two factors, viz. "electrode effect" and atmospheric turbulence. Under uniformly turbulent conditions an increase of F will result in a greater proportion of the positive ions lying close to the ground, i.e. in higher values of $\lambda_{1(z)}/\lambda_w$. Also a low degree of atmospheric turbulence (which is frequently associated with high values of F) will cause $\lambda_{1(z)}/\lambda_w$ to be high for low values of z. As is well known there is a relation between F and λ_w, the former increasing as the latter decreases. Thus as the values of $\lambda_{1(z)}/\lambda_w$ are related to F they may also be expected to be dependent on λ_w. This relation was looked for in the results of Table II using the method employed to give the relation with F. Fig. 5 shows that $\lambda_{1(z)}/\lambda_w$ increases with decreasing λ_w.

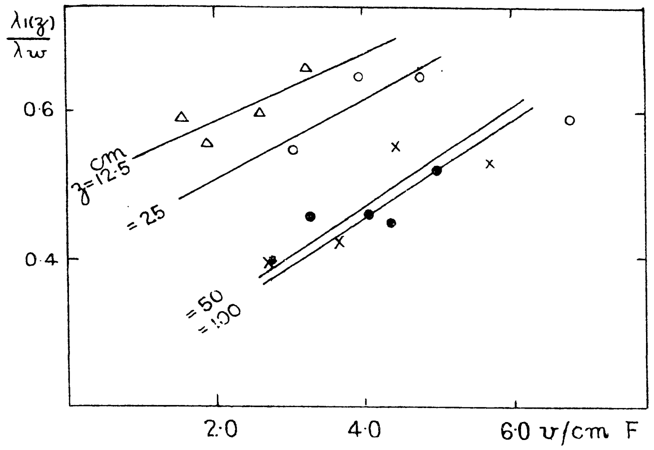

Fig. 4.—The variation of $\lambda_{1(z)}/\lambda_w$ with field strength.

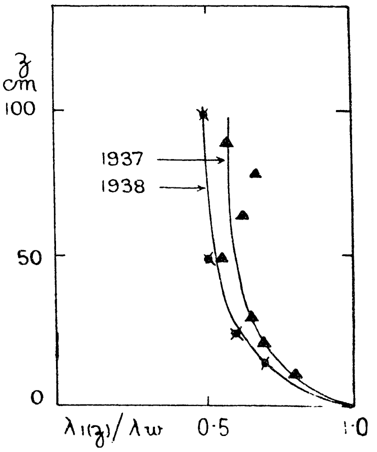

Fig. 6.—Variation with height of $\lambda_{1(z)}/\lambda$ (corrected to constant F=4·0 v/cm.).

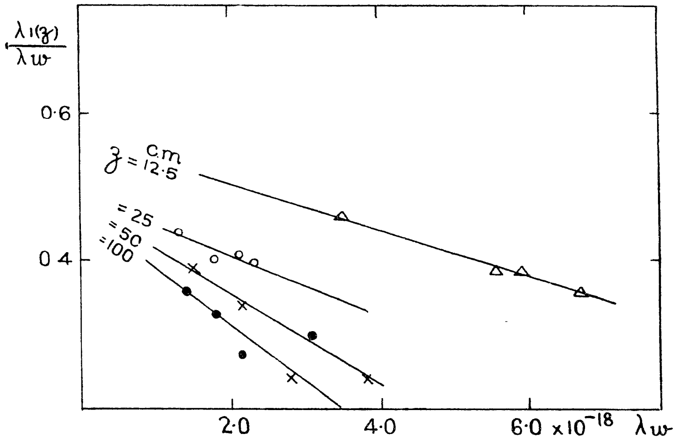

Fig. 5.—The variation of $\lambda_{1(z)}/\lambda_w$ with conductivity.

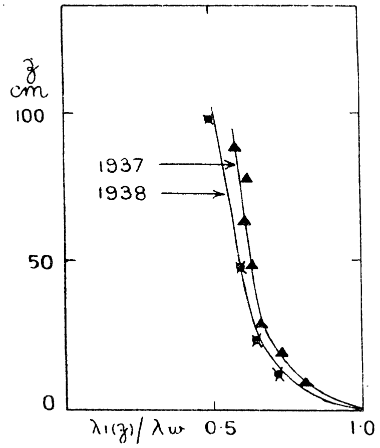

Fig. 7.—Variation with height of $\lambda_{1(z)}/\lambda_w$ (corrected to constant λ_w=20 x 10^{-18} ohm.$^{-1}$ cm.$^{-1}$).

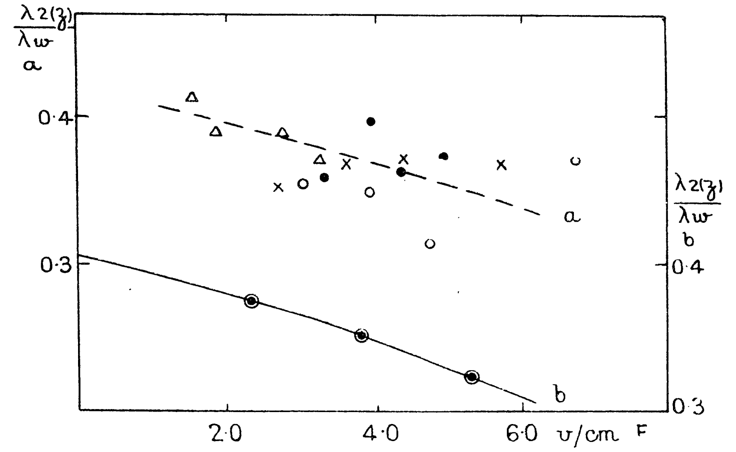

Fig. 8.—Curve for obtaining the repulsion correction to $\lambda_{2(z)}/\lambda_w$.

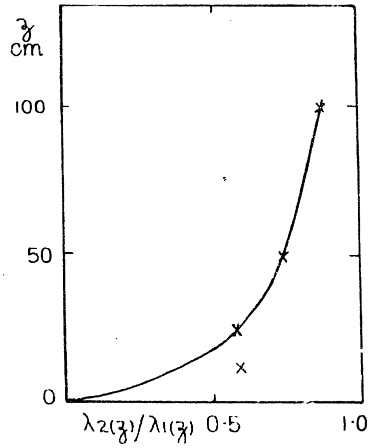

Fig. 9.—Variation of $\lambda_{2(z)}/\lambda_{1(z)}$ with height.

In order to display the true variation of λ_1 with z it is necessary to correct the results of Tables I and II for the variations of F or of λ_w. This has been done by using Figs. 4 and 5 and bringing the results to a constant F of 4.00 v./cm. and a constant λ_w of 20 x 10^{-18} ohm^{-1} cm.$^{-1}$, these being approximately average values for the two series. The corrected values are shown in Fig. 6 (corrected to constant F) and in Fig. 7 (corrected to constant λ_w). There is no great difference between the results corrected to constant F and those corrected to constant λ_w. The means obtained from the two methods of correction applied to each year separately are entered in Tables I and II as $\lambda_{1(z)}/\lambda_w$ (*corrd.*). Both sets show $\lambda_{1(z)}/\lambda_w$ to decrease very rapidly in the first 20 cm. above ground level. The November, 1937, results show lower values of $\lambda_{1(z)}/\lambda_w$ than the January and May, 1938, results. This perhaps may be attributed to a lower degree of atmospheric turbulence existing in November, which is notoriously a foggy month, than in January and May. The question as to whether there is a definite seasonal variation in $d\lambda_1/dz$ requires further investigation.

The variation of λ_2 with z is indicated in Table II by the values of $\lambda_{2(z)}/\lambda_w$. The observed values require correction for the repulsive effect of the earth's field as mentioned in paragraph (*e*) of Section 3A. In order to estimate this correction the results from which Table II was constructed were analysed to determine whether $\lambda_{2(z)}/\lambda_w$ was related to F. The results of this analysis were plotted in Fig. 8 curves " *a* " and " *b* ". Each point around curve " *a* " represents the average of about one quarter of the observations at each level. The results were too scattered to permit of a curve being drawn for each level but a line drawn through the points as a whole indicated that $\lambda_{2(z)}/\lambda_w$ tended to increase with decreasing F as would be expected from the repulsion effect. In order to locate this trend more accurately, the whole of the results, without regard to level, were arranged in increasing order of F and divided into three approximately equal groups. Average values of F and $\lambda_{2(z)}/\lambda_w$ were obtained for each group and plotted as curve " *b* " in Fig. 8. This curve was extrapolated to $F=0$, a point where the repulsive effect due to the earth's field was considered to be zero, and was used to correct the observed values of $\lambda_{2(z)}/\lambda_w$ on a linear basis. The corrected values are shown in Table II. Excluding the results for 12.5 cm. (obtained at a later date and perhaps under different conditions of turbulence) the observations indicate that $\lambda_{2(z)}/\lambda_w$ increases with increasing z.

The change of total conductivity with height was investigated by two methods (i) and (ii). Method (i) consisted in adding the unipolar conductivity values shown in Table II. The sums, shown in Table II (line 7) are repeated for convenience in Table IV. Method (ii) required a combination of results obtained in 1937 and 1938. From the experiments in 1938 it was possible to obtain the ratio $\lambda_{2(z)}/\lambda_{1(z)}$ at four heights; if it be assumed that this ratio was the same in 1937 as in 1938 another series of values of $\lambda_{2(z)}/\lambda_w$ can be derived by applying the ratio to the values of $\lambda_{1(z)}/\lambda_w$ in Table I (1937). In Fig. 9 the ratio $\lambda_{2(z)}/\lambda_{1(z)}$ obtained from the first two lines of Table II was plotted against z. For reasons already stated the value $z=12.5$ cm. was doubtful. Neglecting this value and drawing the curve through the zero a smooth line was obtained. Table III gives the interpolated results of Fig. 9.

Table III.

z cm.	0	12.5	25	50	100
$\lambda_{2(z)}/\lambda_{1(z)}$	0.0	0.40	0.59	0.74	0.88

These values when applied to the observations of $\lambda_{1(z)}/\lambda_w$ made in 1937 gave the $\lambda_{2(z)}/\lambda_w$ results shown in Table IV, line 5.

Table IV.

z cm.	0	12.5	25	50	100	Source.
1. $\lambda_{1(z)}/\lambda_w$ (1937)	(1.0)	0.76	0.66	0.59	0.54	Fig. 6 and 7 interpolated.
2. $\lambda_{1(z)}/\lambda_w$ (1938)	(1.0)	0.69	0.62	0.54	0.50	Table II, line 5.
3. $\lambda_{1(z)}/\lambda_w$ (mean)	(1.0)	0.72	0.64	0.56	0.52	
4. $\lambda_{2(z)}/\lambda_{1(z)}$	(0.0)	0.40	0.59	0.74	0.88	Fig. 9 interpolated.
5. $\lambda_{2(z)}/\lambda_w$ (1937)	(0.0)	0.30	0.38	0.43	0.48	Line 1 x Line 4.
6. $\lambda_{2(z)}/\lambda_w$ (1938)	(0.0)	0.43	0.37	0.39	0.43	Table II, line 6.
7. $\lambda_{2(z)}/\lambda_w$ (mean)	(0.0)	0.36	0.38	0.41	0.46	
8. $(\lambda_{1(z)} + \lambda_{2(z)})/\lambda_w$	(1.0)	1.08	1.02	0.97	0.98	Sum of lines 3 and 7.

The means of the preceding results are shown in Fig. 10 which represents the estimated relations between positive, negative and total conductivity with the height in the first metre of the atmosphere. It will be seen that over the range investigated the total conductivity is equal to the conductivity measured at ground level by the Wilson apparatus.

4. POTENTIAL GRADIENT AND HEIGHT.

If the total conductivity is independent of the height it is to be expected that the potential gradient will also be independent of the height. This conclusion was checked by observing the gradient variation over the range 0—100 cm. It was not expected that any great variation would be found, for observations first by Watson (1929) and later by Scrase (1934), had shown that the potential gradient measured by the Wilson plate apparatus at ground level was very close to the average value deduced from stretched wire measurements at 100 cm. In the present experiments three wires were stretched between insulators at heights of 25 cm., 50 cm., and 100cm., over an open, level and closely cut piece of turf. Each of the wires was provided with a cylindrical polonium collector and each was connected to a Wulf bifilar electrometer of appropriate sensitivity. All of the electrometers were calibrated by reference to the same battery of Weston cells. The averages of over 100 sets of simultaneous readings of $V_{(z)}$, the potential at height z, for the three levels gave the figures set out in Table V, and point to no appreciable change of gradient with height in this range.

Table V.

z *cm.*	25	50	100
$V_{(z)}/z$. (*Volts/cm.*)	3.06	2.95	3.06

Whilst the table can be taken as showing the absence of any large variation of the gradient with the height in the layers closest to the ground, the accuracy of the observations is not such as would warrant the drawing of conclusions as to the presence or absence of relatively small space charges close to the ground. In the first place, the relative accuracy with which a point 25 cm. above such an irregular surface as a piece of turf may be defined is not great. The recent results of Banerji (1938) suggest that errors may arise through the collector failing to attain the potential of the air at its level. On the other hand, the work of Norinder (1921), taken in conjunction with the results of Tuve and Huff (1927) which, in this respect, were confirmed by the observations of Builder (1930) rather suggests that, with the type of cylindrical collector used in the present experiments, the errors arising from this source would be small. Accordingly, the bulk of the evidence would point to there being no very great variation of the potential gradient in the range investigated; a conclusion also arrived at by J. J. Nolan and P. J. Nolan (1935), using a water dropper and a Wilson plate.

5. SPACE CHARGES.

The question of the variation of the gradient near the surface was further investigated by making measurements of the space charge. A large ion counter of the cylinder condenser type was used to measure the total number of ions in the air, positive (N'_1) and negative (N'_2) alternately, and the space charge was deduced as $\rho=(N'_1-N'_2)e$. For the bulk of the observations the total number of positive and negative small ions, as estimated from the observed conductivity results and assumed mobility figures, together amounted to 200 per cm.^{3}; whereas $N_1 + N_2$ was about 100 times greater. N'_1 and N'_2 may therefore be identified approximately with the numbers of positively and negatively charged nuclei in the air, N_1 and N_2.

The effective dimensions and operating conditions of the condenser were—

Inside diameter of outer electrode	5.60	cm.
Outside diameter of inner electrode	2.84	cm.
Length of inner electrode	39.8	cm.
Potential difference between electrodes	420	v.
Air flow	8.3	cm.^{3}/sec.

Accordingly the mobility of the slowest ion caught would be about 5×10^{-5} (cm./sec.)/(volt/cm.) ; previous experiments in another investigation showed that the presence of ions of mobility less than this was not detectable experimentally.

The current in the condenser was measured by a Wulf unifilar electrometer (sensitivity about 250 divisions per volt) which was calibrated for every observation. The air flow was measured by a small jet flow-meter calibrated directly by displacement. In order to avoid errors due to the turning back of ions by the field, the air was made to enter the apparatus at a relatively high velocity through a poorly conducting glass tube along which the potential gradient was of the order of 20 v./cm. The velocity of the larger ions in this field would be small compared with the velocity of the air passing along the tube, and only a small fraction of the ions would be turned back. The repulsion effect noted in the conductivity measurements would also be present here, but, owing to the small mobility of the ions concerned, would be less.

The apparatus was used to make two sets of observations, one a preliminary series in which the air was drawn from a point flush with the roof of the underground laboratory, and a second series in which the air was drawn through a charged tube projecting 12.5 cm. above the roof of the laboratory, as shown in Fig. 1. The results which were obtained in May, 1938, are given in Table VI.

Table VI.

—	N'_1	N'_2	$N'_1 - N'_2$	$N'_1 \div N'_2$	*Obs.*
Series I.	18.9	17.1	1.8	1.10	20
Series II.	7.12	6.5	0.62	1.09	25

Values of N'_1 and N'_2 are expressed in ions per mm^3.

Series I and II were obtained at different times and under quite different meteorological conditions so cannot be compared for the purpose of investigating any change of ρ with z. Series II included measurements of $\lambda_{1(z)}$, $\lambda_{2(z)}$ (aspiration apparatus), λ_w and F (Wilson apparatus). Table VII shows these results, each line giving the average of 10 successive sets of simultaneous conductivity and field readings; with each set the averages of 5 values of N'_1 and 5 values of N'_2 are associated.

Each of the series of observations in Table VI shows an excess of positive charge near the ground. The average value of $\delta F/\delta z$ was, according to Poisson's law, -0.0033 v./cm^2. in the first series and -0.0010 in the other. For the latter case $F_{(o)}$ was determined and it appears that $\frac{\delta F}{\delta z} / F_{(o)}$ was -6 per cent. metre. The results obtained, because of the possibility of the repulsion error, probably represent maximum positive values for the space charge, and accordingly, maximum values for the decrease of the gradient. The results could be interpreted as showing the field at 100 cms. to be practically identical with that at ground level.

Table VII.

$z=12.5$ cm.

Series.	F	λ_w	$\lambda_{1(z)}$	$\lambda_{2(z)}$	$N'_{1(z)}$	$N'_{2(z)}$
1	1.53	60.8	37.8	29.1	6.08	6.61
2	1.80	63.7	32.3	22.7	8.74	7.20
3	1.83	69.2	40.3	26.6	8.08	6.72
4	1.66	56.5	32.1	22.3	7.04	6.62
5	2.03	64.4	35.6	26.1	5.66	5.39
Means	1.77	62.9	35.6	25.4	7.12	6.51

F in volts/cm. λ in ohm^{-1} cm.$^{-1}$ x 10^{-18}
$N'_{1(z)}$ and $N'_{2(z)}$ in cm^{-3} x 10^3.

6. RATE OF IONISATION AND HEIGHT.

In the earlier stages of the investigation, before the repulsion correction was applied to the $\lambda_{2(z)}$ observations, there appeared to be a distinct falling off of both λ_1 and λ_2 with increase of height. It was thought that this might be related to a change in the rate of ionisation with the height. An augmented rate of ionisation near the ground might be explained by the existence of a radioactive precipitate of the type found by Wait and McNish (1934).

Preliminary experiments were made in the underground laboratory with two aspiration instruments, both aspirating from an inlet flush with the ground. One apparatus was used as a control, whilst the inlet to the second was covered by a plate held a few millimetres above ground level, so as to limit the air supply to layers very close to the surface. In these circumstances the covered apparatus gave readings of λ_1 twice as great as the uncovered, thus supporting the idea of an enhanced production of ions at ground level.

To investigate the matter further a special ionisation chamber was built. It consisted of a cylindrical vessel (Fig. 11) 40 cm. in diameter and 15 cm. high, made of galvanized iron. In the base of the vessel a circular window 27.7 cm. in diameter was cut and covered with cellophane. The inside surface of the cellophane was thinly coated with colloidal graphite. Above the cellophane and distant about 0.3 cm. from it, a piece of stainless steel gauze 27 cm. in diameter, was supported on ebonite insulators; in use the gauze was charged to +126 volts. About 3.5 cm. above this gauze was supported a second gauze, insulated by amber and connected to a Lindemann electrometer. The vessel, which was gas tight, was filled with carbon dioxide at atmospheric pressure. In order to check the sensitivity of this apparatus to α radiation, which, as is indicated by observations made at Canberra, can be responsible for a large fraction of the total low-level atmospheric ionisation, use was made of a weak polonium source. It was found that when the source was held within a few millimetres of the cellophane its α radiation notably increased the current in the vessel, whilst with the source 3 cm. or so from the cellophane but little increase in current was observed.

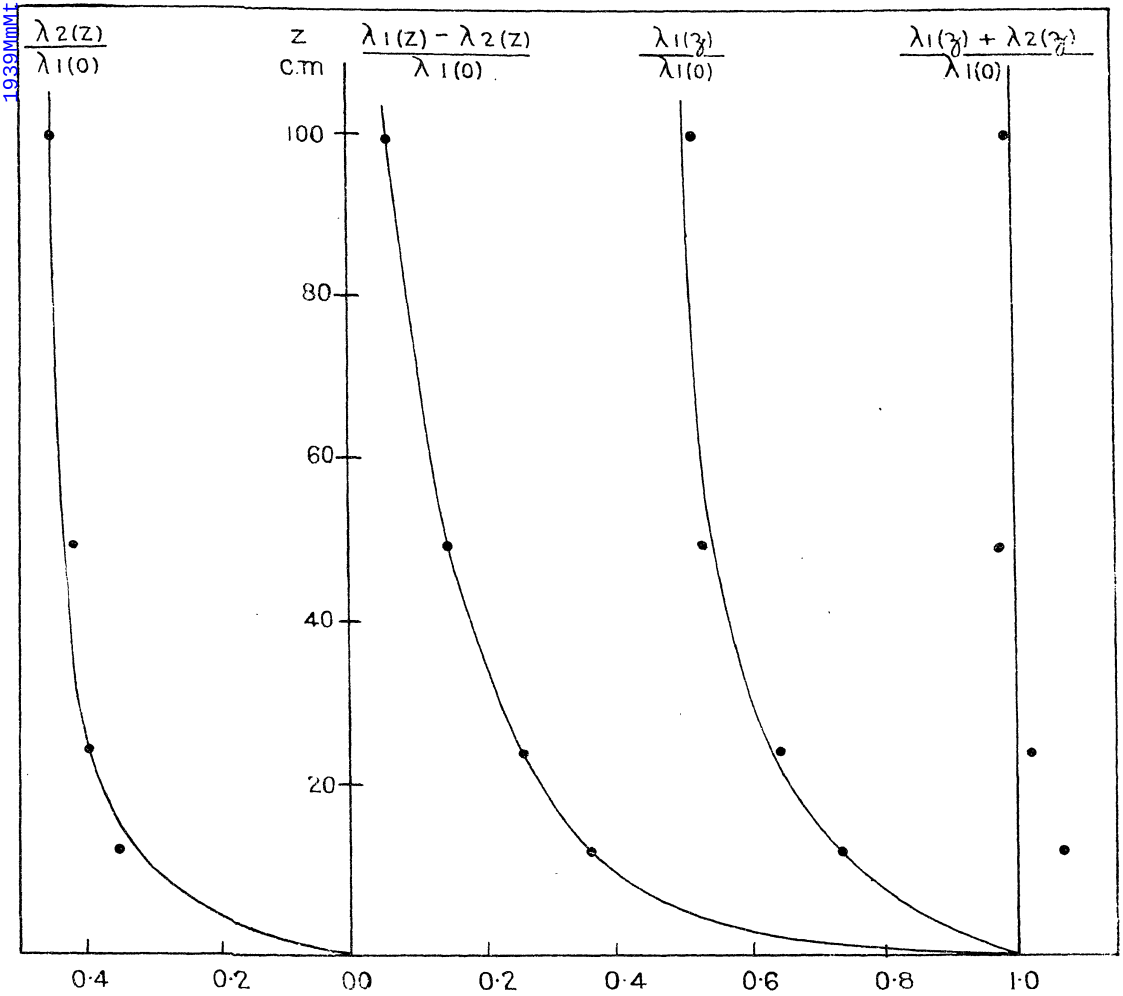

Fig. 10.—Variation of electrical conductivity in the lowest metre of the atmosphere.

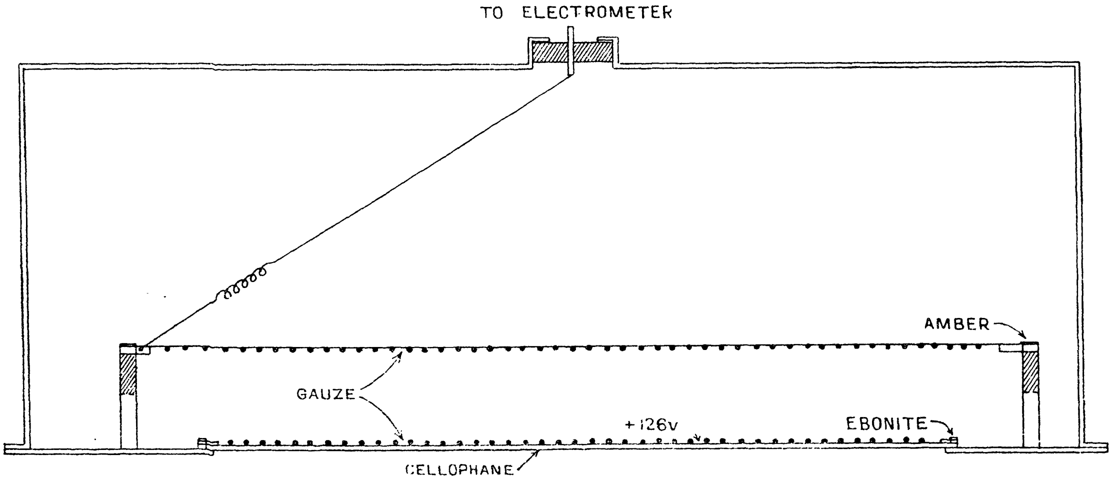

Fig. 11.—Ionisation vessel with cellophane window.

Measurements were made by placing the vessel alternately on the roof of the underground laboratory and on wooden trestles so that the cellophane window was at a height of 1 metre above the roof. The results showed that with the vessel in the former position, the rate of ionisation between the gauzes was 1.22 times the ionisation in the latter position (average of 42 comparisons made on 10 days in March, 1938). This ratio of 1.22 does not necessarily represent the ratio of the rates of ionisation in the free atmosphere at the two levels. To obtain the true ratio it would be necessary to apply various corrections, including those for residual ionisation from the walls of the vessel, for absorption of α radiation in the cellophane, for the screening effect of the vessel, for the hindering of the air circulation by the placing of the vessel on the ground and so on. The actual rate of ionisation of the carbon dioxide was calculated to be very roughly 20 ion pairs per cm^3. per sec. If the vessel had been filled with non-radioactive air the figure would probably be 13 ion pairs per cm^3. per sec.

A short series of observations was also carried out in which the vessel was filled with air alternately from ground level and from 1 metre. For this series the cellophane window was removed and the vessel stood on the roof of the underground laboratory for a period of five minutes. A metal plate was then slipped under the opening in the vessel and the current measured. At the conclusion of this measurement the vessel was lifted clear of the plate to a height of about 1 metre and there exposed to the free air for five minutes. The cover plate was then replaced and a second measurement made. These measurements gave as a mean of three comparisons a value at ground level 1.12 times greater than that at 1 metre. The comparison of this ratio with the figure of 1.22 obtained when using the cellophane window might be adduced as evidence for the existence of a β type radiation coming from the surface of the ground—the radiation passing through the cellophane but not through the metal. A much longer series of observations, preferably with two sets of apparatus used simultaneously, would be needed before this point could be asserted definitely. However, the preliminary experiments with the ion counter and the two sets of experiments with the ionisation vessel indicate that the rate of ionisation at the roof level is measurably greater than that at 1 metre above it.

7. DISCUSSION OF THE OBSERVATIONS.

The observations serve to throw light on the previously noted discrepancy between the values of the actual air-earth current as measured by the Wilson apparatus and the conduction current as calculated from the total conductivity and potential gradient. Previously it was suggested (Watson (1929), Whipple (1930)), that the calculated conduction current was about twice the actual air-earth current, the discrepancy being attributed to the transfer of a space charge by air movements. Thus it was thought that the positive conduction current was independent of the height. A negative conduction current, approximately equal to the positive conduction current was present at 100 cm. but was absent at ground level. It was assumed that a mechanism involving convective displacement of a space charge operated between 0 and 100 cm. and neutralized the positive charge which would arise near the surface layers owing to the escape from them of the negative conduction current. The present observations show that the conduction current at levels between 12.5 cm. and 100 cm. is equal to within a few per cent. to the current entering the ground, i.e. any convection current which does exist is quite small compared with the conduction current. Exact agreement between the actual current and the calculated current was not obtained at all levels but the differences, averaging about 5 per cent., might reasonably be attributed to imperfections in the method of observation. In any case, the discrepancy is very much less than was earlier suspected. Agreement between the actual and the calculated current means that the unipolar conductivities, which are approximately equal to each other at 100 cm. undergo considerable variation with the height in the lowest levels. The variation of $\lambda_{1(z)}$ and $\lambda_{2(z)}$ (see Fig. 10) with height implies the existence of a space charge of small ions near the surface. The trend of this space charge is indicated very approximately by the line $(\lambda_{1(z)}-\lambda_{2(z)})/\lambda_{1(0)}$ in Fig. 10. The existence of a space charge requires a variation of field with the height and this was not definitely detected. The magnitude of the space charge may be obtained from the conductivity observations, neglecting for the moment any space charge due to large ions. Assuming the conductivity to be due to small ions of mobility 1 cm./sec./volt/cm. it can be calculated that the small ions of both signs total less than 200 per cm^3. The mean space charge due to these ions therefore cannot exceed 200e per cm^3. even at the surface of the electrode. As may be seen from Fig. 10 this space charge will be confined mainly to levels below 50 cm. in which it may be assumed for purposes of this calculation to have an average value of +100e per cm^3. Using Poisson's equation it is seen that a space charge of this magnitude implies that the gradient at 50 cm. is approximately 0.01 v/cm. less than the surface gradient. Such a small change could not be detected with certainty in the present observations where the mean value of F was approximately 400 v/cm. Thus the experimental result of unipolar conductivities which change with the height is not at variance with the observation of a gradient which does not alter detectably with the height. With observations in air of higher conductivity and subjected to lower fields there may be some possibility of a gradient change being detected in the lowest levels.

In the preceding paragraph the effect of space charges due to large ions has been ignored. The distribution of the large ions with respect to height has not been directly determined in the present observations, but certain conclusions on this point may be drawn from the results. The large ions of both signs may be taken as together amounting to some 20,000 per cm^3. (Table VI) as against 200 per cm^3. for the small ions. Thus the bulk of the atmospheric electrification resides upon the large ions. As it has been shown that the space charge due to small ions alone was too insignificant to be experimentally detectable here, it follows that the observed effective constancy of gradient with height requires that the space charge due to large ions alone ($(N_1-N_2)e$) be also small. Using the mean results of Table VII it is seen that the space charge carried by the large ions is about +550 e/cm^3. at 12.5 cm. This value implies a variation of the gradient in the first metre of about −0.1 volt per cm. As the observed variation is less than this it might be tentatively concluded that the space charge due to large ions also becomes appreciably less positive with increasing height even in the lowest levels. This conclusion might well be checked by direct measurements.

Thomson (1928) in discussing the conduction of electricity between parallel plane electrodes in a gas containing small ions points out that the distance L from the surface of one electrode to the nearest point where the space charge in the gas has become zero must be such that $L > i/2qe$ where q is the rate of production of the ions. With $q=4.5$ (Scrase (1933)), $i=100 \text{ x}10^{-18}$ amp. cm.$^{-2}$ (Scrase (1935)) it is seen that L must exceed 66 cm. Fig. 10 shows that the small ion space charge is still present at 100 cm. and the observations are apparently in agreement with Thomson's conclusions.

8. ACKNOWLEDGMENTS.

This work has been rendered possible by the joint action of the Minister for the Interior of the Commonwealth of Australia in granting to the writer study-leave from the Commonwealth Solar Observatory, Canberra, and of the Director of the Meteorological Office, London, by granting permission for the writer to work at Kew Observatory.

Further, the writer is very much indebted to Sir George Simpson, F.R.S., for several valuable suggestions and to the Superintendent of Kew Observatory, Dr. F. J. W. Whipple, for offering the greatest encouragement and help throughout the investigation as well as much useful advice and criticism during the discussion of the observations. Mr. A. J. Lander kindly assisted in carrying out some of the Wilson aspiration comparisons.

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By Authority: L. F. Johnston, Commonwealth Government Printer, Canberra.