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UNIVERSITY OF CINCINNATI

May 23, 1931

I hereby recommend that the thesis prepared under my supervision by Charles Harrison Dwight

entitled The Diurnal Variation of the Space Charge and its Effect upon the Potential Gradient

be accepted as fulfilling this part of the requirements for the degree of Doctor of Philosophy

Approved by:

S. J. M. Allen

Form 668—G. S. and Ed.—500—3-30.

THE DIURNAL VARIATION OF THE
SPACE CHARGE
AND ITS EFFECT UPON THE
POTENTIAL GRADIENT

A dissertation submitted in partial
fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

to the Graduate School of the
University of Cincinnati

1931

by

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HISTORICAL DEVELOPMENT

While it had been suspected for many years prior to 1785 that there is a certain amount of "free" electricity in the atmosphere, it was not until then that a systematic investigation was made. In that year Coulomb showed that a charged insulated body gradually lost its charge to the air, regardless of the perfection of the insulation. The explanation given by him was that the neutral molecules of the air were charged by their contact with the body and, receiving then a like charge, were repelled. Thus the charge on the body was finally lost to its surroundings. It was erroneously supposed by some investigators that damp air is a better conductor of electricity than dry air. Actually, however, water is present in damp air in the form of comparatively isolated droplets, which, if charged at all, are too heavy to move appreciablyuunder the electric forces. Between these droplets are the ordinary gas molecules and dust particles. A century after the research of Coulomb it was demonstrated by Linss that there is a greater dissipation of charge in fine, dry weather than on damp days. He also showed that there is a seasonal change in the rate of dissipation.

The modern development of the subject of atmospheric ionization began shortly after the discovery of Roentgen and Becquerel "rays." Air which is exposed to the action of either of these radiations becomes at once conducting and it was demonstrated by Sir. J. J. Thomson (1897) that molecules and atoms can be "ionized" by such agents. It was found that the ionized atoms and molecules usually have a positive charge, equal numerically to that of the "lost" electrons. Experiments had shown that these rays are radiations of very short wave-length. Properly speaking, only one component of the complex Becquerel radiation consists of true "rays," the other two components being particles carrying, in the one case, a positive charge of amount +2e and, in the other case, a negative charge of amount e. The former are found to be identical with the doubly-ionized helium atom, the latter are very swift electrons or "cathode rays." Rutherford (1900) had been able to concentrate the excited radioactivity from thorium emanation upon a thin wire serving as cathode in a strong electric field. Since no effect was found upon reversing the sign of the charge on the wire, it was concluded that the carriers of electricity in the emanation are positively charged. Elster and Geitel were able to draw such positive charges out of the atmosphere and thus prove that air contains radioactive material. Rutherford and Allen (1903) found that the rate of decay of the deposit on such a wire is independent of the material of the wire, its potential or the time of exposure. Later, Allen found that large dust particles are coated with this material and that its activity has several components. Ramsey and Soddy were able to condense this emanation out of the air, and found that there is at all times a natural ionization present, in addition to that caused by the activity of radioactive elements.

Our present idea, as to the dissipation of charge, is due to Elster and Geitel who, in 1900, applied the theory of gaseous ions to the electrical conductivity of the atmosphere and showed that "leakage" is caused by a neutralization of the resident charge by ions of opposite sign in the neighboring gas. These ions are of three classes, described as follows.

1. Small or "molecular" ions. These are composed of a group of about ten molecules to which is attached a positive or a negative charge. The mobility of these ions is as high as 2 cm per sec per volt per cm. They are found everywhere but are proportionately more numerous in pure country air, uncontaminated by products of combustion or dust.

2. Intermediate ions. These are of rare occurrance and of uncertain composition. They were discovered by Pollock in Sydney under certain conditions of humidity.

3. Langevin or "large" ions. This class of ions includes those which are composed of minute dust particles, products of combustion or invisible water droplets, to

which are attached positive or negative charges. The mobility of these ions may be as low as 0.0005 cm per sec per volt per cm. They are found principally in the air above towns and cities, in dusty air and near volcanoes.

Free α-particles and β-particles should properly be classed as ions, although they are not to be included in any of the foregoing classifications because of their relatively small size and high velocity, even when there is no accelerating electric field.

Inasmuch as multiply-charged ions are found under unusually severe conditions (e.g., in discharge tubes or in thunder-storms), it may be taken for granted that ordinary atmospheric ions are singly-charged. The value of this charge is taken as $e=4.774\times10^{-10}$ ESU. It has been found that, on the average, the number of positive ions exceeds that of the negative, the "missing" negative ions probably being located in soil capillaries or at great heights in the atmosphere.

The subject of atmospheric electricity is studied in terms of the various "elements", which are mutually interdependent but which require their own research apparatus and method of investigation. A brief discussion of these elements is given below. (A description of the apparatus used in each case has been omitted for brevity).

THE ATMOSPHERIC-ELECTRIC ELEMENTS

1. Conductivity. The conductivity of the air involves the number of ions of each sign per unit volume, the mobilities of the ions and the charge on each ion. If n_+, n_- be the number of positive and negative ions respectively per cc, k_+, k_- their mobilities, and E the field strength which causes their motion, the current carried by the ions is

$$i = eE(n_+k_+ + n_-k_-),$$

where e is the charge per ion. In general, if there be ions of m sizes, with mobilities and numbers all different, the above expression has to be written in the more general form

$$i = eE(\sum_1^m n_{i+}k_{i+} + \sum_1^m n_{j-}k_{j-}),$$

from which, as also in the previous case, the "specific electrical conductivity" (i/E) can be found. This quantity is also known as the "total conductivity of the air." The product $\lambda = enk$ is called the "polar conductivity" and the "ionic content," or charge of one sign per m^3, is given by $ne \times 10^6$. The determination of the value of n assumes, as a first approximation, that the ions are homogeneous (i.e., all either "heavy" or "light"). The earth usually has a negative charge which causes a drift of positive ions downwards and of negative ions upwards---the net result being the "air-earth current." Separation of the charges is effected also in a mechanical manner by the convection currents due to the absorption of the sun's heat by the earth's surface and the adjacent air. The excess positive or negative charge, measured in ESU/m^3, is known as the "space charge" or "differential ionization." It is usually positive in sign, especially near the ground, and is the algebraic sum of the ionic contents. In the present paper the space charge has been regarded as a separate element.

2. Potential gradient. This element is defined as the increase in potential per unit distance, measured upwards from the ground, and usually expressed in volts per m. It depends, of course, upon the size, distribution and number of ions present. There is reason to believe, as has been suggested by Brown (^{1}), that the potential gradient depends somewhat upon the barometric pressure as well as upon the temperature and humidity of the air. Ultimately, of course, the sun is the chief factor in causing variations of all the atmospheric quantities. The potential gradient is very much influenced by topographical conditions, such as the number and distribution of trees, buildings and hills. All these objects tend to distort the equipotential layers. An increase in altitude results first in a decrease (up to about 8 km) and then in an increase in the potential gradient. During thunder-storms the magnitude of the element may reach the sparking limit

and, after a lightning discharge, may even be temporarily reversed in sign.

3. Radioactivity of the soil. The emanation in the atmosphere breaks down with the emission of α- and β-particles and gamma rays. Other radioactive substances give off particles only. Elster and Geitel have shown that the soil is also radioactive and contains radium and thorium, with their disintegration products. Mineral springs usually contain radium emanation.

4. Penetrating radiation and cosmic rays. Elster and Geitel observed that the charge would leak from a charged vessel even when it was shielded from wind and rain. C.T.R. Wilson found that this leakage has the same rate for filtered air whether the latter be in the laboratory or in the country; that the rate is independent of the sign of the charge and that it is the same for darkness as for diffuse daylight. Since the ionization that causes this leakage is found to increase with altitude, the conclusion is that this leakage is approximately proportional to the air pressure. This fact was substantiated more fully by Gockel in 1910, who took an enclosed electroscope in a balloon to a height of 4500 m and found that the ionization is greater at this height than it is near the ground. A few years later Hess and Kolhorster took such an electroscope to a height of 9000 m. In 1921 Millikan and Bowen sent sounding balloons

up to a height of 15,500 m (i.e., nine-tenths of the way to the extremity of the atmosphere) and found the newly observed leakage rate to be much less than had been expected, thus indicating that the radiation causing the ionization is really more penetrating than was supposed. In 1926 Millikan and Cameron (^{2}) sank recording electroscopes in lakes in the high Andes, and in California, and found that this penetrating radiation is effective even after passing through 190 ft of water.

5. Stormy weather phenomena. An outline of the development of the subject of atmospheric electricity should include the very important branch involving stormy weather phenomena, the chief of which is the thunder-storm. In fact, as will be treated more fully later, one of the theories as to the maintenance of the earth's charge requires the agency of lightning. Franklin's experiment (1752) was the crucial test as to whether lightning is similar to the spark obtained upon discharging a Leyden jar. Other investigators had approached the problem before this time and had set up apparatus (e.g., a long vertical rod upon the ground) that showed the presence of electricity of considerable amount in the air during a thunder-storm. But Franklin insisted that no conclusion could be drawn that lightning <u>in the clouds</u> is of the same nature as the electricity found near the earth. We now know that even in calm weather large

electric charges accumulate upon airships, balloons, kites sent up by the Weather Bureau, and other objects that are similarly insulated from the ground. A satisfactory theory of the thunder-storm has been worked out by Simpson (^{3}) upon the basis of many thousands of observations in India, and the subject has been experimentally studied from a commercial standpoint also in order that adequate protection may be given to oil reservoirs, transmission lines etc. In this country most of the work has been done by Peek of the General Electric Company. In England (Manchester) the Metropolitan-Vickers Electrical Company maintains a high-voltage research laboratory. In addition to the theories of the thunder-storm proposed by C.T.R. Wilson and Simpson, Elster and Geitel suggested one which has subsequently been abandoned. We shall not attempt here to enter into any discussion of the various types of lightning discharge or such quiet discharges as St. Elmo's Fire and coronae. A more complete treatment of the mechanism of the thunder-storm will, however, be given in the present paper in a later section.

THEORIES OF THE MAINTENANCE OF THE EARTH'S ELECTRIC FIELD

It is evident from an inspection of the vast amount of data already at hand with regard to the earth's electric field that no one cause is either sufficient or adequate to account for the changes observed. For not only do the elements vary daily, yearly, with latitude and with altitude, but also, as in the case of the potential gradient, with topography. Apart from all these factors, the particular local conditions under which the experiment is conducted will perhaps cause the observations to vary to an enormous extent from the mean value of that element found elsewhere. There are a number of possible factors responsible for the maintenance of the earth's electric field, each one making its own contribution to the total effect. They may be briefly described as follows. (Cf. Hess).

1. Photoelectric effect. Even though the most important constituents of the earth's surface (water, ice, stones, plants etc.) are photoelectrically sensitive to a small degree, the spectral regions which are active in exciting them are completely absent in the lower layers of the atmosphere---at least as high up as the border of the troposphere (10 km), the latter being the region within which a vertical temperature gradient exists. It is possible that there is phoelectric emission from the highest cirrus clouds due to the solar radiation, for these clouds contain ice crystals. But in any case, the phoelectrons would at once be joined by neutral molecules and small negative ions would be formed.

2. Ultra-violet light. Another important effect of

the solar radiation is the ionizing action upon the gas molecules through which the radiation passes. There are, in this case, equal numbers of ions of both signs formed, as distinguished from the case of the photoelectric effect, from which only negative ions result. But the chief constituents of the atmosphere (oxygen and nitrogen) are rendered active by ultra-violet light only in the restricted region between $\lambda1200$ and $\lambda1800$ and this region is absent in the solar spectrum below a considerable height above the earth's surface. Impurities, such as carbon dioxide and ammonia, are affected by longer wavelengths than those cited. However, at great heights the ultra-violet light from the sun is the chief factor in producing the intense ionization found there. Much work has been done on this subject by Hulburt, who shows that the aurorae, zodiacal light, the gegenschein and ozone, as well as the phenomena observed in wireless telegraphy can doubtless be explained in this connection. The theories developed agree fairly well with the data actually observed and explain the "drift currents" of the upper atmosphere. We shall quote rather freely the theory of high-altitude ionization as proposed by Hulburt,(4) dividing the problem into several parts.

(i) The uppermost layers of the atmosphere are ionized mainly by ultra-violet light from the sun and somewhat by cosmic radiation (q.v.). The "penetrating radiation from the earth is wholly negligible at these altitudes. The ultra-violet light from the sun produces electron and ion densities here which are in agreement with those inferred from wireless telegraphy. The free electrons formed by the action of the light disappear in three ways: (1) by diffusion into other regions, (2) by combining with positive ions and (3) by attaching themselves to neutral molecules or atoms. In considering such diffusion we assume that each element of volume of the upper atmosphere is electrically neutral and remains so at all times. Thus the potential gradient and vertical electric current vanish. The equal numbers of positive and negative particles in each volume element diffuse about so as to obtain, as far as possible, their equilibrium pressures. The magnetic field of the earth has little effect upon the ionic diffusion unless the pressure of the air has fallen to 10^{-8} atmosphere. With regard to the combination of electrons with positive ions it is to be noted that Sir J. J. Thomson has found that electrons or negative ions, upon collision with a positive ion, combine with the ion only if the energy of recombination is dissipated in such a way as by the action of a neutral molecule. In this "three-body collision" it is assumed that the energy goes into heat and nothing is said of possible radiation. There is no theory now available to account for the attachment of electrons to neutral molecules or atoms, although for the case of oxygen we may assume the following to be true. Attachment of free electrons to neutral oxygen molecules may take place in the rare atmosphere of high altitudes but only after some 10^5 "kinetic theory collisions" have already been made. Such a combination of electrons with neutral oxygen molecules is observed even at ordinary temperatures and pressures, when the electrons and molecules are in thermal equilibrium. At the great altitudes mentioned, attachment of free electrons to neutral molecules of elements other than oxygen is very much less frequent than it is for the case of oxygen.

(ii) An expression is set up giving the relation between the ionization for a certain wave-length in terms of the molecular (or atomic) light absorption coefficient of the gas for the given wave-length, the directions made by the light with the vertical, the total molecular density (number per cc) and the height in cm above the earth's surface.

(iii) Assuming that <u>all</u> the absorbed energy causes ionization, we calculate the number of ion pairs or electrons produced per cc per sec at this height for the regions of the spectrum concerned in the given ionization. If the light be totally absorbed in going down from, say, interstellar space to the level determined upon, then the total number of electrons liberated per sec in a column of 1 cm^2 cross-section and extending from the given level to infinity may be calculated. It may be shown that in the Summer day the number of ion pairs so formed is $2x10^8$ at a height of 190 km, with the sun assumed to be a black body at 6000° K and the absorbed wave-length λ890. Above this level there are $6.6x10^{16}$ molecules in the unit column of air. The number of ion pairs just given is satisfactory for the explanation of the wireless wave effects. On a Summer day most of the electrons are produced above, roughly, the 200-km level. There is thus an electron layer at this altitude formed by by the solar ultra-violet light.

(iv) In the daytime an equilibrium of electron density exists, the time rate of change of density being equal in general to the difference between the rates of production and loss of electrons. A density vs. altitude curve may be drawn, having a maximum at the point where the removal of electrons predominates over the supply due to diffusion. For Washington in Summer, this maximum occurs at a height of 190 km with an electron density of $3x10^5$. A low value of the density occurs very abruptly at about 186 km. The height of maximum density is independent of the intensity of the light but is dependent upon the physical constants of the high atmosphere. This variation of the electron distances agrees with the observed "skip distances," especially the rapid change of the density below the critical height. The wireless waves are apparently reflected from an ionized layer 190 km in elevation. At night the term in the expression for the change in electron density that involves the sunlight vanishes. The high atmosphere cools, the height for a given molecular density is less and the curve is shifted downward about 50 km. This phenomenon agrees with the observations of skip distances at night.

(v) In the attenuated atmosphere of high altitudes ions will have a gravitational drift and, by virtue of the acquired velocity, be equivalent to an electric current. If this drift takes place in the presence of a magnetic field also, it is possible to write the expression for the velocity of the drift in terms of the mass of the ion, the strengths of the two fields and the angle between them. The drift will be perpendicular to the two vectors representing the fields and will occur only when the free path of the ions is sufficiently long (e.g., at an altitude of more than 150 km at a Summer noon). Maris and Hulburt have explained certain features of a magnetic storm by means of this drift current while Chapman uses it to explain the quiet day magnetic variation.

(vi) We must assume that there is an abrupt change from long to short free path ions on the equator at the 150-km level. Above this height the diamagnetism and drift are complete. It is assumed also that the geographic and magnetic poles coincide and that the temperature, to two-thirds of which diamagnetism owes its effect, varies from the equator to the pole along the noon meridian. If the velocity of thermal agitation of the ion be known, the radius of gyration of the ion in a given magnetic field can be expressed at once and hence the curvature of the path of the ion found.

(vii) The total number of ion pairs in a vertical column of unit area in cross-section in the long free path region is calculated in terms of the ion density at the "critical level" (e.g., 150 km). In each cc there are equal numbers of positive and negative ions. Directly under the sun there are found to be 1.5×10^{16} ion pairs in this typical column and this number is that required by the diamagnetic theory of the diurnal magnetic variation.

(viii) The density vs. level curves (cf. sec. iv) are calculated for all latitudes and longitudes of the earth.

(ix) For ionic equilibrium the rate of formation of ions equals the rate of loss, the latter being due to recombination and to gravity diffusion. In considering recombination, only the spatial distribution of the ions is taken into account and two factors are neglected: (a) recombination as a function of the energy states of the ions and (b) recombination by a direct two-body collision, with a transfer of energy into excitation or emission of radiation or both.

(x) In the higher, long free path region, the density vs. level curve is more complex because an electric field is added to the gravitational and magnetic fields. The general direction of the magnetic field being North and the gravitational drift of the ions downwards (thus, for the positive ions, forming an earthward current), there will be and East-West component to the drift, resulting, for the case of the positive ions, in an eastward current and hence an East-West electric field or potential gradient. At night the direction of the gradient will be reversed. The field established in the long free path region causes a motion of the ions in the short free path region below but, in order that the circuit may be complete and all currents accounted for, it is assumed that a fraction of the upper current continues around to the night side of the earth. The values of the current sheets are calculated respectively to be 1.16×10^7, 8.7×10^6 and 2.9×10^6 amperes. The net effect is that of an eastward current flowing perpetually of value about 2.9×10^6 amperes.

(xi) The ions moving directly into the lower region from the upper because of gravitational drift are so much less in number than those produced directly by the sunlight that the drift current between the two regions may be neglected.

(xii) At night the two regions must be treated separately. For the ions of short free path, in the lower region, the decrease in density is about an order of magnitude in nine hours, neglecting the effect of gravity diffusion. (If the latter be not neglected, the decrease will be greater). The ions of longer free path, in the upper region, move upward at night because of the eastward electric field. The new regions being of lower molecular density, the loss from recombination is reduced.

(xiii) A very elementary photochemical action has been assumed in accounting for the 1.5×10^{16} ion pairs: (a) the splitting of a neutral particle into a positive ion and an electron and (b) the attachment of the electron to an oxygen molecule. Possibly the light may form the ions directly, as by breaking, say, a nitrogen molecule into positive and negative nitrogen atoms.

(xiv) The current sheets postulated above give a magnetic field at the equator which agrees very closely with that suggested by Bauer.

(xv) The transport of ions by winds does not enter into the problem.

(xvi) At sunset the liberation of electrons at high altitudes ceases but the ions produced by the photoelectrons are maintained for 48 min thereafter at the daytime production rate.

(xvii) That some other agent than merely ions must be postulated for the conductivity of the atmosphere below 150 km is evident when it is found that even at this level the ion layer is too weak to cause appreciable refraction and absorption of wireless waves even as long as 1000 m. But such effects actually exist, even reflection from an 80-km level, and hence there _is_ light which penetrates below 190 km and produces ions and electrons even as low as the 80-km level. It may be that this wave-length is near the principal series limits of the atmospheric gases. It is known that λ1250 causes fluorescence and maybe ionization. An ionic density of 5×10^9 ions per cc at a level of 110-130 km or 5×10^4 electrons per cc at a level of 130-150 km or a proper combination of ions and electrons at these heights (and a fewer number at lower levels) is sufficient for taking care of the overhead absorption coefficient of wireless waves in agreement with those data that have been observed. As has been suggested in a previous section, calculations based on recombination and diffusion formulas indicate that an ionic density of 10^9 or 10^{10} in the region between 100 and 190 km

(Summer day) or between 80 and 150 km (Winter day) may be expected to decrease by an order of magnitude or so at night, thus causing a marked diminution of overhead absorption, particularly of certain wave-lengths in wireless transmission. It is well-known now that this sort of ionization causing absorption and refraction of radio waves accounts in general for the diurnal and seasonal variation of the propagation phenomena of such waves. The proper mixture of ions and electrons in the upper atmosphere will account quantitatively for many facts of radio transmission: skip distances, limiting wave-lengths, apparent heights reached by waves, overhead absorption, range of waves and seasonal and diurnal variation. The ionization is in keeping with the action of the ultra-violet light of the sun.

(xviii) Charged particles, penetrating radiations and (maybe) cosmic rays are quite unnecessary to consider except possibly in explaining secondary or unusual effects correlating sunspots and radio transmission. It may be that the "non polar aurora" of night sky light is due to solar energy that is stored in the high atmosphere in the form of ionized or excited atoms and then liberated in the form of recombination or other types of spectra. Calculation shows that less than one percent of the solar energy stored in the atmosphere as ionization will suffice to maintain the non polar aurora all night.

(xix) A complete theory of the effects from the high atmosphere must take care of <u>radiation</u> and <u>heat</u>. We should be able to account for the disposition of <u>all</u> the solar radiation from $\lambda 0$ to $\lambda 2900$.

3. Cosmic radiation. By this as a means of atmospheric ionization we mean specifically the hard gamma rays that apparently have been shown to come from interstellar space, and <u>not</u> charged particles and radiation from the sun or even the "penetrating radiation" from the earth. These last effects will be discussed later. Cosmic radiation has been defined as "that small portion of the 'penetrating radiation'' which is of cosmic origin. In the same year (1900) in which Elster and Geitel described their experiments made with a protected electroscope in the open air, C.T.R. Wilson was able to show that ionization can be detected in a small closed vessel containing dust-free air not exposed to any known ionizing agents. (Cf. sec. (4), page 9). It was found that about 25 ions are produced per cc per sec at at atmospheric pressure. There seems to be a certain minimum ionization always present as a normal property of the air. Measurements made underground indicate no diminution because of absorption by the ground of external radiation. Crookes has shown that in a high vacuum a pair of gold leaves can maintain their charge for months, thus indicating a

dearth of ionizable molecules in the vessel. In this case there is nothing upon which the very hard radiation can act. For quite a while physicists doubted whether there are any rays of cosmic origin and a great diversity was found in the values for the intensity by Swann, Hoffman, Kolhorster and Cameron. In 1903 McLennan, Rutherford and their collaborators observed the marked reduction of the rate of leakage of a charged electroscope when lead plates are successively added as a screen, the final thickness of the screen being several cm. It had been suggested by Richardson in 1906 that the radiation is due, at least in part, to causes outside of the earth's influence. Several years later the balloon observations previously mentioned (cf. sec. (4), pages 9 and 10), leading to the conclusions that the "rays," if coming from above, are more penetrating than had been supposed and are thus less absorbed. In order to be sure that there are not radioactive particles of unknown origin spread throughout the upper regions of the atmosphere that might be the cause of the radiation, experiments were performed to measure the absorption coefficients directly. (If there are radioactive substances present, it can safely be assumed that their radiation will not be much harder than that of the known radioactive materials on the earth). In 1923 Kolhorster in Europe and Millikan and Otis in America, using Alpine glaciers and shallow bodies of water at sea level in the first case and thick lead screens at Pike's Peak in the second case, performed the first of a series of experiments to measure the absorption coefficient of such rays. However, the work was not considered as definite evidence that "cosmic" radiation exists. Swann had been convinced that his work on ionization in vessels under 75 atmospheres pressure was incompatible with the cosmic ray interpretation of the phenomena. In 1925 Millikan and Cameron (loc. cit.) sank sealed electroscopes in deep, high-altitude, snow-fed lakes and found that the ionization decreases steadily with depth from 13.3 ions per cc per sec at the surface to 3.6 ions per cc per sec at a depth of 18 m below the surface. An important incident in the experiment was that for the first time the zero of an electroscope was obtained. The readings were repeated 300 mi further South at an altitude 2060 m lower and were found to agree with the previous set after a correction had been made for the layer of air included between the two levels. This layer was found to have the same absorbing power as 6 ft of water. The conclusions drawn from the entire research were: (a) the effects at the mountain lake were not due to radioactivity in the water, (b) the source of the rays is not at all in the layer of atmosphere between the two altitudes, since the layer acted as an absorbing screen, as though the rays entered from above, (c) in different localities 300 mi apart (North and South) there is exact similarity between the rays at the same altitude, (d) the rays come in equally from all parts of the sky, (e) the observed absorption coefficient and the total cosmic ray ionization at the high altitude agrees with the results obtained in the balloon flight and (f) the high altitude rays do not originate in the atmosphere, at least in the lower nine-tenths of it. In 1926 and 1927 two more experiments were carried out, the one in the high Andes, the other in California. The problems to solve were (I) whether there is any latitude effect which might be attributed to high-speed β-particles that are acted upon by the earth's magnetic field, especially near the poles, (II) whether the hypothesis of C.T.R. Wilson were true (viz., that the rays are due to the integration of the effects of the impact in the atmosphere of electrons of high energy from thunder-storms), (III) what was the cause of the wide divergence of the sea-level readings for cosmic rays as found by various experimenters and (IV) whether the Milky Way is more or less effective than other portions of the sky in sending these rays to the earth. Experiments showed that (I) and (IV) gave negative results, (II) could be dismissed---for the lakes in the high Andes are ideally screened from thunder-storms---and elaborate tests showed as to (III) that there is no variation of the sea-level reading with geographical position. Millikan and Cameron agree with Kolhorster as to the mean absorption coefficients but no one else showed the non-homogeneity of the rays ($\lambda 0.00063$-$\lambda 0.00038$), except that Hoffman and Steinke suggested that even harder rays might exist. More accurate readings and sensitive apparatus have permitted much better results to be obtained and the penetrating power of the radiation has been found to be such as to cause effects through 190 ft of water or 16.7 ft of lead. The wave-length range represented is from $\lambda 0.00053$ to $\lambda 0.00021$, the corresponding absorption coefficients (per m of water) being 0.25 and 0.10. In the cosmic ray experiments there habe been three possible explanations of the radiation: (i) that it is caused by atom-building processes, not in the stars but in the depths of space, (ii) that there is atom-annihilation in which the fields of positive and negative electrons overlap and (iii) that there is a condensation of radiation into atoms somewhere in space. These problems arise in modern cosmogony. Millikan and his associates have shown that the cosmic rays have the structure of spectral bands which are interpretable, not in terms of radioactive or disintegrating atomic processes or many-million-volt electronic impacts, but in terms of definite atom-building processes. The greatest wave-length observed in 1925 corresponds exactly to the energy required by Einstein's equation for the formation of helium out of hydrogen. We may, in passing, verify this numerically. Making use of Einstein's equation, $E = mc^2$, where E is the energy equivalent to the mass m and c is the velocity of light, and the relations $\lambda = c/\nu$ and $\nu = E/h$, where λ and ν are the wave-length and frequency, respectively, of the radiation emitted by the loss of the mass m, and h is Planck's constant, we obtain the wave-length (in A.U.) as

$$\lambda = \frac{h \times 10^8}{mxc} .$$

The mass m will be that from four atoms of hydrogen. If A be the atomic weight of hydrogen and N be Avogadro's Number, we may write the proportion $m/0.032=4/4AN$, where 0.032 is the number of g lost when 4AN atoms of hydrogen combine to form helium. Substituting $A=1.008$, $N=6.06x10^{23}$ and $h/c=2.182x10^{-37}$ in the above two relations, we obtain for the wave-length emitted by the combining hydrogen the value

$$\lambda = 0.00045 \text{ A.U.}$$

We have neglected the mass of the electrons in the above calculation of m but what error there may be is inconsiderable in this numerical check.

We can state in conclusion, then, that cosmic radiation is a factor in the ionization of the air but it cannot be classed as one of the most important.

4. α- and β-particles from the sun. Swann (5) has shown that there is an absence of ionization by electrons with speeds comparable with that of light and we might safely infer that the same reasoning would apply to α-particles, which, though heavier and less deflected by the earth's magnetic field, would have far less penetrating power when once the atmosphere was reached. Such particles, of both signs, might supposedly be shot from the solar atmosphere as a result of a sort of radioactive disintegration. The fundamental difficulty is that, if extra-terrestrial electrons be the entire source of the atmospheric ionization, there would be an entry of 1500 per cm^2 per sec. If their velocity be 95 percent of that of light, 40 ions would be produced per cm of path and hence we should expect 60,000 ions per cm^3 near the earth's surface. Actually, there are about 1/10,000 of this number, and even this fraction may be accounted for by other causes. But we can further observe that even if there were these high-speed β-particles entering the earth's atmosphere, intense ionization is not to be expected. The reasoning is as follows. Let a high-speed "corpuscle" pass near the electron in an atom along its path.. The electron in the orbit will be ejected if the energy imparted be sufficient. But the

greater the velocity the less the time in which momentum can be received by the orbital electron. As the velocity of light is approached, the field of the corpuscle crowds up towards the equatorial plane and the time for acting is still further reduced---but the field intensity, while it lasts, is increased. Bohr has shown that if nothing else be considered, the energy communicated to the free electron in the atom will be unaffected by the concentration of the field. The radiation of energy, even from the impartation of a small amount of energy, may be large if the time be very short. The nearer the velocity of the flying corpuscle is to that of light, the more suddenly does the corpuscle communicate energy to the electron. If the velocity ratio be 95:100, but not so great as to involve radiation considerations (for we can assume that the radiation is proportional to the square of the acceleration), Swann shows that the corpuscle must approach the electron in an atom of oxygen to less than 0.7×10^{-10} cm in order to impart enough energy to insure ejection from the atom. If the minimum distance of approach be less than this, the energy communicated will be greater; and conversely. In fact, a velocity can be assigned so high that the corpuscle will be unable to eject an electron from the atom at all. Calculation shows that the difference between the velocity of light and the velocity of the β-particle would have to equal to, or greater than, 45 m per sec in order that the corpuscle be able to produce ionization of the atom. This value is for oxygen, the most easily ionized constituent of the atmosphere. As a matter of fact, the ionization actually ceases for a velocity difference greater than the value cited. The latter is what Birkeland assigns to solar electrons if a bending in the earth's magnetic field is to account for the aurorae. If the β-particles were slower, the deviations would be too great. It is the increase in the *mass* rather than in the *velocity* that results in a diminished bending. If the present theory were true, the corpuscles cited by Birkeland could not ionize at all; but it is now believed that aurorae are really caused by high atmospheric ions (4'). In order that an electron, shot from infinity in the equatorial plane of the earth, might reach the latter without being turned back by the magnetic field of the earth, the velocity would have to be much greater than the value calculated above, for with such a value the distance of nearest approach would be 32,000 mi. With regard to the absorption of the high-speed β-particles by the atmosphere, it is to be remarked that in 1915 Bohr gave the theory which predicts the decrease of the velocity of swiftly moving particles in passing through matter. But the range of the particles found experimentally does not agree with the theory. If electrons could reach the earth's surface because of their high velocity and in spite of the magnetic field, they would pass right through the atmosphere with little absorption and fail to ionize the air.

5. Radioactivity of the soil and air. (Cf. Hess). The work of Elster and Geitel and of Rutherford and Allen has already been mentioned (page 4). It is now known that the earth's crust, terrestrial bodies of water and the air contain greater or less amounts of radium, thorium and actinium, in the form of compounds or their products. The earth's crust also contains uranium and the other radioactive elements and their decomposition products as well, but bodies of water, and stagnant air in caves and circulating air out-of-doors, do not in general give evidence of the presence of these substances. The "active deposit" frequently found on dust or cloud particles is the result of the breakdown of an "emanation" of radium, thorium or actinium. The α-particles emitted in the breakdown will collect upon negatively-charged wires. The short-lived emanations of actinium and thorium are not found far from the earth's surface and the radium A content has been observed to be smaller by a factor of 1/10 to 1/100 at a height of some 3 m than what it is at the ground. The emanation content falls off rapidly with altitude and in

certain regions it is very erratic: practically zero at a certain height and fairly intense below this level. In general it may be said that volcanic rocks are richer in radium and thorium than are sedimentary rocks, from which the radioactive constituents were probably dissolved away during formation. The radium content of most minerals is about 10^{-12} g of radium per g of mineral, while the uranium content may be $3x10^6$ times as much. The thorium content is around 10^{-5} g per g of mineral. Since most salts of uranium, radium and thorium are soluble in water, these elements are found in lakes and traces of radium emanation are found in spring waters, often along with an appreciable quantity of dissolved radium. But the emanation content of spring waters and natural gases (including the vapors from volcahoes) is important to atmospheric electricity only at certain places. All samples of earth give off emanation and the soil gases that are in intimate contact with the "soil capillaries" of the earth contain radium and thorium emanation. It has been estimated that the mean value of the amount of radium emanation in the soil gases is 2000 times as great as the average emanation content of the free atmosphere. In the earth's crust, granite formations are the most radioactive and sandy soils are the least. Weathering is a very important factor since it brings out the activity of some rocks of less total activity sooner than it brings out the activity of other rocks that are of more resistant materials and perhaps possessing a greater intrinsic amount of that property. The emanation accumulates at greater depths during heavy rains or surface freezing, while a warming of the soil---as by strong sunlight, strong winds, or a fall of barometric pressure---tends to enhance the external effect of the emanation by drawing it out from the soil. It is believed that at a depth of from 1.5 to 2 m the emanation content of the soil gases becomes constant. Sanderson and Bloc estimate that more than half of the total ionization of the soil gases is due to the activity of the thorium products. However, the exhalation of these gases into the atmosphere is more important for our study. The average amount of radium emanation entering the atmosphere per cc per sec is 0.74×10^{-16} curie. (1 curie is the amount of radium emanation that is in equilibrium with 1 g of radium, where by "equilibrium" between a radioactive substance and its products is meant the condition in which the loss of one by disintegration is just equalized by the formation of new by the decomposition of a higher order). The percentage (10 to 20) of thorium activity in the total activity decreases with altitude but it has been shown that radium emanation is responsible for from 1.5 to 5 times as much ionization as that produced by the emanation of thorium. Measurements of the complete precipitation of the radium and thorium decomposition products from a definite quantity of air are made in two ways: (1) in moving air, using the Gerdien process and (2) in still air, using the method of Eve. Swann calls attention to the fact that probably quite a number of the positive ions from radioactive disintegrations recombine with negative electrons and hence introduce an uncertainty in the observed results for the radioactive content of the atmosphere. Salpeter, assuming that there are 700 negative ions per cc and that the coefficient of recombination is $\alpha=3\times10^{-6}$, calculates that 64 percent of the radium A carriers are charged, but this can only be regarded as giving the order of magnitude of the quantity. Over the sea the radioactive decomposition products are appreciably smaller in amount. The activities (in curies per cc) over land, near land, and far out at sea are, respectively, 100×10^{-18}, 7.99×10^{-18} and 1.14×10^{-18}. It is evident, then, that the radium emanation comes from solid parts of the earth. If it came from the sun, it surely would have been detected before this on the "Carnegie" cruises. That the presence of emanation or its products in the atmosphere is closely connected with the ionic content and conductivity is seen by the observations of the variations of both phenomena: the two elements increase when the emanation, radium A and radium C increase. Such seasonal variation as has been detected in the radioactivity of the air depends upon the wind and the rainfall. If there be any diurnal variation, it must needs depend upon the wind, for it has been observed that the activity is greater in the stagnant air near the ground at night than in the daytime, when there is a liklihood of winds and convection currents. The question arises as to whether the radium emanation content as observed near the surface of the ground can be explained by considering an equilibrium which may exist between the increase due to the aspiration from the soil and the decrease due to the removal to higher layers by vertical air currents and to decomposition into other products. Experimental data and the assumptions as to exchange by irregular currents in the air indicate that the concentration of thorium emanation at 160 cm above the ground is but 10 percent of its value at the ground, while the concentration of the longer-lived thorium B is reduced to 50 percent of its ground value only at a height of from 100 to 150 m. End-products of the radium series (Ra D to Ra E) are present without diminution to a height of about 10 km---provided that other factors do not enter in. The concentration of radium emanation is calculated by Schmidt to be 50 percent at a height of 13 m of what it is at 1 m and 1 percent at 150 m. Pure diffusion of emanation from the soil (i.e., without the agency of wind, sunlight, reduced barometric pressure, etc.) can hardly account for one-tenth of the total measured amount in the air. At sea some radium emanation may be given off by the spraying of wave crests and by evaporation but it is very likely of small amount. Freshly-fallen snow or rain contains traces of radioactive substances, as was shown by C.T.R. Wilson. These substances are chiefly radium A, radium B and radium C---the decomposition products of radium emanation. Snow lying on the ground can contain emanation from the soil itself as well as what is acquired by the slow drift downwards through the atmosphere. M. Curie has shown that the radioactive carriers can act as condensation nuclei.

6. Penetrating radiation. This source of atmospheric ionization is a mixture of several factors. It usually refers to the residual effect observed in closed vessels after all the radioactive substances originally present have disappeared. The activity is due to radiation of short wave-length coming from the outside and also to traces of radioactive substances in the walls of the vessel, or possibly to some peculiar activity of the material of the walls. The radiation that arises from the last two causes is called the "residual radiation" or "wall radiation."

The gamma-radiation of the substances in the earth's crust ("earth radiation") and in the air itself ("atmospheric radiation") and the above-mentioned <u>hohenstrahlung</u> are possible explanations of the ionization observed. But we do not need to discuss at any length this source of ionization as if it were something different, for the "penetrating radiation" may be traced ultimately to either radioactive substances in or on the earth or to extra-terrestrial sources. What affects the air inside observing vessels does not directly concern our present case.

7. Dust, snow, combustion products and spray. It has been observed that very large negative charges sometimes accompany dust clouds and thus local variations of the atmospheric-electric elements may occur of considerable amount, and be very erratic in nature. But we can scarcely regard dust as a source of atmospheric ionization, for the charge on the particles is seldom created by the latter but is due to ions originally present in the air. It is true that charges can be generated by friction and then separated by air currents and probably some of the ionization of the air---especially of the sort caused by snow---is produced in this way. What applies to dust particles will apply to soot, smoke and such products of combustion. The spraying of a liquid is, however, itself a source of ions. Lenard (1892) found that the newly-formed drops of

water are positively charged and that the surrounding air is negatively charged. This ionization occurs also when larger drops break up into smaller ones, an effect which is important in Simpson's theory of the thunder-storm (q. v.) When drops of water impinge upon a solid wall, when a stream of liquid is broken up or splashed (as, for instance, gasoline in tanks or in cleaning operations) and when gas bubbles through a liquid or bubbles break on the surface of a liquid there is an electrification of the surrounding region. This does not occur with mere evaporation. Lenard explained these phenomena as being due to two extremely thin electrical layers within the liquid. The order of magnitude of the thickness of the layers is that of the molecular sphere of influence (c. 10^{-6} cm). In pure water the negative layer is uppermost so that the residue is positively charged. Rapidity of ejection through this outer layer is essential in that recombination must be prevented. A slow division of the drops or formation thereof is not enough. Busse has shown that any type of rapid division, such as bubbling or impact of drops upon an obstacle or (especially) spraying, produces positive ions. Upon Lenard's theory the outer negative layer goes first and then the positive. In any case the ions are of the Langevin type but are of wisely varying mobilities. If even minute quantities of sodium chloride or sulphuric acid be added to water, there is an excess of positive ionization. Although the ionizing action of spraying etc. is very great in certain localities, where there are waterfalls, rapids, breaking waves and surf, yet on the average over the earth's surface it makes no important contribution to the total ionization. Near ocean surf there is a high positive potential gradient while near places where fresh water is scattered, as at waterfalls, the surrounding air is very considerably negative. Even over the sea the effect of spray is not great, for it is found that the mean value of the potential gradient is even lower there than it is on shore. None of these effects can be estimated with any accuracy and, as far as conductivity measurements are concerned, the ions formed are so large that their effect is negligible.

8. Other ionizing factors. In the laboratory ionization can be produced by chemical means, by flames, by heated metals and salts and by ionic collision. Of these agencies, only the last is to be considered in the subject of atmospheric ionization, and even then we discuss it only in connection with lightning discharges. Ionic collision, as an ionizing agent, does not start much below a field strength of 30,000 volts per cm. It is possible that corona discharges, St. Elmo's Fire and other silent electrical phenomena can be explained in terms of intense local

ionization, where, however, conditions are not ripe for a disruptive discharge. C.T.R. Wilson considers the ionizing effect of thunder-storms very important, taking the earth's atmosphere as a whole, yet the work of Millikan and Cameron (loc. cit.) apparently disproves the theory.

DESTRUCTION OF IONS

A few words should be said regarding the destruction or disappearance of ions. There is a distinction between the removal and the destruction of ions which has been well emphasized by Hess.([illegible] .

(1) Removal of ions. Ions tend to diffuse from a region where they are more concentrated to one in which they are less so. They are also adsorbed by contact with solid or liquid surfaces, such as water, rocks, vegation, soil capillaries and atmospheric particles (solid and liquid). Ebert has calculated that the adsorptive effect near a solid or liquid surface is only important throughout a layer of gas 0.01 mm thick next to the surface. The effect is essentially an electrostatic one. In general the negative ions diffuse faster than do the positive. Adsorption of ions by soil capillaries and the later diffusion of the ionized air into the outer regions have been discussion already under Radioactivity. There is also the mechanical transportation of ions by convection currents

in the air and by winds, as these are ever present in the atmosphere. Ions are also moved by electric fields. The potential gradient set up by the separation of some ions causes the motion of others.

(2) Actual destruction of ions. We have seen that a certain percentage of the radium A carriers must be uncharged, which means that there is much recombination of unlike charges in the atmosphere, for these radioactive bodies are but a fraction of the total number of charged particles present. The recombination of ions is so important that much work has been done to find an expression that will take care of ions of all sizes, adsorption etc. Recombination will be more rapid the greater the number of ions of each sign present in the gas. If there be n ions of each sign per cc and q pairs of ions be formed per sec per cc by an ionizing agent, the simplest theory gives the change in the number of ions of (one) sign as

$$\frac{dn}{dt} = q - \alpha n^2,$$

where α is the "recombination coefficient." We have assumed that there are only small ions present, in equal numbers, and that recombination is the only cause of ion "loss." The dimensions of α are L^3/T and its numerical value lies between about 1.5×10^{-6} for dry, dust-free air and about 4.5×10^{-6} for ordinary free air out-of-doors, or, for air in cellars, about 6.5×10^{-6}. The difference between the dust-free and the "ordinary" air is doubtless due to recombination, in the latter case, between large and small ions. The numerical values just given for α are really too small. Schweidler was the first to attempt to work out a complete theory that would take care of the recombination of ions of all sizes as well as the agglomeration of ions to uncharged nuclei. When there is equilibrium between the production and the destruction of ions the simple theory gives $q=\alpha n^2$. If the number of uncharged nuclei be N_1 and the number of large ions be N_2, then a new term may be added to the above equation, viz., γnN, where γ is a new recombination coefficient between n and N, the latter being equivalent to N_1+N_2. Thus the previous expression of equilibrium becomes

$$q = \alpha n^2 + \gamma nN,$$

and, if γN be written as β and $\alpha'=(\alpha + \beta/n)$ be taken as a more comprehensive recombination coefficient, the better relation

$$q = \alpha' n^2$$

is obtained. Schweidler, using the method already employed by Rutherford and McClung, determined α' for the case of artificial ionization. Experiments at Innsbruck give α' a mean value of 29×10^{-6}. Because α' is so high, an ionization of 10 to 15 pairs of ions per cc per sec in air rich in nuclei may only product 1000 ions per cc. Because of the absence of nuclei over the sea the ion number is as high there as over the land even though the ionization is very much less. Because α' is itself a function of the number of ions, Schweidler writes a "linear law of recombination" as

$$q = \beta' n,$$

where $\beta' = \alpha' n + \beta$ is known as the "diminution constant" and represents that fraction of the existing light ions which disappears in unit time through recombination in all ways and through agglomeration (adsorption). Since $\beta' = q/n$ is the rate of production of ions per ion present, the reciprocal $\Theta = n/q$ signifies the "average life" of the small ions. Thus when $\beta' = 16 \times 10^{-3}$, $\Theta = 62.5$ sec. Of course, it is far from true that all collisions between positive and negative ions result in recombination and neutralization of the charges. The fraction of the total number of collisions that does so result in neutralization has been found by Kohlrausch to be 0.45 for free air and by Langevin to be 0.27 for very pure dry air. Recombination between large ions themselves is almost negligible. The coefficients of recombination between small ions and nuclei and small ions and large ions are nearly ten times as large as the coefficient of recombination for small ions themselves. Local conditions affect the values of the coefficients. At Dublin the number of large ions was at one time found to be 10,000 per cc and the number of small ions 116; at a small village on the Irish coast the respective quantities were 1000 and 700.

IONIZATION BALANCE

We have seen that near the surface of the earth (e.g., up to a height of 1 m) the only important ionizaing agents are the radioactivity of the soil and air and the ultra-gamma radiation from space. It will be well to calculate whether these two sources can account for the disappearance rate that is observed. (Cf. Hess, p. 167 ff). The amount of emanation that is normally in equilibrium with 1 g of radium has a volume (under standard conditions) of 0.63 mm^3 and a mass of 6.01×10^{-6} g. This amount of emanation is "1 curie." The amount of the emanation in the atmosphere may be taken as 130×10^{-18} curie per cc. Since 1 g of radium gives off 3.72×10^{10} α-particles per sec, the number of particles in the emanation will be $3.72\times10^{10}\times130\times10^{-18}=48.3\times10^{-8}$ per cc. A table may now be prepared, based on data obtained by Eve, Hess et al. as follows, giving the value of "ion pairs per cc per sec" ("I") produced by the several sources.

I. Rate of Formation of Ions. Value of I

(a) Ionization in the air from 1 α-particle.
Radium emanation.........1.69×10^5
Radium A.................1.84
Radium C.................2.37
Ionization due to 48.3×10^{-8} α-particles
is then $48.3\times10^{-8}\times(1.69+1.84+2.37)\times10^5$...2.85
Ionization due to thorium products
(about 60 percent of the above)..........1.70
Ionization due to β-particles.................0.20
Ionization due to gamma-radiation............0.15
Total ionization from the air itself.........4.90

(b) Ionization due to β-particles from earth......0.10
Ionization due to gamma-radiation from earth..3.00
Total ionization from the earth itself.......3.10

(c) Estimated ionization due to ultra-gamma rays..1.50

Total amount of ionization due to all chief
causes in the earth, atmpshere and space...... 9.50

II.
III.Estimated loss of ions..........................12.25

The following statements and qualifications should be made with regard to the foregoing.

1. Fairly good agreement can be observed between the rates of formation and disappearance of the ions, considering the assumptions made.

2. The effect of the actinium products has been neglected.

3. α-particles from the earth are not effective as high as 1 m, especially when there is vegetation.

4. The average radium content of the ground is to taken as 2×10^{-12} g per cc.

5. The effects of the β-radiation from uranium X_1,

uranium X_2, radium, radium D and radium E are all small because of the low penetrating power of the radiation.

6. The β-radiation from the decomposition of emanation is neglected. The earth's field will, according to Schweidler, form a surface deposit.

7. The gamma-radiation effect has been corrected for the secondary radiation from the walls of the observing vessel.

8. The ultra-gamma radiation is difficult to estimate as the proportions of the ionization due to this and to the secondary radiation mentioned in (7) are unknown. There will always be secondary radiation from the ultra-gamma rays. It is assumed that at the earth's surface this radiation is the same as that from a vessel, as in (7).

9. About half of the total ionization of the air is due to radioactive substances, the effect of which vary from 0 (mid-ocean) to 30; the earth radiation may vary between 0 (over water) and about 15; the cosmic radiation portion is, of course, fairly constant, since it enters the atmosphere from above and is independent of the surface below it.

10. Taking the mean number of small ions in the air as $n=700$ per cc and the "diminution constant" as $\beta'=17.5\text{x}10^{-3}$ (a mean between $16\text{x}10^{-3}$ and $19\text{x}10^{-3}$), the loss of ions per cc per sec is 12.25. We assume that there is a much larger

number of large ions and dust nuclei over land than over the sea.

The early assumption that emanation from dry land would be carried out to sea has been given up because it has been found that the content of the emanation is about 100 times as small in regions far removed from land as it is on land and yet the area of these distant oceanic regions is nearly half that of the earth's entire surface. The ionization over the sea is not yet entirely explained, for neither the radioactive substances in the air nor in the water play an important part. The thorium products are absent and the radium products are very weak. Simpson has estimated that the total gamma radiation of all the elements in the radium group in the sea only accounts for 0.01 ion per cc per sec. However, a very important clue is given to the problem by the knowledge of the existance of cosmic radiation. This is sufficient to account for the ionization found at sea if a small number of nuclei be present. The ion number is too great if we assume that all the ions are small. It is likely that there are present minute particles of the various salts that have been dissolved in the sea water and then thrown into the air from evaporated spray. These act as nuclei. The spray itself produces some ionization, as we have seen, but there is a tendency to overestimate it. The value of n actually observed at sea is from 500 to 600, considerably less that obtained if all the ions be assumed to be small; it is possible that the larger ions present escape detection but the trouble probably lies in the use of the simple equation $q=an^2$ in the calculation of n.

THEORIES OF THE THUNDER-STORM

1. Elster and Geitel Theory.

An electric field already is in existance and the raindrops are "influenced" or polarized by it so that, say, the upper portion of the drops is negative and the lower portion positive. Raindrops, in the form of fine spray, are blown against these drops and, rebounding (though without coalescence), take with them some of the charge on that side of the larger drop. The winds then whisk these smaller drops to other heights and as a result there is a separation of the electricity in the cloud, aided very considerably by the precipitation of the heavier drops. This theory implies that there is a tendency for the original field to increase, rather than to decrease, as we should suppose. At the time of collision there may be splashing of the drops, with attendent electrification.

2. C. T. R. **Wilson** Theory, (6).

The mechanism of the thundercloud is either like that of a frictional machine (proposed by Simpson) or like that of an influence machine (proposed by Elster and Geitel). The former describes the thundercloud as being negatively charged on top and positively charged at the base; the latter theory states the converse. The rate of separation of the positive and negative charges when the raindrops are broken up (cf. the Lenard Effect) indicates that a current of several amperes and a P.D. of perhaps 10^9 volts are present in the cloud. The charges may recombine either by "short circuits" between the poles of the cloud or by continuous or discontinuous discharges through circuits that may involve the earth and an elevated point upon it, or the cloud and the upper atmosphere. There are three effects produced by the electric field of a thundercloud that are of interest as possible sources of atmospheric ionization.

(i) Ionization in the upper atmosphere. When the electric forces due to a cloud of given electric moment at a large horizontal and vertical distance are calculated, the mean value of the electric moment of a lightning flash is found to be of the order of 3×10^{16} ESU-cm and, in fact, the mean electric moment of a cloud on the point of discharge is probably greater than this. As the height of the cloud increases, the electric force exerted by it falls off rapidly, as the inverse square of the distance. On account of the rapidly decreasing density of the air, the electric force required to produce sparking falls off even more rapidly and at a certain height the former will exceed the latter. At the height of 60 km the density of the air is but 1.6×10^{-4} of what it is at the ground and so at this height the critical field value is but $30{,}000 \times 1.6 \times 10^{-4} = 4.8$ volts per cm, the sparking potential at the ground being taken as 30,000 volts per cm. The corresponding electric moment is 1.7×10^{18} ESU-cm. We could assume, then, that by the time the next 20 km was reached the thundercloud, if its moment increased but 10 percent, would produce a field which would exceed the critical value and sparking would occur. Hence it is probable that a thundercloud itself could cause ionization in the upper atmosphere. However, we can assume that there is a conducting layer with its lower boundry at this elevation (i.e., about 80 km=50 mi). The cloud will drag ions out of this field, of a sign oopposite to that of the nearer pole of the cloud. If the field strength be above a certain value, these ions will cause ionization by collision; if the effect be strong and persist for quite a distance downward, a discharge of the upper pole of the cloud may occur to the upper atmosphere, as previously suggested. If the ions dragged out of the cloud be electrons, a lower critical ionizing field is sufficient. As a matter of fact there are usually several clouds in the neighborhood and it is their combined effect that is observed. A large rain cloud might even produce discharges into the upper air. It is likely that "atmospherics" are caused by these high-altitude discharges. These "strays" often originate in regions of rain where there is, however, no thunder.

(ii) Ionization by point discharge from earth-connected conductors. Due to the intense fields beneath thunderclouds it is comparatively easy to obtain brush discharges from pointed earthed conductors, grass, trees etc. It has been found that an appreciable discharge takes place from the ends of grass blades when the latter are negatively charged in a field of 15,000 volts per m. The field has to be increased about 33 percent to obtain the same effect if the grass be positively charged. The current increases very rapidly as the potential gradient is increased. The vertical current is, for all except small heights, proportional to the square of the field strength and inversely proportional to the height (h). If k be the mobility of the ions, F the vertical electric force and δ the ion density, the vertical electric current (charge x velocity) per unit area is

$$i = k \times \delta \times F$$

But

$$\frac{dF}{dh} = 4\pi\delta = \frac{4\pi i}{kF}$$

or

$$kFdF = 4\pi idh,$$

giving

$$F^2 = \frac{8\pi ih}{k}.$$

The current and ionization given above are what we should expect if the field below the cloud were maintained almost up to the sparking limit. The rate of separation of charges within the cloud must exceed the value of this current in order that a discharge may pass from the cloud to the earth. The case cited is an ideal one and it is safe to assume that in practice the situation is complicated: e.g., the sparking limit in the lower field may be reached only as a result of discharges of the upper pole of the cloud into the adjacent air.

(iii) Production of penetrating radiation. The intense electric fields of thunderclouds will have an important effect upon any β-particles that may be present. But for the field they would lose their energy along their path by ionizing and otherwise affecting neighboring atoms. The energy falls off approximately as the square of the velocity. The field of the cloud may well compensate for the loss of energy if the velocity be sufficiently high and velocities approaching that of light may be easily reached by the β-particle. The limiting value of the rate of loss of energy is less than 1000 volts per cm. The chances of accidental deflection out of the accelerating field become less and less as the energy of the particle increases. β-particles are doubtless continually emitted in the strongest parts of a thunder-storm field and elsewhere and, along with many that are secondarily produced, attain tremendous velocity ---their energies exceeding those of the fastest β-particles from radioactive substances. The final energy may be that of a 10^9-volt drop. Such particles might be expected to have profound effect even upon the nucleus of an atom, for at these speeds the mass will be comparable with that of a hydrogen nucleus. At very great heights, of course, the magnetic field of the earth will tend to counteract the electric field of the thundercloud and the β-particles will tend to follow the lines of the magnetic field. The corpuscular radiation due to the thundercloud, and the gamma-radiation which it produces, may constitute a penetrating radiation similar to that which is found in the atmosphere. The conclusions of Millikan and Cameron (loc. cit.) do not agree with this theory, however.

3. G. C. Simpson Theory ([3]).

This theory follows as a result of many observations at Simla, India, at an elevation of about 7000 ft. The amount of rainfall and the charge on the rain were automatically recorded, as well as the potential gradient and the occurrance of each lightning discharge. The Simpson

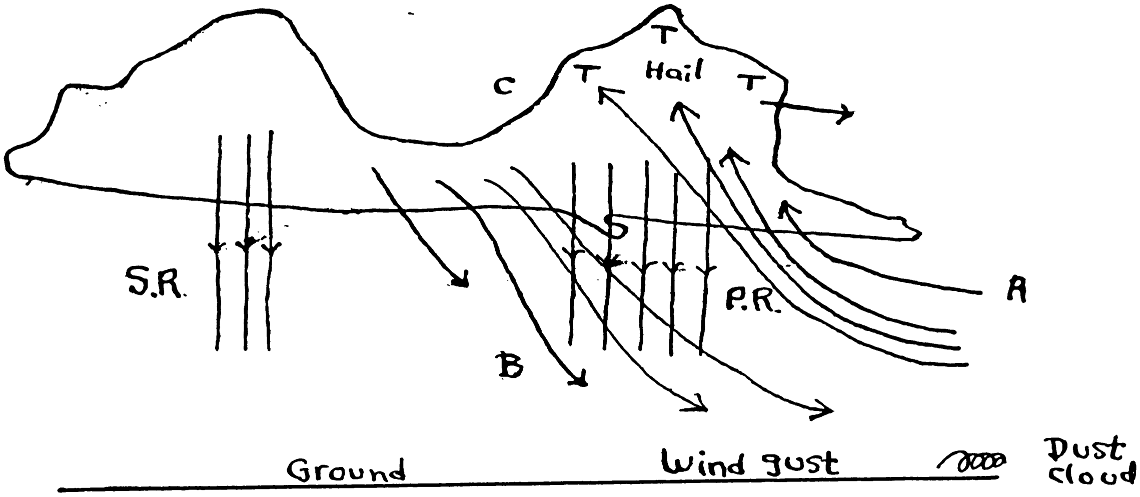


Fig. 1

theory of the <u>heat type</u> of thunder-storm is as follows. The cumulus cloud C (Fig. 1) with thunderheads T is drifting

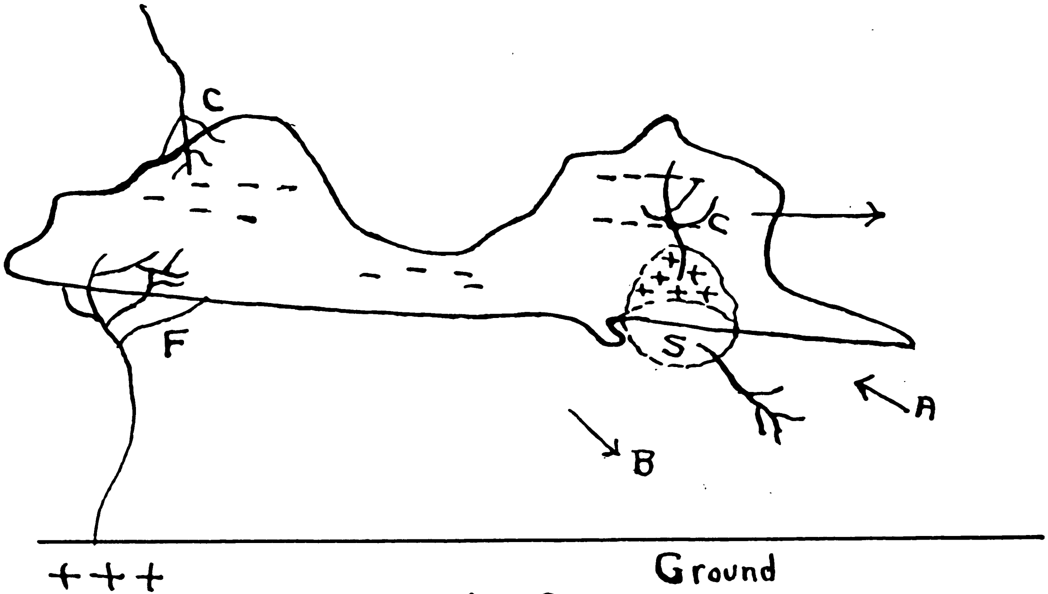


Fig. 2

to the right, against the wind entering the base upwards at A. The streamlines show the warm, ascending air current and the cool, descending air current, the latter being evidenced by the "wind gust" and the "dust cloud." (This is the ideal thundercloud, to illustrate the theory). Coming with the descending breeze is the "primary rain " P.R., composed of large drops. Following this first rain there is usually a lull and then the gentle "secondary rain" S.R. The wind velocities in the cloud are indicated by the relative closeness of the streamlines. The greatest velocity occurs forward of the "scud roll," through an oval region denoted by S (Fig. 2). The wind velocity here may be as high as 8 m per sec and since no drop of water with a diameter of 0.5 cm or more can fall through air with a velocity greater than 8 m per sec, large drops cannot fall through the opening at S. They are unstable and will be broken up by the wind and driven upward again. The littlest drops will follow the streamlines in the cloud. There will be a fairly large region above S in which rain is accumulating, extending perhaps to a height of 4 km. This water, falling back of the cloud opening, will appear as the primary rain. If the updraft of air be very violent, the rain may be blown up to and above the zero degree isothermal surface and hail will form, each excursion of the particle meaning a new shell of ice. Electrically, the state of affairs is as shown in Fig. 2. By the Lenard Effect the breaking of the drops by the wind creates positive charges, the surrounding air becoming negatively charged. The light, negative ions are carried by the wind far up and back into the cloud, while the positively charged water falls as the primary rain. The effect of the wind is spiriting away the negative ions is, of course, slightly resisted by the electric field, but the effect may be neglected. If the drops fall only to be broken up again, they receive an additional positive charge. After repeated operations of this kind the rain is highly positive and the cloud highly negative. "Chain lightning" C may pass between the region of extreme condensation and the rest of the cloud, or between the negative region and some distant positive portion of the cloud or even to some adjacent cloud. Lightning discharges may even take place before the rain comes, as shown between A and B. In the case of discharges between the cloud and the earth, the phenomenon occurs between the lower part of the cloud, where the light rain has already concentrated the charge, and the positive image on the earth's surface. Such discharges, as F (popularly known as "forked lightning"), may cause damage to the point from which they originate. Electrification in the thundercloud takes place wherever rain is falling and the relative velocity between the falling rain and the upward-moving air produces a separation of the positive and negative electricity. These regions are relatively unimportant, however, as high field strengths are not developed here. It is assumed that a lightning discharge always starts from a positively charged element and branches towards the negatively charged element, the sinuous path being caused by varying ionization. Flashes are, in reality, multiple, the successive bifurcations dying away as the discharges follow more and more the central, better conducting, path. A lightning discharge may be considered as the first quarter cycle of a very steep, highly-damped, high frequency wave. On Simpson's theory it is assumed that, at least as regards strokes within the cloud itself, after the sparking potential has been reached in any part of the atmosphere, a discharge starts at that point and progresses along a channel which constantly extends away from the origin of the positive charge. There is a further branching out into regions where the initial field is much below the sparking potential. It is possible that the discharge never reaches the negative charge towards which it is directed. The current is always carried by the electrons. The electric field may be very complicated within a storm, with portions of varying strength and different sign. Damage from lightning is less in tropical countries because the region S is higher and the flashes are not long enough to reach the ground. In the case of cold weather storms, the breaking of the raindrops is replaced by the friction between ice crystals etc.

STATEMENT OF THE PRESENT RESEARCH PROBLEM

The work was started in the Spring of 1926 in the laboratory of physics at the University of Cincinnati. The problem was to measure the space charge at essentially ground level by the method employed by Obolensky (7), simultaneously with the measurement of the potential gradient in the immediate neighborhood. Because of delays in trying out various means of aspirating the air and measuring the charge, no data of value were taken at Cincinnati until the Spring of 1930. In the Summer of 1928 an observation hut was built on the plains of the island of Martha's Vineyard, Mass., and the absolute value of the potential gradient was obtained there for a number of weeks in that and the following year. In 1929 some data on the space charge were taken, as well. The data obtained in 1928 and 1929 are on file with the Department of Terrestrial Magnetism of the Carnegie Institution at Washington. The absolute value of the potential gradient cannot be obtained at the laboratory in Cincinnati, owing to the very irregular topography, nor can a reduction factor be determined. It was found satisfactory enough, however, to measure the values of the potential of a collector-wire supported at a constant distance parallel to the side of the building at a considerable height above the ground. (Photographs of the apparatus and general set-up accompany this report). The maxima and minima of the potential as measured correspond to the times of maxima and minima of the true potential gradient.

The theory of the space charge measurement is as follows.

If v_t be the volume of ionized air drawn through the Faraday pail in the period of observation t and d be the deflection of the electrometer of sensitivity s, the charge is

$$q = \frac{C \times d}{s},$$

where C is the capacity of the system, comprising the electrometer, Faraday pail and connections. The space charge will then be

$$Q = \frac{q}{v_t}$$

$$= \frac{C}{s} \times \frac{d}{v_t}.$$

If d be measured in mm, v_t in ft^3, C in cm and s in mm/volt, Q will be expressed in ESU/m^3. The working equation then is

$$Q = k \times \frac{d}{v_t},$$

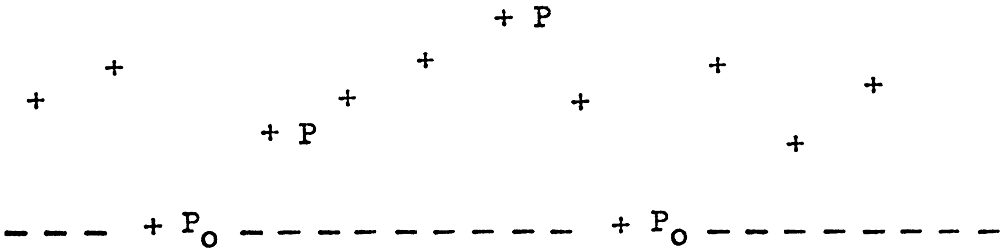
where k includes the value of C, the ratio between ft^3 and m^3 and the ratio between the volt and the ESU of P.D. The value of s is that for the scale distance actually used. Since 35.2 ft^3=1 m^3 and 300 volts=1 ESU, a typical value of k is 0.0072 when C=61.6 cm and s=1000 mm/volt. s and k are to be determined each day. The electrometer need not be grounded or brought to zero before taking a reading, as the quantity d may be expressed as the difference $r - r_o$ between the final and initial scale readings, provided r_o be not too far from the center of the range covered in determining s. The volume of the air aspirated is the difference $R - R_o$ between the final and initial readings of the gasmeter. We shall describe separately the work done at Cincinnati and at Martha's Vineyard, dividing the discussion between the two atmospheric-electric elements. Diagrams and graphs are given later.

Research at Cincinnati

1. Description of the apparatus.

The space-charge apparatus, shown in Fig. 1, was inclosed in a large wooden box AB which was lined with tinfoil. The latter was earthed. The Faraday pail FP rested upon sulphur supports and for most of its length was tightly filled with steel wool of fine grade. The purpose of the wool was to catch all the ions, regardless of size. The wool was held in place by a piece of metal screening S. The connection between the Faraday pail and the aspiration system, comprising the gasmeter G and the rotary blower, was made by means of a tube of sulphur TS which was formed on a lathe from a piece of warm, cast sulphur. The Dolezalek electrometer E was placed at the far end of the box, the end of the tube supporting the moving system projecting through a tin disc D so that the torsion head could be turned from outside the box. A scale Sc, a lamp L and a telescope T comprised the optical system. The entire apparatus was shielded from fields outside the building by fine-meshed copper netting C, which was grounded. A tin funnel and pipe FP', the inner end of the latter closed by a perforated metal disc, projected through the window board WB; the smaller end of the funnel was inside of the Faraday pail but did not touch it. Thus a small amount of air entered the pail from the laboratory---probably very much less than entered from the outside.

The potential gradient apparatus, shown in Fig. 2, rested upon a heavy baseboard BB. The entire apparatus was enclosed by opaque curtains on account of the photographic paper which was employed for the automatic records. The Dolezalek electrometer E was provided with a copper damping vane (the damping vane house shown as D) and a damping magnet M. The wire from the outside air was brought to the electrometer through a carefully insulated lead-in, shown in detail in Fig. 3. A very simple type of chronograph C was set up opposite the electrometer. By means of clockwork (not shown in the diagram) the light L was turned on once every 8 min. The electrometer mirror threw an image of the lamp filament upon the sensitized paper which was rolled upon the drums D, D' in the chronograph. After the light was turned off, the clockwork then operated an electromagnet which permitted the clockthen operated an electromagnet which permitted the clockwork drive CL in the chronograph to run for a few seconds in order that the paper might move ahead **sufficiently** so that the next reading would not be superimposed upon the one just recorded. After every fifth reading the clockwork operated a grounding switch which brought the electrometer deflection back to zero and then turned on the light so that this fiducial mark would be recorded upon the paper. In the figure below is shown a portion of a typical record, the motion of the paper being from left to right. A pencil line was later drawn through the fiducial points P_o. The perpendicular distance of a point P from the fiducial line was obviously a measure of the potential of the collector-wire with respect to the ground (in arbitrary units). The <u>times</u> corresponding to the recorded points were known from identifying marks placed near exposed points on the paper at the moment of recording. It was not attempted to reduce the deflections PP_o to volts since the true gradient could not be found anyhow. The paper used was Solar Bromide, cut into strips 5 in wide and several yards long.



Figs. 4 and 5 show the electrical connections between the clockwork (contacts C_1, C_2, C_3) and the various circuits, along with the potentiometer set-up ($EK_1R_1R_2$) used in calibrating the space charge electrometer and the circuits (controlled by K_2) used in charging and grounding the needle. Short-circuiting switches (S_1', S_2', S_3') were provided so that the lamp (L), chronograph (M') and the grounding switch (M) could be operated without waiting for the clockwork to function. The B batteries for the space charge electrometer needle were enclosed in a screened and grounded box and a two-pole key (K_2) was mounted on top of the box, the former so constructed that the electrometer needle, connected to the central terminal, could be connected either to the pole which was grounded or to the pole which was connected to the (positive) terminal of the B battery. In this way the needle could be discharged while the torsion head was being turned to bring the mirror parallel to the scale and facing the latter during adjustment. This procedure (bringing the needle back) was an exceedingly vexatious operation until the key was used in the circuit. A grid leak was connected between the needle and the key to prevent a short-circuiting of the former should there be accidental contact with the grounded quadrants of the electrometer.

The electrometer of the space charge apparatus was used heterostatically, with a needle voltage of about +160. The average scale distance was 58.3 cm and the average sensitivity was about 1000 mm/volt. The electrometer used for measuring the potential gradient was of very low sensitivity, of the order of 0.5 mm/volt at a scale distance of some 80 cm. In practice, the sensitivity was adjusted until a full-scale deflection was obtained for a P.D. of some 200 volts between the wire and the ground. By "full-scale" is meant a deflection that would bring the spot of light from the "zero" position P_o (page 63) on one side of the photographic paper almost to the other edge of the paper ---about 10 cm. All the deflections were in one direction. The collector-wire was connected to the needle of the electrometer and the positive terminal of the B battery (voltage about 45) was connected to one pair of quadrants. The negative terminal of the battery and the other pair of quadrants were, of course, grounded.

The collector-wire was 14.5 m long and supported by sulphur insulators at each end. The insulators were themselves hung from pulleys, flag-pole fashion, at the ends of horizontal metalsrods which were set in window boards. The wire could be drawn laterally aside by means of the cords attached to the pulleys and hence the insulators were readily accessible for cleaning and inspection. The wire carried an ionium collector at its center, approximately 1 m from the side of the building. The windows used were those on the third floor.

2. Experimental results obtained.

(i) Spring of 1929.

(a) Potential gradient measurements.

Instead of the collector-wire being hung at a considerable height from the ground and parallel to the side of the building, the method adopted later as more desirable, a preliminary experiment was performed with the wire strung between the top of a first floor window of the laboratory and a tree on the opposite side of the university driveway, just high enough to clear passing trucks. But the disturbing effect of the latter was very marked. The length of the wire was 11.5 m and the ionium collector was placed at the mid-point. No absolute value of the potential gradient could be obtained but 159 readings of the average potential of the wire were taken, showing maxima at noon and at 8 p.m. (Graph No. 1). Interesting effects were observed during thunder gusts and on two fair days, July 3 and 4. (Graph No. 2). The potential gradient varied very greatly in magnitude and sign on the first day. On the second day it was negative in the morning, with the sky clear, but became positive in the afternoon when the weather became sultry. There were no local thunder-showers. A rough measurement of the space charge on July 3 showed a value estimated at 100 times the normal.

(b) Space charge measurements.

A few readings (32) of the space charge were made, using a Compton electrometer of low sensitivity. The range of positive values was from 0.027 to 0.107 ESU/m^3, the mean being 0.09. The latter does not include the large negative values of July 3. Readings covered the time of day from 8 a.m. to 11:30 p.m. Maxima were found at 2 p.m. and 9 p.m.; minima occurred at 10 a.m. and 10 p.m. However, the scarcity of readings (spread over so many quarter-hour intervals) prevents all but a very rough idea to be obtained of the diurnal variation of the space charge.

(ii) Spring of 1930.

(a) Potential gradient measurements.

The apparatus was arranged as described in the general discussion (page 61. Readings were automatically recorded approximately every eight minutes, the values finally tabulated being obtained either from the actual photographic record or by interpolation. 624 separate values of the potential of the wire were used in calculating the means, the average for the quarter hour being plotted against that time (Graph No. 3). The sum of the 624 readings is 2418.3 cm, giving 3.87 cm as the average. All the readings are positive. After the quarter-hourly means were plotted, smooth curves were drawn through the points so that the main fluctuations of the potential could be detected. The following results appear.

1. The potential gradient is higher during the day than during the night.

2. Maxima occur at 8h 45m and 20h 30m; minima occur at 0h 0m and 4h 30m.

3. The error in measuring the potential of the wire is appreciable for any one reading but the positions of the maxima and minima are not affected by the error. The chief fault in the apparatus was the failure of the electrometer grounding key to maintain a positive contact when operated by the clockwork. Thus the positions of three or more consecutive fiducial points (P_o) are not always collinear.

(b) Space charge measurements.

1251 direct readings of the space charge were made on calm days, the frequency of the readings being four per hour. The algebraic sum of the charges drawn into the Faraday pail in the entire experiment is 24.71 ESU/m^3, giving a mean value of the space charge as Q=+0.02 ESU/m^3. Because of adjacent shrubbery, the apparatus was considerably shielded from the earth's field. The latter was weak anyway in the entire neighborhood due to trees and buildings.

After the quarter-hourly means of the space charge were plotted a smooth curve was drawn through the points. The following results appear.

1. The space charge is as much below the mean value during the day as it is above the same during the night, although a minimum at 0h 0m just about reaches the mean.

2. Maxima appear at 4h 30m and 20h 30m; minima are manifest at 0h 0m and 14h 30m.

3. The error in obtaining the space charge readings was made up of five parts, viz.:

(i) Error in reading the electrometer scale at the beginning of the run.

(ii) Error in reading the electrometer scale at the end of the run.

(iii) Error in reading the volume of the air aspirated.

(iv) Error due to leakage of the charge over the sulphur insulators.

(v) Error due to vibration of the building or to sudden puffs of wind at the entrance of the Faraday pail or to a change in the electrometer sensitivity.

Errors (i) to (iii) may have totalled 20 percent but there were times when the deflection was sufficiently great (e.g., 10 mm) so that the percent of error was small. In fact, we may neglect error (iii) on account of the large ratio between cubic meters and cubic feet, the gasmeter having been calibrated to read the latter. As the apparatus was actually set up, using a high sensitivity electrometer, the effect of leakage could not be distinguished from the variation of the reading caused by the agents cited in (v). If a charge were put on the system at a certain instant, the deflection was as likely to increase as to decrease from then on. The erratic behavior resulted partly from mechanical causes and partly from electrical causes. In the former case there might be a flexure of the window board or electrometer support, in the latter case there might be unknown amounts of charged air that enter the Faraday pail, slight variation in the needle potential caused by stray fields or fluctuations in the B battery e.m.f. In the last analysis, both sources of error are electrical, for the motion of the electrometer mechanically always results in a change of the relative positions of the needle and quadrants, thus changing the sensitivity. The electrometer itself was shielded from stray fields but the wire leading to the pail was connected, en route, to the grounding switch. As can be seen from the diagram of the electrical connections, the switch was so arranged that the system could be either grounded or raised to a small positive potential (e.g., 0.1 volt) when calibration was required. The errors of

(v) were never constant and hence we need not include in them the effect of the potentiometer.

4. The maxima of the space charge curve do not coincide with those of the potential gradient. The latter shows a minimum at 4h 30m when the former is at a maximum. When the potential gradient is going through a maximum at 8h 45m, the space charge is decreasing, although both elements show a minimum at 14h 30m. There is agreement of the maxima of the elements at 20h 30m and of the minima at 0h 0m. In general, the readings of the space charge taken during the night, when the building suffers less vibration and the outside air is quiet, are more satisfactory. Practically all of the space charge values are positive in sign. Such negative values as occur do so around noon.

3. Conclusions.

We shall at this time tabulate all of the data taken in this entire work, both at Cincinnati and at Martha's Vineyard, and then draw certain conclusions from the evidence at hand. (The Martha's Vineyard data will be separately discussed later). The times of occurrance of the maxima and minima of the two elements are herewith given, together with the "standard" times: i.e., those at which the extreme generally appear elsewhere. The hours are given in Eastern Standard Time throughout this paper.

Potential Gradient

Year	Place	Maxima	Minima	Standard Max.	 Min.
1929	Cincinnati	112h 0m	(14h 0m)	11h 0m	5h 0m
"	"	(20h 0m)	22h 0m	22h 0m	14h 0m
1930	"	8h 45m	(0h 0m)	.....	.....
"	"	20h 30m	4h 30m	.....	.....
1928	Katama(M.V.)	10h 0m	8h 0m	.....	.....
"	"		11h 0m	.....	.....
"	"	13h 30m	14h 0m	.....	.....
11929	"	11h 30m	7h 30m	.....	.....
"	"	13h 0m	12h 30m	.....	.....

Space Charge

1929	Cincinnati	14h 0m	10h 0m	0h 0m	(10h 0m)
"	"	21h 0m	22h 0m	(12h 0m)	(16h0m)
11930	"	4h 30m	0h 0m	.....	.....
"	"	20h 30m	14h 30m	.....	.....
1929	Katama	(10h 0m)	11h 30m	.....	.....
"	"	12h 30m	(13h 30m)	.....	.....
"	"	(17h 0m)	16h 30m	.....	.....
"	"		(19h 0m)	.....	.....

The "standard" values given for the space charge are taken from Obolensky's report (loc. cit.) and we should not expect them to agree with those for the present problem, in view of the difference in locality etc. Obolensky found that in the Summer (e.g., August) that the space charge is

~~is~~ predominantly negative, varying from +0.05 to -0.16 ESU/m^3. The apparatus was set up at the edge of a park and readings were taken on days that were free from fog and violent wind.

The conclusions to be drawn from the present investigation may be grouped as follows.

1. Evidence from the tabulated values of the elements.

(a) Potential gradient measurements, 1929.

If Graph No. 1 be averaged in the same manner as was Graph No. 2, the maximum tabulated as occurring at 20h 0m and the minimum tabulated as occurring at 14h 0m will disappear. The remaining extremes agree fairly well with those found elsewhere. Graph No. 2 has already been discussed on page 66 of this report. It will be noted that on that day the potential gradient was permanently positive after about 11h 0m, was fairly steady throughout the later afternoon and then fell off towards sunset. There were no thunder-storms in the vicinity all day and only in nearby towns in the late afternoon. The day being a holiday (July 4), there was an absence of motor cars that could have changed conditions by passing under the collector-wire.

(b) Potential gradient measurements, 1930.

The table shows that the maxima occur approximately two hours earlier than those usually observed, while the early morning minimum agrees well with the "standard." The minimum found around mid-night perhaps should be regarded as a part of the general early morning minimum although it really occurs in the transition period between the pronounced maximum at 20h 30m and the minimum at 4h 30m. It would be better to disregard it. In fact, the observed minimum at mid-night might disappear if the graph were further smoothed out as was done above. The minimum usually found at 14h 0m hardly shows on the present graph (No. 3), although the mid-point of the lower level between the maxima at 8h 45m and 20h 30m occurs at about that time. But the lowest values in this period are noted at 19h 0m, just before the maximum.

The small number of readings of the potential gradient in 1929 make it inadvisable to compare the data taken then with those taken in 1930. The most that we can say is that there is rough agreement with the positions of the maxima and one of the minima. It is to be expected that better results would be yielded by the improved apparatus of the second year.

(c) Space charge measurements, 1929.

The table shows that a maximum occurs at about 21h 0m, some **three** hours before the corresponding extreme value found by Obolensky. The other observed maximum (at 14h 0m) takes place about two hours after the maximum found at noon by Obolensky. One of the minima (at 10h 0m) is seen to agree exactly with Obolensky's value, while the other minimum occurs at 22h 0m, about six hours later than that observed by him. In this instance, as in dealing with the data on the potential gradient obtained in 1929, we cannot put much credence upon the experimental results. The apparatus was then in a preliminary stage.

(d) Space charge measurements, 1930.

The results do not at first appear to agree at all with those obtained by Obolensky: the maxima are about five and eight hours too late and one of the minima (at 0h 0m) does not occur at the time at which the corresponding(?) minimum was observed by Obolensky. However, there are two minima recorded by the latter, at 10h 0m and 16h 0m, separated by a subsidiary maximum about 12h 0m, the magnitude of which is so far below (positively) the other maximum that the entire period between 10h 0m and 16h 0m might fairly accurately be regarded as a time of low (negative) space charge, the center of the period occurring at about 13h 0m. This last figure agrees fairly well with the minimum observed at Cincinnati as occurring at about 14h 30m. The minimum found at the Cincinnati laboratory around mid-night does not correspond with any experimental values found elsewhere, either in this work or in that of Obolensky, who found a maximum at that hour. However, there is no doubt that a maximum occurs in the space charge at this time in the present instance for the readings taken during the night are more accurate than those taken during the day, even though they are fewer in number. The topgraphy is very different near the two laboratories.

2. Correlation between the potential gradient and space charge diurnal variations. (The real purpose of the present research).

It is logical to assume that the potential gradient is a function of the state of ionization of the air, for, until there are charges there can be no electric field. A study of the simultaneous variation of the space charge and the potential gradient should give a clue as to the dependence of the latter upon the former. In the present research it was not possible to carry out this program in just the manner most desirable but the variations of the elements are recorded on similar days and the curves showing the variation of the means per quarter hour are to be studied. The apparatus was situated near the ground, in the wall of the building and in the vicinity of some shrubbery, and hence the field of the earth was not important in its effect upon the space charge. But since we can assume that what was true in this locality was probably true also a few meters distant, the variations observed in the potential gradient may be correlated with those of the observed space charge. The factors which can affect the value of the space charge near the ground should now be discussed in connection with their possible bearing upon the present problem.

(i) Sunlight.

(a) Ionization of the air. This phenomenon may be caused in two ways: by the emission of photoelectrons and by the direct ionizing action of the ultra-violet light. Because of the high absorption of the lower air levels for the short wave-lengths of the solar spectrum the ionization of the air by either means must be disregarded in the present case. This has been previously discussed (pages 12 and 13).

(b) Thermal convection currents in the air. It is to be expected that the greater the altitude of the sun, the greater will be the amount of heat reradiated by the earth directly beneath it and absorbed by the layers of air near the ground. There will thus be convection currents set up in the air caused by the decreased air density. The effect will be enhanced by the heat absorbed directly by the air itself. This air circulation will translate the ions that are near the ground to various heights, depending upon their size and sign, and thus alter the distribution of the space charge. A corresponding change in the potential gradient will occur at the same time. Since we do not know the size and number of ions of non-radioactive origin near the ground, we cannot estimate what effect their motion will have in the distribution changes of the space charge, although we are certain that there are no free electrons in the atmospheric air at low levels. We know also that the number of positive small ions exceeds in general that of the negative, and that the converse is true for the Langevin ions. Thus in the vicinity of towns the latter type of ions outnumbers the former and we might assume that the space charge would tend to be negative in such a situation. But it is possible that the number of the large ions is so much greater than that of the small that the upward air current, drawing the negative ions from the lower air layers, has much more of a resultant electrical effect in dispersing the negative charges than it has in dispersing the positive charges. The number of small ions in unit volume of air has been estimated at 700 and the number of large ions may be as high as 10,000. The rate of production of ions near the ground by radioactive agents and ultra-gamma radiation has been calculated to be 9.5 per cc per sec (page 46) and this does not include the actual α- and β-particles themselves which may be present very close to the earth. The conclusion we may draw from the effect of sunlight is that the convection currents in the air disperse the ions that are initially present in the given region. If there has been an excess of negative ions, the dispersion will be evidenced by a relative increase in space charge in a positive sense; if there has been an excess of positive ions, the opposite effect will be found. The net result is that we should expect to find either a maximum or a minimum of the space charge around noon. This has been found in the present investigation to be the case. Extreme values of the space charge occur at sunrise and sunset, when the effect of the sun is either just becoming apparent or just ceasing. The air convection currents also draw radioactive gases from the soil capillaries. The latter tend to retain the negative charges by adsorption and so the air drawn from the capillaries is positively charged. The actual positive ionization of the outside air will be thereby increased. The sunlight would account for the increase in the positive space charge between 6 a.m. and 8 p.m. if we assume that large negative ions predominate in the air and that convection currents draw out positively charged air from the soil. As a matter of fact, however, the space charge was found to be positive at all times. This might be explained by the fact that the exodus of positive ions from the soil is sufficient to prevent the remainder of the negative charge that was not carried away by the convection currents from producing a net negative value for the space charge. The minimum observed at noon might be explained by the increased motor traffic on the driveway adjacent to the apparatus. This would increase the number of heavy ions (as products of combustion). The increase of negative ions towards noon would account for the reduction in the net positive charge, in spite of the fact that soil respiration would now be at a maximum.

Along with the convection currents produced by solar radiation we should mention the similar effects of wind and, as far as the soil capillaries are concerned, of barometric pressure in dispersing the charges near the surface of the earth. Obolensky explains the 1 p.m. minimum observed by him as due to the maximum action of the earth's surface upon the layers of air which are nearest to it, the wind drawing up negatively charged particles. At this time there would be an ascending air current which would become feebler towards sunset. After nightfall the air current would be in the opposite sense and the negative particles would gradually settle down, tending to produce the minimum observed during the night. The positive charge would be built up more and more in the lower strata, with a maximum about 8 p.m.

(ii) Radioactivity of the soil and air.

This shows itself in two ways: the direct ionization produced by α- and β-particles and gamma radiation, and the secondary radiation produced by the products of the collisions or absorption. The major effect comes from the radioactive products in the soil itself and is manifest when the soil gases, highly ionized, are sucked out of the soil capillaries by convection currents, wind and a decreased barometric pressure. Radium emanation is also drawn out of the soil. β-particles and gamma radiation penetrate a fair amount into the atmosphere and produce ionization for a distance of several meters above the ground. A large part of the ionization observed is produced by the gamma radiation. The fact that the ions produced are not of the same size permits us to expect an appreciable dispersion of the ions from the radioactive products under the action of the convection currents etc. The phenomena of soil respiration go a long way towards accounting for the presence of a positive space charge near the surface of the earth. These phenomena have been shownd to be associated with the thermal currents and the barometric pressure and will be somewhat further discussed in a succeeding section. It has been found that in the absence of wind the stagnant air near the ground, whether indoors or in caves, shows a considerable emanation content. We should expect the space charge to show a maximum in the early morning because of this fact. A maximum is found to occur about 4h 30m, 30m, which may be caused by the joint action of the emanation and the rising sun.

(iii) Barometric pressure, wind velocity and humidity.

We have just seen that the soil respiration depends very much upon the strength of the sunlight, wind velocity and the air pressure. Data from the Weather Bureau show that the average diurnal variation of the barometric pressure is such as to give maxima around 10h 0m and 22h 0m and minima around 4h 0m and 16h 0m. The positions of the maxima of the space charge curve agree in the present case very well with the positions of the minima of the barometric pressure, thus indicating some correlation between the two phenomena: the rate of soil respiration being the connection. The converse is not evident from the curves drawn, nor should we expect the effect to be pronounced in any actual case. Data with regard to the wind velocity is not precise but it is known that the higher velocities occur towards the middle of the day in the Summer. A maximum of the space charge should be found at about that time. As the present apparatus was set up, the velocity changes were very erratic due to eddies about the building. It should be mentioned, too, that the situation of the laboratory on a hill means a fairly constant breeze throughout the day and little expectation of a pronounced space charge maximum on account of the wind velocity.

The presence of water vapor and atmospheric ions, as possible condensation nuclei, indicates in general the liklihood of large ions sooner or later and hence we should expect the humidity to have an effect upon the conductivity and the space charge. The effect upon the latter would probably be, through an increase in the Langevin ions, an increase in the negative value.

(iv) Products of combustion.

The experiments described in this report were performed in a region of much smoke and high humidity. Thus was furnished at once the basis for large ion formation. It was shown by Allen (page 4) that the dust of the city is highly radioactive and it is certain that the large ions found here are mostly dust particles with a deposit of a radium or a thorium product. It is not possible to state whether there would be any periodicity in the formation of these smoke particles (other than the general increase during the morning hours) and certainly the raising of dust would be erratic. But there is this tendency for the greatest amount of smoke to be in the air during the day, as suggested above, and hence the average value of the space charge should be a little lower (positively) during the day than during the night. The graph of the diurnal variation of the space charge (No. 3) actually shows this to be so. The daytime minimum is below the mean value while the night-time minimum just reaches the mean.

(v) Possible effect of the Heaviside Layer.

If there be any effect upon ion drift due to the highly ionized Heaviside Layer, it would tend to affect mainly the small ions because of their comparatively great mobility. Since the majority of the ions in the atmosphere near the apparatus were large, we need not expect much, if any, effect caused by the Heaviside Layer.

We shall summarize a little later the foregoing conclusions (page 73 ff).

Research at Katama

1. Description of the apparatus.

Katama is a subdivision on the level moorlands of the island of Martha's Vineyard, Mass., one mile inland from the southern shore of the island and approximately given by long. 70° 32' W. and lat. 41° 21' N., two miles distant from the nearest town and ideally situated for observations of the atmospheric-electric elements. The experimental hut was designed, as to height above ground and location with respect to the collector-wire, so that no reduction factor is required in measuring the potential gradient. (Cf. photographs accompanying this report). The hut is situated in the S.W. corner of a plot of ground 50x100 ft. upon which the grass is cut to a height of about 6 in. The collector-wire is supported by weatherproof sulphur insulators from posts 60 ft apart, set in a North-South line, and hung one meter from the ground. The grass under the wire for an area of 60x15 ft. is kept mowed very short. The lead-in wire is 28 ft in length and runs at an angle of 30° from the collector-wire to the hut. The nearest point of the latter is 47 ft from the collector and the highest point of the hut above the surface of the earth is 4.5 ft. These specification comply with the requirements given by the Department of Terrestrial Magnetism. The hut is 8x8 ft in area and has a floor space of 2.25x6.25 ft^2, obtained by excavating to a depth of 2.25 ft. There is thus head-room for comfortable working. A stone pier, 3.5x1.75 ft, together with shelving for the apparatus, fills the remainder of the space inside the hut. For photographic purposes the hut is made light-tight and, for electrical shielding, is completely covered with fine mesh wire netting that is continued on each side below ground. Electrical connections to the earth are accomplished by means of an iron pipe sunk outside the hut to a depth of about 2.5 ft and kept filled with water. The latter, seeping out at the open end of the pipe, keeps the ground satisfactorily moist. There is a second stone pier inside the hut to accommodate auxiliary apparatus. The hut is electrically lighted from storage batteries. The latter also run such small motors and magnetic relays as may be required.

In the years 1928 and 1929 the box containing the Faraday pail was placed on the larger pier so that the larger end of the funnel connected with the outside air on the South side of the observation hut. The arrangement of the electrometers and other essential parts of the apparatus was similar to what is was in the laboratory in Cincinnati.

2. Experimental results obtained.

(i) Summer of 1928.

No space charge readings were taken but a number of determinations of the potential gradient were made, using an electroscope as well as an electrometer. An approximate idea was obtained of the time of the maxima and minima throughout the day. Effects of lightning flashes from a storm far down the shore were easily detected with the electroscope. The potential gradient data are given in the table under (ii).

(ii) Summer of 1929.

76 readings of the space charge were made, using a Compton electrometer of low sensitivity. The mean value of the element was $Q=+0.016$ ESU/m^3. Serious delays were occasioned by the breakage of electrometer fibres and

faulty design of the Faraday pail. The data show an forenoon maximum of the space charge at 10h 0m and afternoon maxima at 12h 30m and 17h 0m, with minima at 11h 30m and 13h 30m, 16h 30m and 19h 0m. Although these may be the result of spurious effects, it should be noted that the corresponding maxima observed by Obolensky are at 0h 0m and 13h 30m and the corresponding minima are at 10h 0m and 16h 0m. There is rough agreement with the noon maximum and the minima. However, it is found that the plotting of the Katama data give minima for one element as occurring at the same time as the maxima for the other. 254 readings of the potential gradient were made, the average number for each quarter hour throughout the day being five. The mean value of the potential gradient is +143 volts/m. The data for this element give the following extreme values.

Summer of:	1928	1929	Standard
Forenoon maximum............	10h 0m	11h 30m	11h 0m
" minimum............	8h 0m	7h 30m	5h 0m
Afternoon maximum...........	13h 30m	13h 0m	22h 0m
" minimum...........	14h 0m	12h 30m	14h 0m
Subsidiary minimum(morning).	11h 0m	....	....

3. Conclusions.

There seems to be rough agreement between the Katama maxima and minima and those observed by Obolensky but it is hard to account for the fact that the maxima of the one element occur at the times of the minima of the other. In the country air at Katama it may be assumed that the ions are mostly of molecular size and that possibly when their number increases the potential gradient decreases by a sort of "IR-drop" procedure, the air becoming more conducting and the potential difference therefore dropping. The wind blows continually over the plain at Katama and what ionized gases may come from the sandy soil doubtless have some effect in supplying ions. The surf on the shore is too far away to produce much effect, although the prevailing winds blow in from the sea. The air becomes decidedly cooler after sunset and readings are not possible at that time because of the deposition of dew on the insulators. There is little trouble from spider webs and insects but there is always error due to the blowing of wind into the Faraday pail. Many of the potential gradient values are very high, due probably to dust or fine sand in the air, but none are greater than 340 volts/m. At least values apparently larger than this are so uncertain as to be neglected, as the calibration curve of the electrometer could not safely be extrapolated beyond that value. What might be called subsidiary maxima in the variation of the potential gradient are observed about 16h 0m and 18h 0m; likewise minima occur at 17h 0m and 19h 0m. The last seem to be represented, in the data of 1928, by the minimum at 18h 0m. All the potential gradient readings are positive. Data are too scanty to permit definite conclusions to be drawn as to the space charge although a change of sign seemed to be detected when the wind blew from the town rather than from the shore. In the latter case the readings were negative.

4. Future work at Katama.

Further research is to be done at the Katama observatory in the subject of potential gradient variation. It is hoped that greater accuracy can be obtained by having improved insulators and automatic recording, readings being taken hourly throughout the twenty-four hours. It is hardly feasible to set up space charge apparatus owing to the length of time required for setting up the apparatus and the shortness of the working season.

GENERAL CONCLUSIONS

In summarizing the main points of this research, as suggested in the conclusions previously mentioned (page 77 ff) we shall confine our attention to the data obtained at Cincinnati in the Spring of 1930. The general conclusions are as follows.

1. The potential gradient is positive in sign.

2. The space charge is positive (mean value, +0.02 ESU/m^3), except occasionally around noon.

3. Soil respiration, an increase of the Langevin ions towards noon due to increased motor traffic, and sunlight

are the three agents that satisfactorily account for the diurnal variation of the space charge. The effect of the sunlight is to set up atmospheric convection currents that disperse the charges lying near the ground and thus tend to draw up the smaller ions.

4. The average diurnal variation of the barometric pressure is found to agree with that observed for the space charge. Minima of pressure coincide with maxima of charge due to the suction of the soil gases under reduced pressure.

5. In the early morning there is a maximum of the space charge which may be explained by assuming that there is little wind and that the air near the ground, being stagnant, is positively charged from the efflux of the soil gases. Such ions as are present near the collector-wire are small (or are few in number?) and hence, because of their high mobility, the potential gradient is at a minimum at this time.

6. There is a maximum of the potential gradient at about 8h 45m which may be explained by supposing that the larger ions, of low mobility, now predominate and are increasing more rapidly than the ions from the soil capillaries. Thus the conductivity of the air decreases.

7. The space charge falls off towards noon because, probably, there is an increase of dust carrying a negative

charge; there is also the increase of Langevin ions, as mentioned in (6). The increased respiration of the soil is probably overbalanced by the increased production of large negative ions. However, the dispersion of the positive ions (at a greater rate than for the negative ions) is a factor in reducing the net positive charge near the ground.

8. The space charge increases towards sunset as the negative ions decrease in number or settle to the earth and the air becomes more stagnant near the surface of the earth. With little dispersion caused by thermal convection currents, the highly positive soil gases predominate more and more.

9. There is a maximum of the potential gradient coincident with the sunset maximum of the space charge which is hard to explain. It cannot be caused by large ions or by the entire absence of ions, for the space charge is not zero. It may be caused by a general equality of the number of ions of both signs near the wire, even though the space charge near the ground is not zero.

10. The space charge and the potential gradient both decrease towards midnight, the reason possibly being the convection currents set up by the radiation from the stone and brick walls of the building after sunset. There is a small amount of dispersion of the positive charges near the

ground. The situation is similar to (5) as far as the potential gradient is concerned.

11. The space charge is below its mean value during the day and above it during the night. The potential gradient is relatively higher during the day. This can be explained in terms of large ions.

12. Maxima of the potential gradient occur at 8h 45m and 20h 30m, which agree pretty well with the times usually observed; minima occur at 0h 0m and 4h 30m, of which the second agrees with common observation.

13. Maxima of the space charge occur at 4h 30m and 20 h 30m, of which the second agrees approximately with that found by Obolensky; minima occur at 0h 0m and 14h 30m, with which there is no agreement in Obolensky's results unless the minima observed by him at 10h 0m and 16h 0m are but extremes of a general minimum occurring during a period of which the center is at 13h 0m. This seems to be a likely explanation.

14. Because of the electrically shielded position of the Faraday pail and of the entire space charge apparatus (due to the proximity of the shrubbery and the building) the earth's field has little effect in causing a circulation of the ions. Hence we need not look to the Heaviside Layer as a cause of ion drift. That ions actually were aspirated into the pail was proven by producing ions

artificially in large numbers at the mouth of the funnel, drawing them into the pail, and then comparing the electrometer reading with what was observed when the ions were compelled to pass between two condenser plates before entering the funnel.

15. We may rule out at once the electrical effect of sunlight in causing the ejection of photoelectrons from air molecules or ionizing the molecules, for there are no effects present at low atmospheric levels.

....

It is instructive to note some of the conclusions reached by Brown ([1]) who has recently completed a year's study of the diurnal variation of the space charge and the potential gradient at Stanford University. These are:

1. The earth has a negative surface charge and a positive space charge.

2. The mean distribution of the positive space charge can be inferred from the potential gradient at various elevations. Fifty percent of the charge occurs in the first kilometer.

3. Variations in the distribution of the space charge will cause variations in the potential gradient at any point by changing the relative magnitude of the space charge in (a) horizontal layers and (b) vertical columns.

TABULATION OF DATA OF 1930

Table 1.

Values of the space charge from 8h 30m to 10h 0m for all the days of observation from March 31 until June 27. These data are typical of the entire amount.

Table 2.

Values of the potential gradient (in arbitrary units) from 8h 30m to 10h 0m for all the days of observation from March 27 to June 23.

Table 3.

Mean values of both elements for each quarter hour of the day throughout the entire season. These data are plotted as Graph No. 3.

Table 1......Space Charge

Hour Date	8h30m	8h45m	9h 0m	9h15m	9h30m	9h45m	10h 0m
3.31	0.033	0.022	0.017	0.016	0.016	0.010	0.017
4.2							0.006
4.4			0.000	0.000	0.018	0.003	
4.5			0.018				
4.8	0.064			0.000			
4.9					0.034		
4.10	0.071	0.048	0.052	0.064	0.071	0.050	(0.105)
4.12	0.066	0.038	0.052				
4.23	0.006	0.032	0.020	0.026	0.063	0.004	
5.5			0.080	0.043	0.023	0.028	(0.172)
5.7							-0.014
5.8		0.026	0.024	0.036	0.085		0.021
5.9			0.039	0.038	0.027	0.036	0.019
5.10						0.014	
5.15	-0.021	-0.016	0.052	-0.018		0.030	0.018
5.20					0.017	0.008	
5.24	0.012			0.017	-0.013	-0.019	-0.025
5.29		0.009	0.011	0.016	0.005		
5.30	0.035						
6.2	0.043	0.042	0.035	0.038	0.048	0.037	
6.3					0.066	0.045	0.030
6.9	0.023	0.020	0.026	0.063			
6.11		-0.024	0.027		0.042	0.054	(0.100)
6.12	0.059	0.017					
6.18	0.026	0.010	0.017	0.007			
6.20			0.014	0.020	0.023	0.012	0.023
6.21	0.026	0.032	0.068	0.052	0.048	0.033	-0.037
6.23	0.020	0.013	0.011	-0.003	0.000	0.002	-0.011
6.26			0.021	-0.018	-0.014	0.003	0.003
6.27	0.002	0.002	0.007	0.007	0.008	0.008	0.005
Mean	0.024	0.017	0.028	0.022	0.025	0.017	0.004
No. of rdgs.	16	16	21	20	20	19	12

(Note: The error involved in tabulating but three figures for each entry amounts to 0.001 in each case but this does not affect the positions of the maxima and minima).

Table 2.....Potential Gradient

Hour Date	8h30m	8h45m	9h 0m	9h15m	9h30m	9h45m	10h 0m
3.27						0.8	0.6
4.1	3.8						
4.2		6.4	7.0	6.8	7.8	7.8	6.1
4.5			4.4	4.8	6.0	6.5	7.2
4.10	3.2	5.4	6.8			8.2	
5.8			1.0	1.2	2.1	1.6	3.4
5.14			0.8		1.7		
5.16	1.0	2.1	1.6	2.0			
5.23		2.3		0.8	0.9	0.9	1.0
5.29	2.5		1.2		1.5	0.9	1.8
6.2	4.4	5.4	6.1	7.0	6.3	6.3	7.0
6.3					7.0	8.2	9.2
6.5							0.4
6.9	7.8				6.4	7.7	
6.11	4.1	4.1	4.2	4.6	5.6	4.4	8.1
6.20		2.9		2.3	2.5	2.3	2.7
6.23	3.2		3.2	3.1	1.7		
<u>Mean</u>	3.5	4.1	3.6	3.6	4.1	4.6	4.3
No. of rdgs.	9	7	10	9	12	12	11

Table 3....Mean Values

Hour	Space charge No. of rdgs.	 Mean (ESU/m^3)	Potential gradient No. of rdgs.	 Mean (cm defl.)
0h 0m	9	0.020	4	2.1
15m	8	0.017	4	2.5
30m	9	0.027	3	2.4
45m	9	0.027	4	2.2
1h 0m	9	0.024	4	2.1
15m	9	0.014	1	0.0
30m	9	0.027	4	2.9
45m	8	0.030	2	1.7
2h 0m	9	0.028	3	2.6
15m	7	0.027	4	1.9
30m	8	0.032	5	2.2
45m	9	0.032	4	2.0
3h 0m	7	0.022	3	1.4
15m	8	0.021	4	1.9
30m	6	0.038	4	1.9
45m	7	0.039	3	1.5
4h 0m	5	0.033	4	1.7
15m	7	0.023	2	1.1
30m	8	0.037	2	1.3
45m	7	0.031	2	0.6
5h 0m	7	0.031	2	0.3
15m	7	0.024	2	4.1
30m	8	0.024	1	4.0
45m	8	0.021	2	2.7
6h 0m	8	0.021	2	1.4
15m	8	0.025	2	1.4
30m	8	0.023	2	1.5
45m	8	0.020	1	1.3
7h 0m	8	0.018	3	2.4
15m	7	0.020	2	3.5
30m	11	0.018	2	5.0
45m	12	0.025	2	6.3
8h 0m	13	0.021	3	6.2
15m	11	0.030	5	4.2
30m	16	0.024	9	3.5
45m	16	0.017	7	4.1
9h 0m	21	0.028	10	3.6
15m	20	0.021	9	3.6
30m	20	0.025	12	4.1
45m	19	0.017	12	4.6
10h 0m	12	0.004	11	4.3
15m	17	0.026	12	4.0
30m	18	0.016	14	3.9
45m	14	0.019	10	3.9

Table 3........(cont'd)

11h 0m	23	0.014	17	3.8
15m	23	0.030	13	4.3
30m	17	0.008	13	4.1
45m	19	0.006	12	3.9
12h 0m	9	0.024	13	4.2
15m	4	-0.005	10	3.4
30m	11	0.000	13	3.7
45m	15	0.016	15	3.9
13h 0m	18	0.014	17	3.7
15m	19	0.013	17	3.6
30m	24	0.016	20	4.0
45m	24	0.009	19	3.4
14h 0m	23	0.010	17	3.8
15m	24	0.006	12	4.5
30m	19	0.012	19	3.5
45m	19	0.008	15	4.3
15h 0m	25	0.015	14	3.3
15m	22	0.003	10	3.6
30m	21	0.005	14	4.2
45m	19	0.017	10	3.5
16h 0m	22	0.018	13	4.4
15m	22	0.013	10	3.4
30m	22	0.017	8	2.7
45m	20	0.019	10	3.9
17h 0m	21	0.023	12	3.6
15m	21	0.017	7	4.3
30m	18	0.008	8	4.4
45m	11	0.018	7	4.1
18h 0m	8	0.017	7	3.2
15m	11	0.017	5	3.5
30m	15	0.027	6	2.8
45m	16	0.025	4	2.3
19h 0m	14	0.029	7	3.7
15m	16	0.031	5	2.5
30m	17	0.017	8	4.3
45m	18	0.019	4	4.3
20h 0m	16	0.032	7	4.0
15m	13	0.037	7	6.0
30m	15	0.030	3	5.3
45m	14	0.030	4	5.6
21h 0m	13	0.031	4	3.9
15m	10	0.032	2	3.2
30m	11	0.025	4	3.2
45m	13	0.024	4	2.1
22h 0m	12	0.024	5	2.1
15m	10	0.021	5	2.3
30m	8	0.030	5	2.5

Table 3........(cont'd)

22h 45m	9	0.021	3	1.0
23h 0m	9	0.025	3	2.5
15m	9	0.027	3	3.1
30m	9	0.021	4	2.2
45m	9	0.023	3	3.2
Means	13	0.020	6	3.9

DESCRIPTION OF PHOTOGRAPHS

View No. 1. Apparatus at Cincinnati showing:
C - chronograph
GM - gas meter
T - telescope
AB - wooden box for space charge apparatus

View No. 2. Apparatus at Cincinnati showing:
E - potential gradient electrometer
E' - space charge electrometer
C - chronograph
FP - Faraday pail
GM - gas meter
BB - base board for p.g. apparatus
T' - tube from pail to blower
GS grounding switch for p.g. apparatus
T - telescope for space charge apparatus

(Note: opaque cloths are shown drawn aside and side of space charge box is open).

View No. 3. Apparatus at Cincinnati showing:
Same as View No. 2 but for the enclosing of the apparatus by the opaque cloths and the wooden box.
GM - gas meter
B - B battery for space charge electrometer
CL - clockwork controlling p.g. readings
BL - Cenco blower for aspirating air
AC - high speed A.C. motor for blower

View No. 4. Photograph of Graph No. 3 so that the general positions of the maxima and minima can be easily seen in their relative positions.

View No. 5. Laboratory at Cincinnati showing:
WW' - collector-wire
LL' - wire connecting with lead-in

View No. 6. Laboratory at Cincinnati showing:
C - copper netting in window
I - inlet pipe to funnel of Faraday pail
L - lead-in

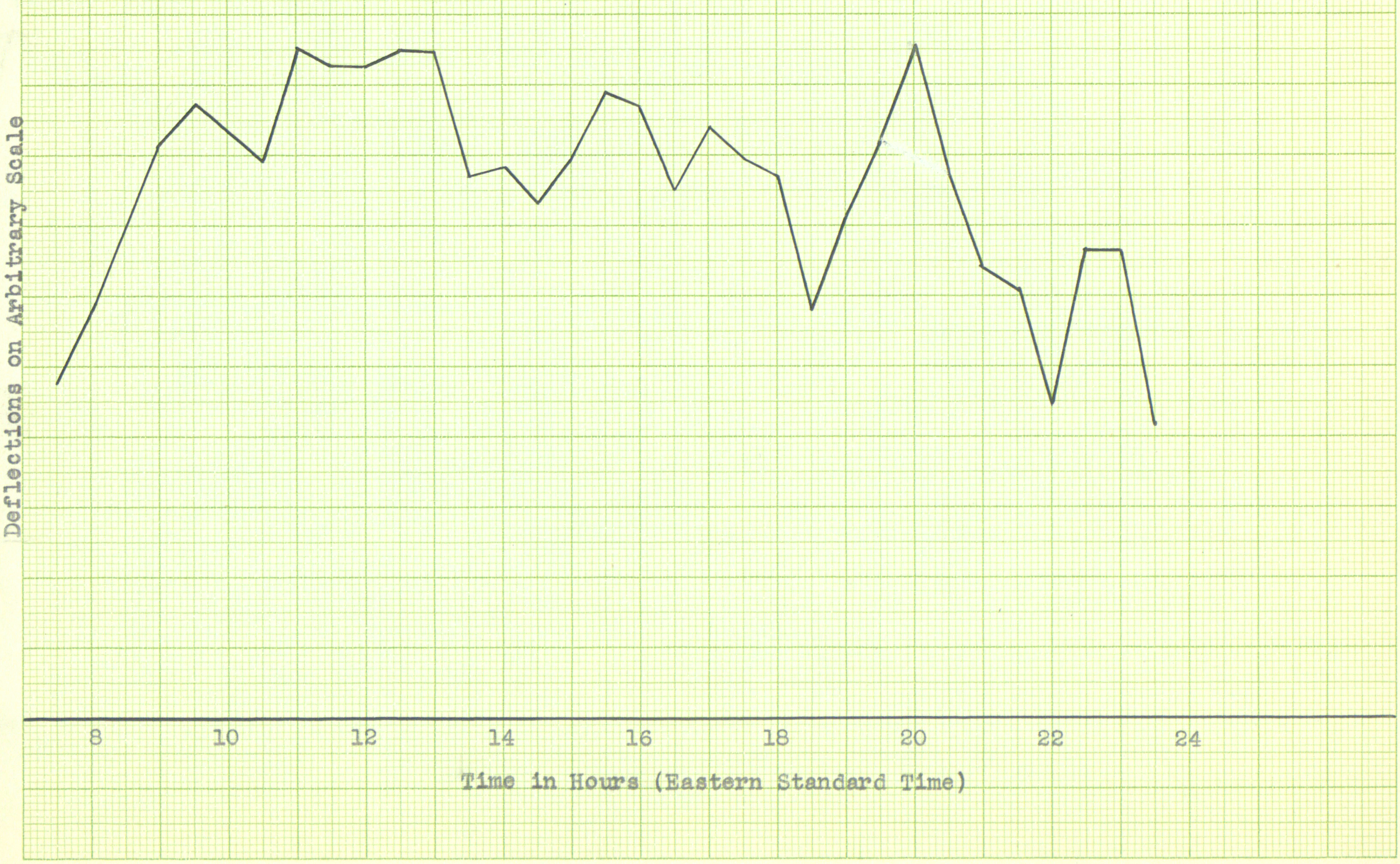
View No. 7. Observation hut at Katama (during construction) showing: larger stone pier, excavation for flooring and head room, general aspect of topography. View looking W.S.W.

View No. 8. Observation hut at Katama showing: cleared space beneath collector-wire, posts supporting the latter, character of land. View looking S.W. (in the distance blow-holes in sand bluffs on the shore can easily be seen).

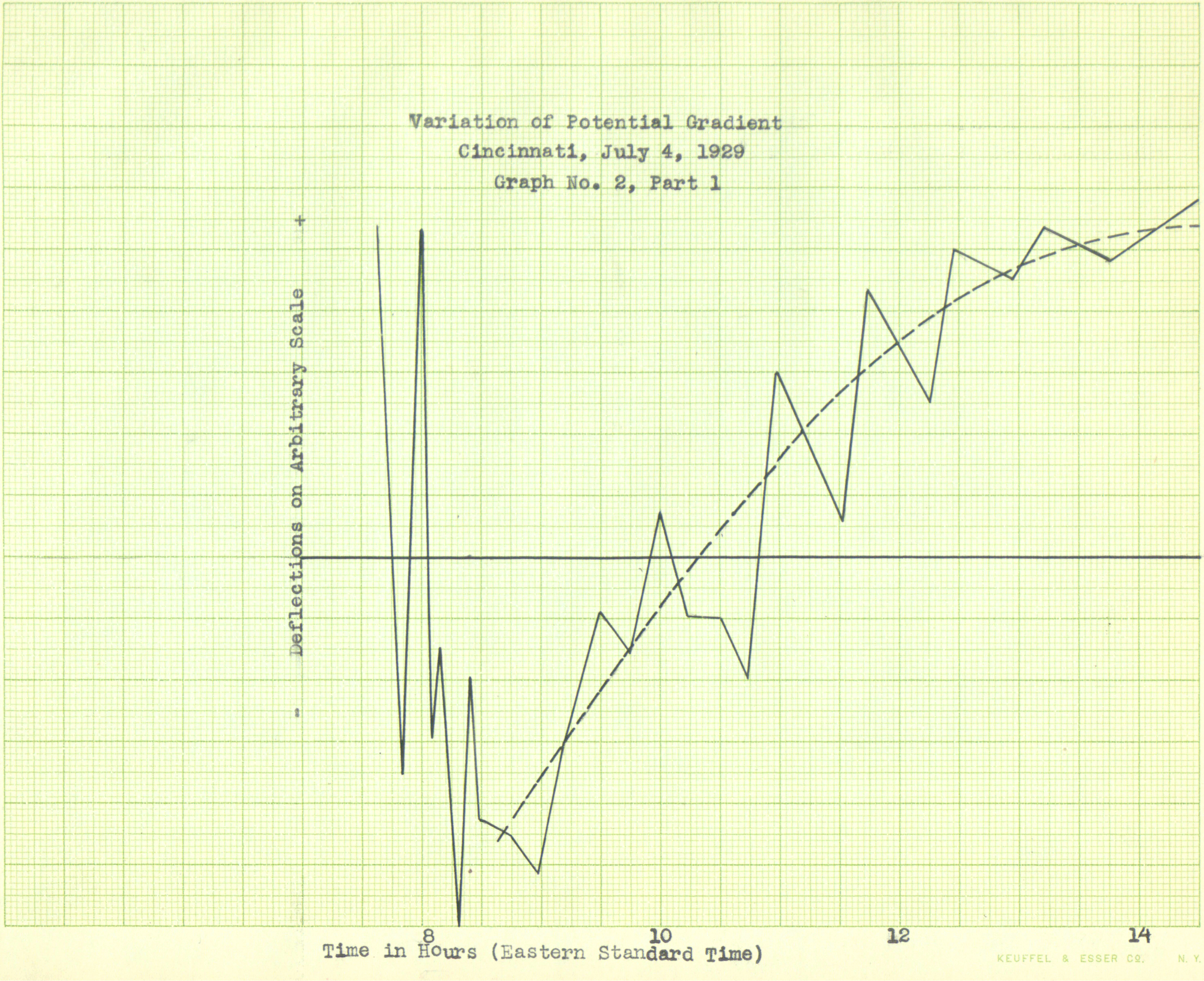
ACKNOWLEDGEMENTS

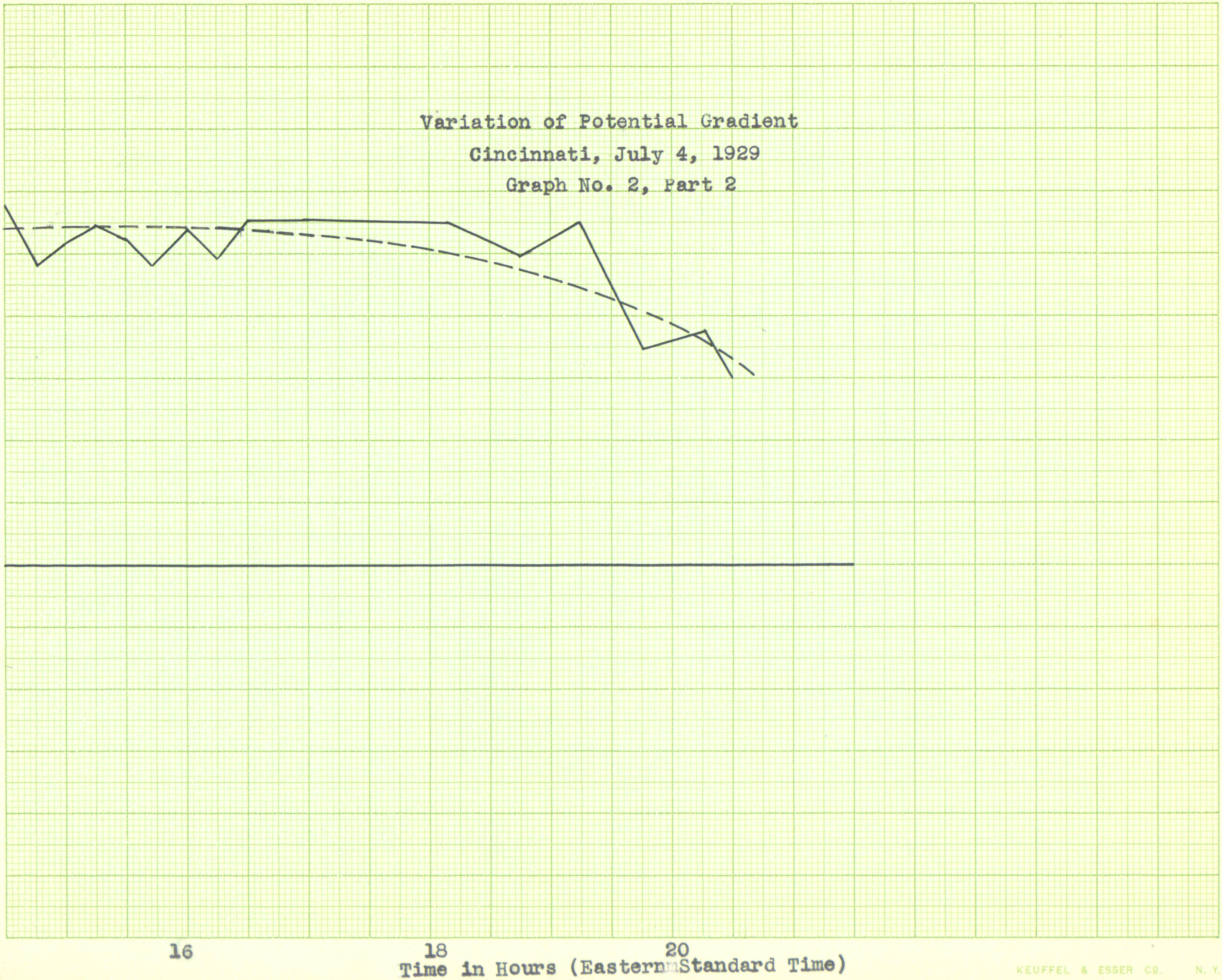
The writer wishes to express his thanks to Professor S. J. M. Allen for his constant interest in the problem and to the other members of the Staff for timely suggestions; to Dr. J. A. Fleming and others of the Department of Terrestrial Magnetism for helpful suggestions, loan of ionium collectors and funds for the construction of the hut at Katama and to Mr. Frederick Kattler, of Springfield, Mass., for his loan of the land upon which the hut is built.

Diurnal Variation of Potential Gradient
Cincinnati, June 22-July 2, 1929
Graph No. 1



Variation of Potential Gradient
Cincinnati, July 4, 1929
Graph No. 2, Part 1



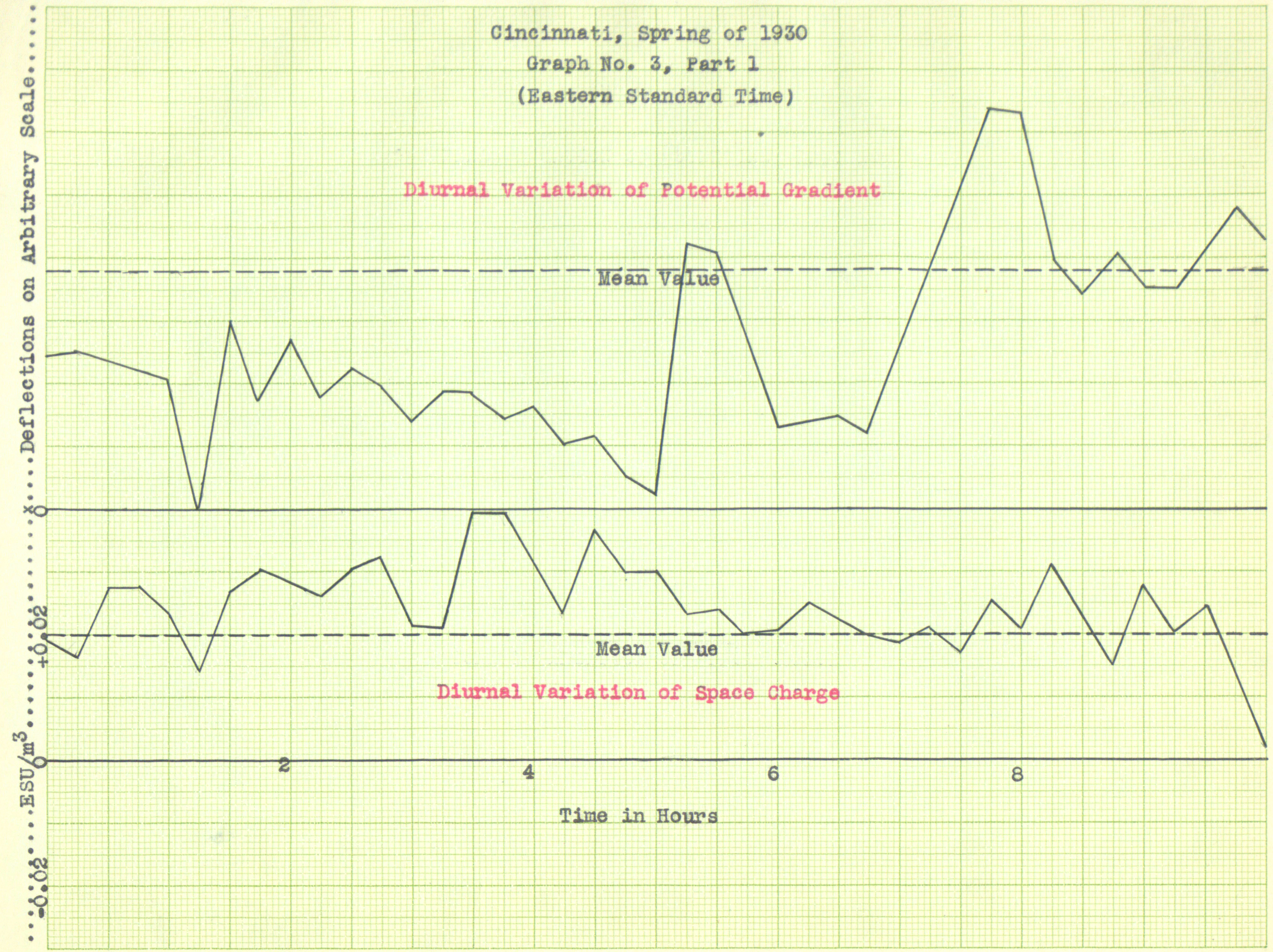


Variation of Potential Gradient

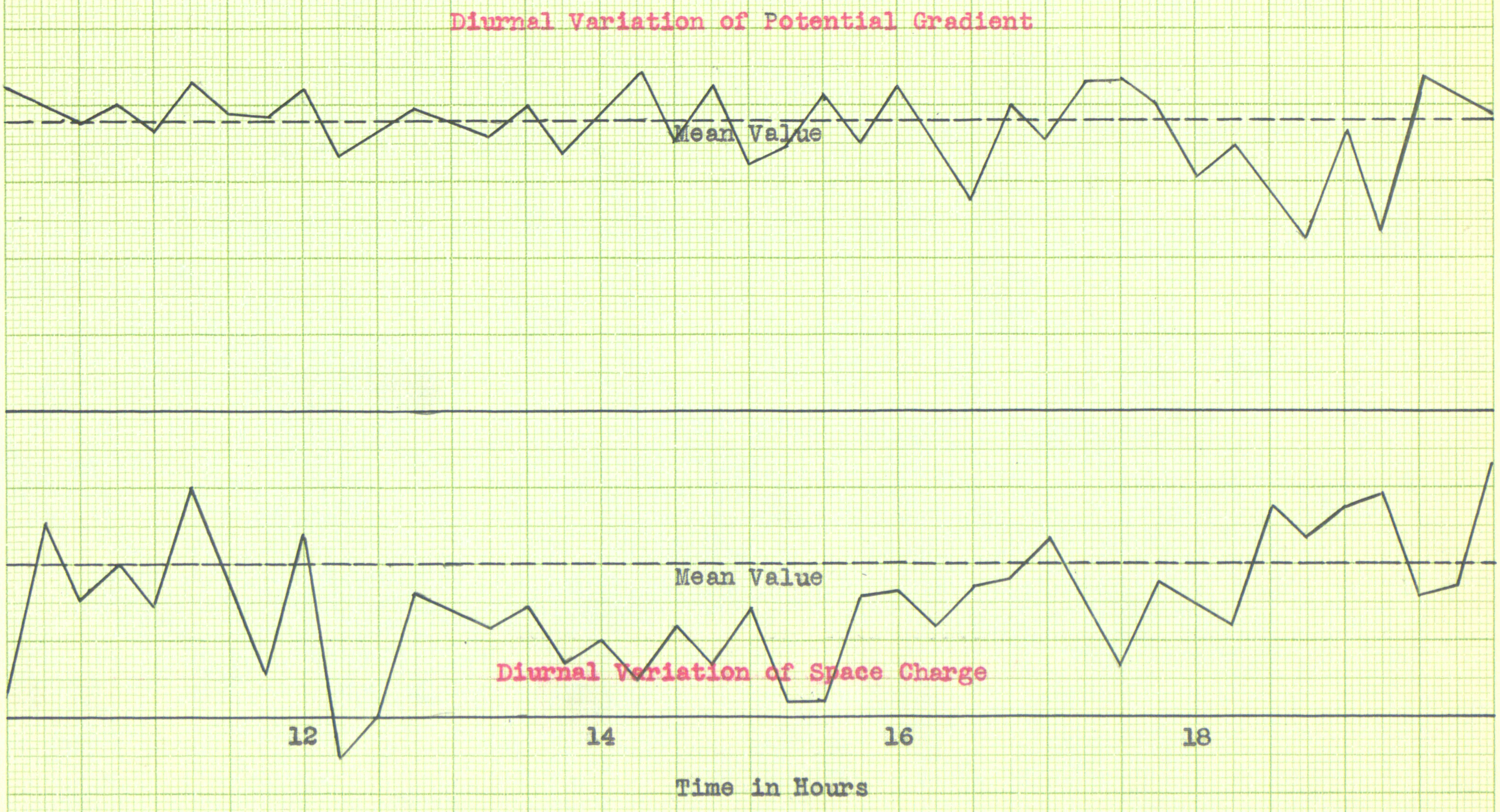
Cincinnati, July 4, 1929

Graph No. 2, Part 2

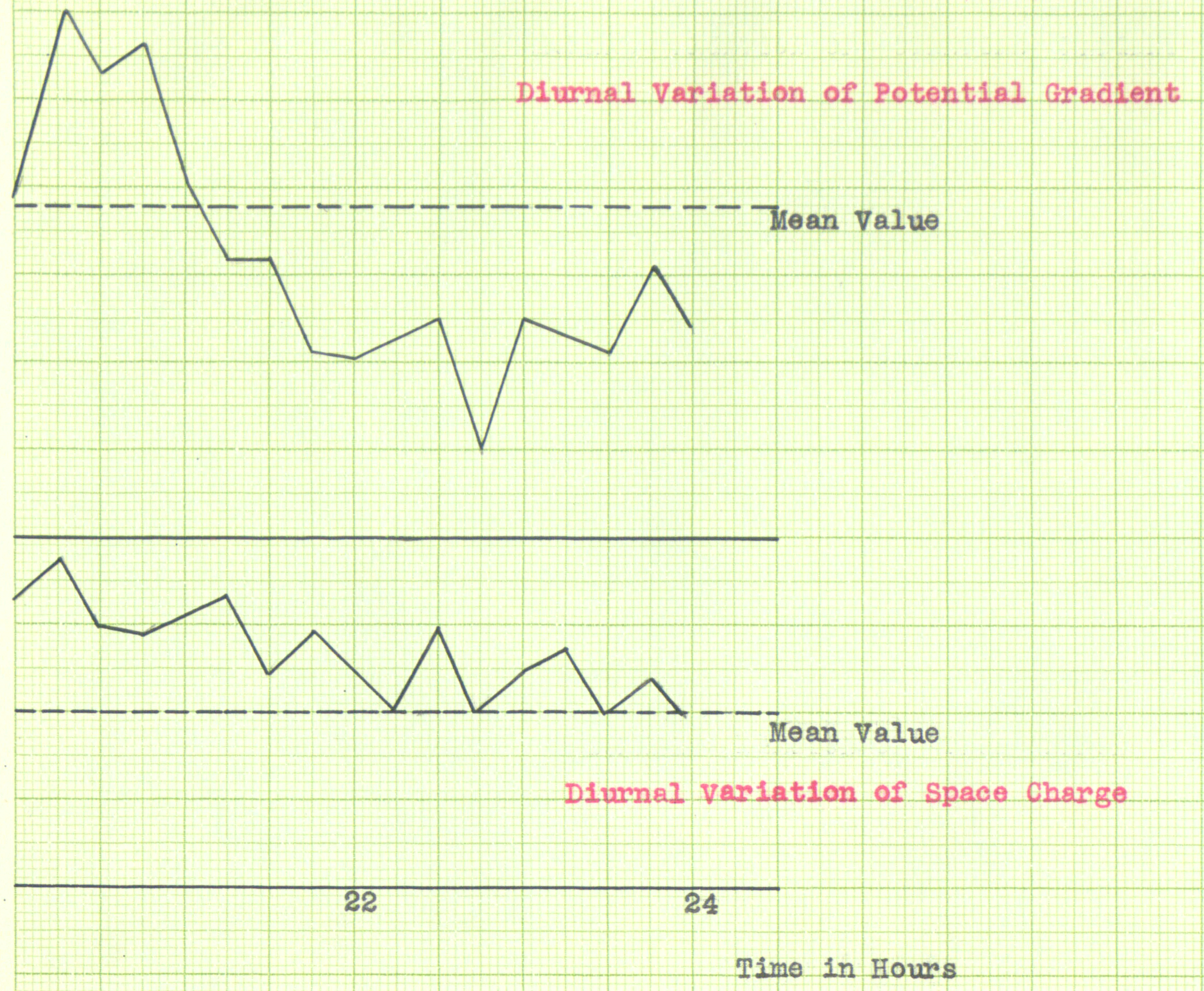
Cincinnati, Spring of 1930
Graph No. 3, Part 1
(Eastern Standard Time)



Cincinnati, Spring of 1930
Graph No. 3, Part 2
(Eastern Standard Time)



Cincinnati, Spring of 1930
Graph No. 3, Part 3
(Eastern Standard Time)



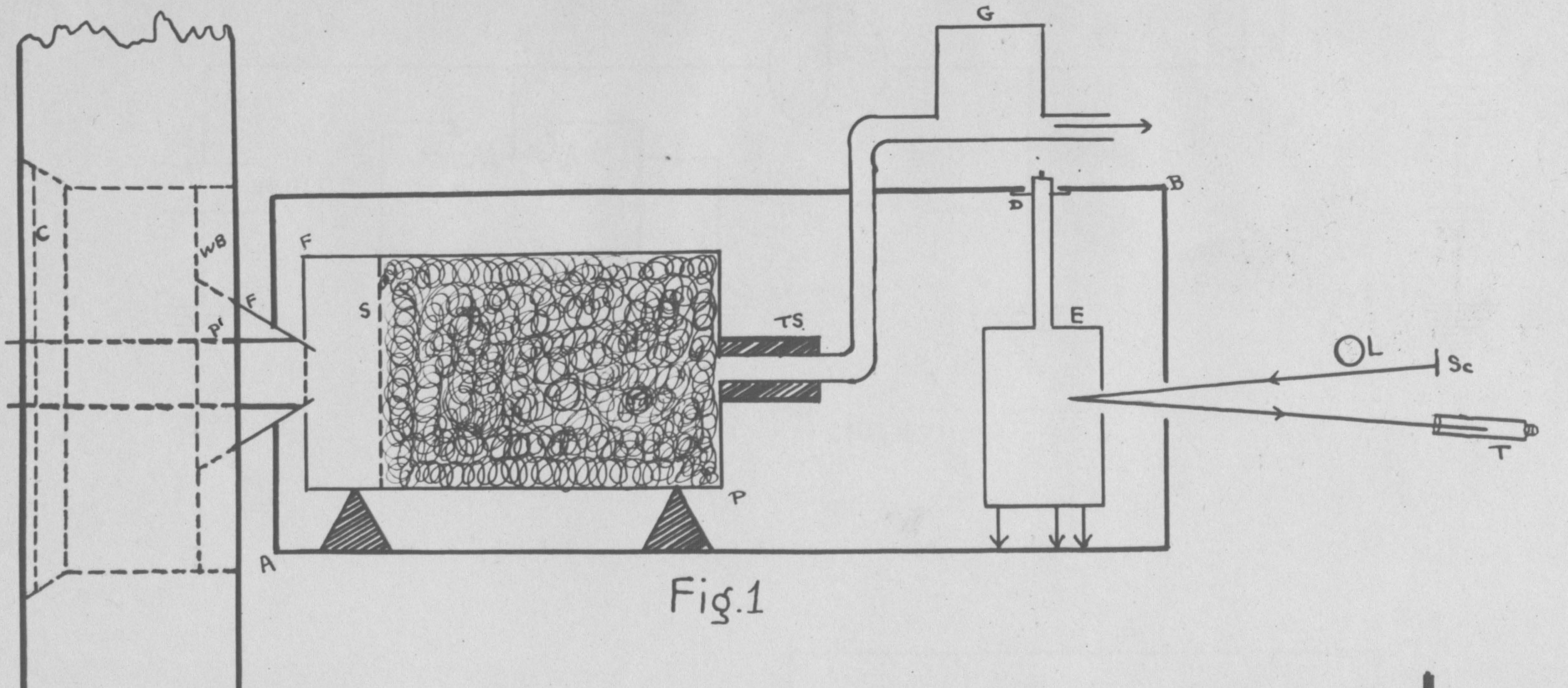


Fig.1

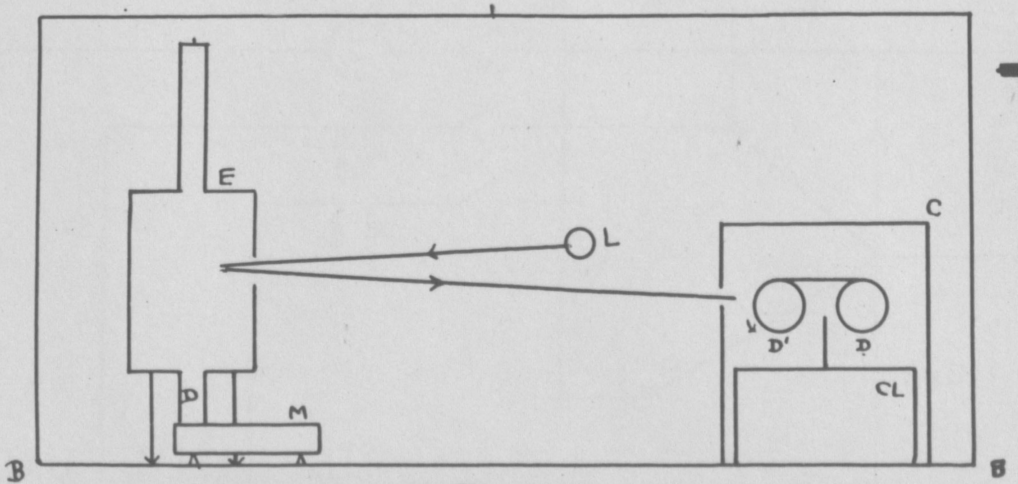


Fig. 2

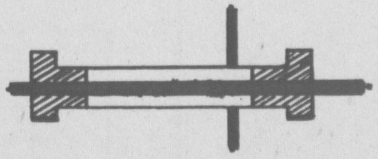
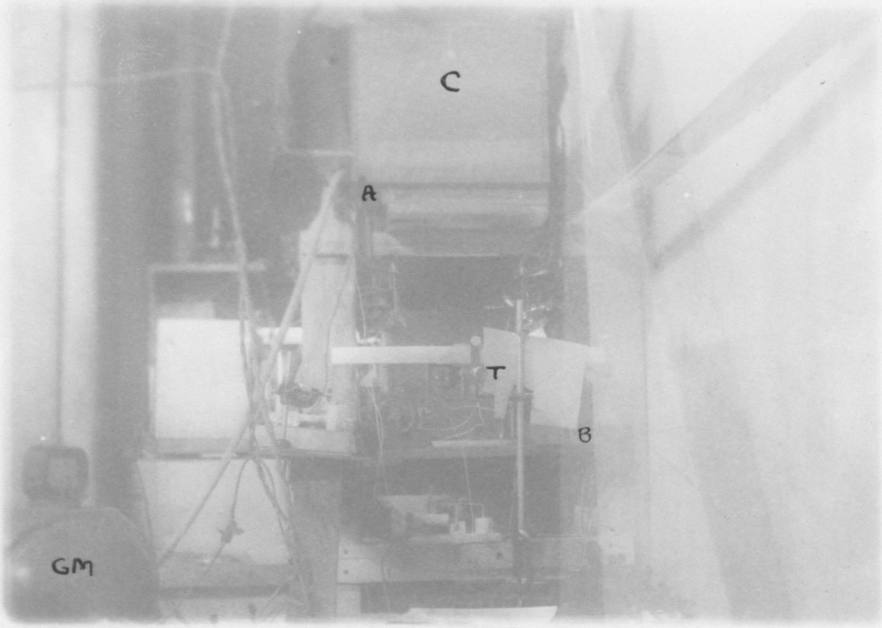


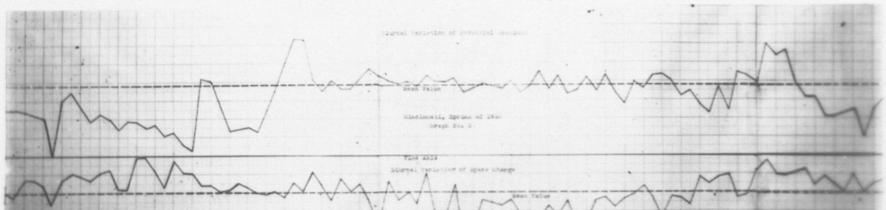
Fig.3



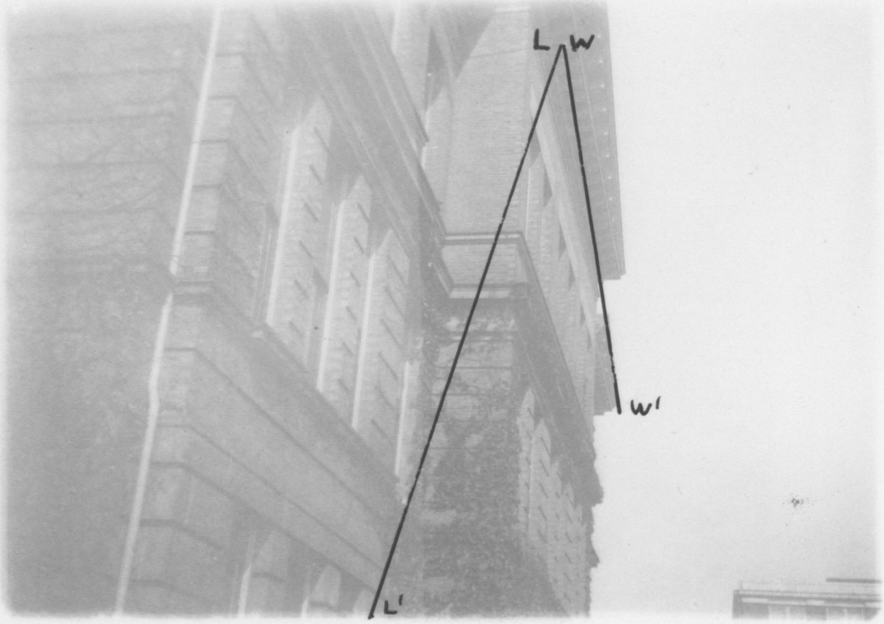
View No.1

View No.2

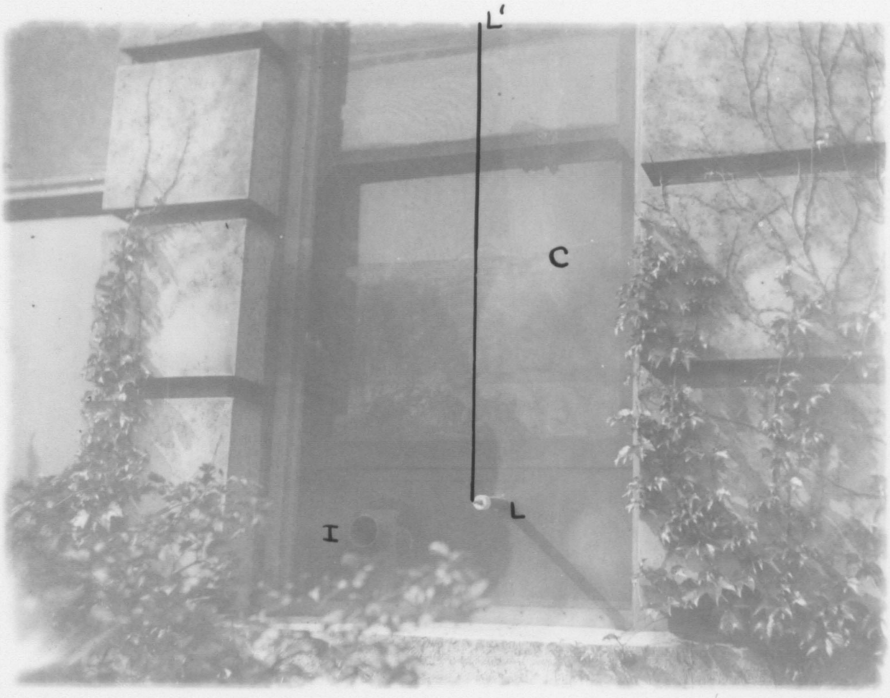
View No.3



View No.4

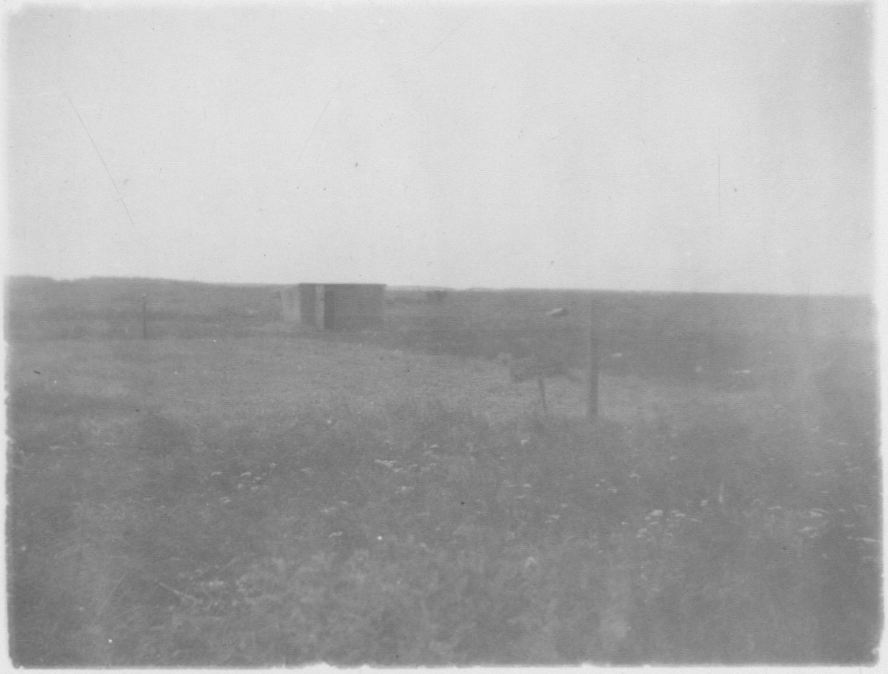


View No.5



View No.6

View No.7



View No.8