THE ULTRAVIOLET LIGHT THEORY OF AURORAE AND MAGNETIC STORMS. CONTINUED*

By E. O. Hulburt
Naval Research Laboratory

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Abstract

The ultraviolet light theory of aurorae and magnetic storms, Phys. Rev. **33**, 412 (1929), **34**, 344 (1929), did not agree with all the facts. Making use of the further development of the theory of the outer atmosphere, Phys. Rev. **34**, 1167 (1929), **35**, 240 (1930), the discrepancies in the ultraviolet theory are removed with no change in the original assumptions. The first phase of the average world-wide magnetic storm is attributed to the sudden increase in the eastward ion drift current which girdles the earth caused by an increase in the long free path ions produced by a solar ultraviolet flare. The second phase of the storm comes about from the heating of the high atmosphere by the flare. The atmosphere expands and the outward movement of the ionized regions across the earth's magnetic field gives rise to a westward current in the high atmosphere flowing around the earth. The movement also decreases the long free path ions and increases the short free path ions; this prolongs the westward current.

Assuming that the earth has no excess charge the high flying ions distilled from low latitudes fall into the top of the atmosphere of the auroral latitudes in maximum numbers at about 1 P.M. It takes them until about 6 P.M. to fall by diffusion and electrical drift down to the short free path levels at 100 km. They set up a system of electrical currents in the high atmosphere wheeling in a rather distorted course around a focus at about 6 P.M. in latitude 60° to 70°, one system in the arctic and one in the antarctic. The current systems give rise to the diurnal variations of the average world-wide magnetic storm. If the earth has a resultant charge in excess of about 50 coulombs the present theory would probably be untenable, or would require extensive modification.

The lower limits of the long and short free path ion banks of the polar atmosphere agree, respectively, with the observed lower boundaries of the streamers and the structureless luminosity of the aurora.

1. Introduction

THE ultraviolet light theory of aurorae and magnetic storms,[1] which was sketched out last year, was found to agree with the main features of the phenomena. However, the theory contained some unsettled points and did not agree with certain details of the observations. At the time it was difficult to know where the trouble lay. The further development of the theory of the high atmosphere[2,3] has permitted a clearer insight into the actions which occur there and, as shown in the present paper, has removed some of the discrepancies which existed in the ultraviolet light storm theory. So that the theory without any changes in the original assumptions begins to assume a more finished appearance.

* Published with the permission of the Navy Department.

[1] Maris and Hulburt, Phys. Rev. **33**, 412 (1929).

[2] Hulburt, Phys. Rev. **34**, 1167 (1929).

[3] Hulburt, Phys. Rev. **35**, 240 (1930).

2. The World-wide Magnetic Storm

During the average world-wide magnetic storm the horizontal component H_1 of the earth's magnetic field H increases quickly for a few minutes or a half-hour, the initial phase, and then in a few hours decreases to a value below normal returning gradually to normal in a day or so, the final phase. The vertical component H_2 experiences the opposite series of changes, first decreasing quickly then increasing to a value above normal and descending to its normal value slowly. (See the curves of Fig. 3, ref. 1.) The ultraviolet light theory attributed the initial phase of the storm to the eastward ion drift currents in the high atmosphere arising from a sudden increase in the ionization above 150 km levels caused by a sudden flare of ultraviolet light from the sun. The theory suggested that the final phase of the storm was due to the reaction of induced currents in the earth. Such a reaction would cause changes in agreement with those observed for H_1 but not for H_2. It is now seen that all of the average storm variations of H_1 and H_2 are attributable to effects in the high atmosphere and that the earth currents are of secondary importance. Chapman[4] in a recent criticism has dwelt upon the discrepancy which existed in the case of H_2. The difficulty lay, however, in the fact that we used Chapman's[5] value of the earth's conductivity to estimate the induced earth currents, and with his value the earth currents could not be neglected. It has turned out, see section 3, that his value is probably widely in error.

It was shown[2] that during solar quiescence there is a steady current of about 3×10^6 amperes flowing eastward around the earth in the high atmosphere which produces a northward magnetic field of about 400γ (γ is 10^{-5} gauss) at the equator in agreement with the observed value 450γ of the field of external origin. The current is due to the magnetic gravitational drift of the long free path ions. Over the daylight hemisphere the 3×10^6 ampere current is made up of an eastward current sheet of about 12×10^6 amperes in the long free path ion region, the D region, and a westward current sheet of 9×10^6 amperes in the underlying short free path ion region, the S region. The height z_c above sea-level of the boundary between the D and S regions is at about 150 km at equinoxial noon at the equator. In the night hemisphere the current flows eastward in both the D and S regions and amounts to 3×10^6 amperes. The ultraviolet flare may be expected in general to increase the ionization in both the D and S regions, although different flares may increase the D and the S ions by different amounts. An increase in the D ions results in an increase in the eastward current in the daylight D region and hence in the 3×10^6 ampere current which girdles the earth. H_1 then increases and H_2 decreases as in the first phase of the storm. An increase in the daylight S ions causes an increase in the electrical conductivity of the daylight S region and hence an increase in the westward daylight S current. This reduces the eastward 3×10^6 ampere current and therefore amounts to a westward

[4] Chapman, Monthly Notices Roy. Ast. Soc., Geophys. Sup. **2,** 296 (1930).

[5] Chapman, Phil. Trans. **A218,** 1 (1919).

storm current girdling the earth; H_1 is reduced and H_2 is increased, as in the second phase of the storm.

There is an additional effect which is common to all types of flares, namely a heating of the high atmosphere above the, say, 50 km level. The heating may be due to a direct absorption of the energy of certain wave-lengths in the spectrum of the flare or may come about directly. For example, the ionization produced at high levels descends to lower levels where recombination takes place and the energy of recombination heats the atmosphere. The heating causes an outward expansion of the upper atmosphere which has already been calculated for a particular case.[1] Evidence of the expansion is afforded by experiments with pulses of wireless signals which indicated that the ionized layers are lifted up during a magnetic storm.[1] The expansion of the atmosphere produces two reactions, a "dynamo" effect and an "engulfing" effect. The dynamo effect is the result of the movement of the S region across the earth's magnetic field, and is a maximum in tropical latitudes where H is approximately horizontal. An upward motion of the daytime S region gives rise to an induced westward electric field and therefore causes a westward current flowing around the earth; this reduces H_1. An upward velocity of 25 km hr^{-1} of the S region reduces H_1 by about 250γ at the equator, the case of an intense storm (ref. 2, section 30). The engulfing effect, also a maximum in tropical latitudes, depends on the fact that where H is approximately horizontal the D ions can only move a short distance across H between collisions and are therefore hindered from moving upward freely with the neutral particles of the expanding atmosphere. Thus, after the initiation of the storm, the D ions near the z_c level find themselves in a mounting tide of air molecules; their free paths are shortened and they become S ions. Since the D ions experience many collisions before being lost by recombination (ref. 2, section 29), the daylight S ions are increased at the expense of the D ions with a consequent effective westward storm current.

We may picture the sequence of events in the average world wide storm as follows: the solar flare by its ionizing energy first increases the D ions, increasing H_1 to a value above normal, as in the initial phase of the storm. In the second phase the heating effects of the flare make themselves felt, the high atmosphere expands, the ionized layers move upward and H_1 decreases for a few hours. When the layers cease their upward movement H_1 would increase to its previous value above normal were it not for the fact that in the meantime the engulfing effect has reduced the D ions, so that actually H_1 increases to some value below normal. Thereafter H_1 increases slowly to its normal value as the flare dies away, the storm ionization diminishes and the atmosphere settles down to its quiet day condition. Magnetic storms in which the initial phase is not pronounced, or is absent altogether, and which therefore consist only of the second phase, are fairly common. In these cases we may suppose that the flare emits mainly energy which heats the high atmosphere and produces S ionization without much D ionization. Storms made up only of the first phase are rare. Such a storm would be produced by a flare which gave rise to D ionization with little S ionization or heating; this would seem to require a flare with unusual spectral characteristics. The fact that in general the most intense storms are of short duration is in keeping with the present theory because the more rapid the outward expansion of the atmosphere the greater is the induced westward current, due to dynamo action, in the second phase of the storm.

The intensity of the world-wide storm is a maximum at the equator, decreases with increasing latitude to a minimum at about 50° or 60° north or south, and then increases in the auroral zones around 70°. These facts find a simple explanation on the ultraviolet theory. The eastward storm current of the first phase of the storm has already been shown to be a maximum at the equator (ref. 1, section 13). With regard to the westward current during the second phase of the storm we note that the magnetic field H is horizontal at the equator and tilts up with increasing latitude; H is inclined 49°, 70° and 90° to the horizontal at magnetic latitudes 30°, 60° and 90° respectively. Therefore the dynamo effect in the S region and the engulfing of the D ions by the heated and expanding atmosphere are a maximum at the equator and fall off rapidly with increasing latitude. Hence the westward storm current is a maximum at the equator. The auroral latitudes receive a double contribution of ionization, that produced directly by the solar flare and that which distills in from the lower latitudes (see curve 2, Fig. 1). Therefore the storm effects will increase again at the high latitudes. It is hardly necessary to mention, what we have often stated before, that a complete theory would probable consider the winds which flow from the daylight to the night areas. In the high atmosphere the winds may be very rapid, especially during a magnetic storm and their effects may be important.

3. The Induced Currents in the Earth

The electrical currents in the high atmosphere to which the present theory attributes the average world-wide storm variations in H will induce currents in the earth. From certain facts of the quiet day diurnal variations in H Chapman,[5] following the method of Schuster, has calculated the resistivity ρ of the core of the earth to be 2.5×10^{12} e.m.u. the calculation was based on the assumption that ρ was constant throughout the earth, except of course for an outer crust of higher resistivity. The assumption was obviously faulty, and Gunn[6] has recently shown that the method gives no exact information about ρ in the core of the earth. We can go a step farther and show that the value 2.5×10^{12} is untenable. The relaxation time τ for the current in a circuit of inductance L and total resistance R to fall to $1/\epsilon$'th of its value is

$$\tau = L/R. \quad (1)$$

The inductance of the earth[7] is 7.8×10^{8} e.m.u. and with $\rho=2.5\times10^{12}$ R is about 10^{4} e.m.u. From (2) $\tau=22$ hours, which is roughly the duration of the westward atmospheric current during an average magnetic storm.

[6] Gunn, Terr. Mag. and Atmos. Elec. **35**, September (1930).
[7] Lamb, Phil. Trans. **174**, 519 (1883).

Therefore there would be a westward current induced in the earth after the westward atmospheric storm current dies away which would cause certain variations in H; it would reverse the storm decrease in H_1 and maintain the storm increase in H_2. Such variations are not observed and therefore ρ can not be 2.5×10^{12} in the earth's core. Because the core is hot it is reasonable to think that ρ is much less than 2.5×10^{12}. In such a case, taking into account "skin effect" calculated from the usual formula,[8] the relaxation time will be much longer than 22 hours and the induced reactions in the core would be negligible for periods of the order of a day or less.

The effects of the induced reactions in the oceans are probably appreciable. The current will flow in large loops. With a loop about 30,000 km around, 10,000 km wide and 5 km thick, as might occur in the South Pacific Ocean, and with $\rho=2\times 10^{10}$ e.m.u. for sea water τ is about an hour, probably an over-estimate. Thus if the atmospheric currents undergo fluctuations of periods of an hour or so, as they often do, the ocean reactions may be pronounced. To work out the effects to be expected at any magnetic observatory due to the neighboring oceans promises to be complicated and we shall not go farther with the problem at this time. It may require a careful scrutiny of the data of magnetic observatories scattered over the earth. For earth girdling currents in the S region of the atmosphere τ is about 20 minutes.

4. Diurnal Magnetic Storm Variations

The diurnal magnetic storm change in H varies with the local time of the observing station according to the curves of Fig. 4, ref. 1. By mistake curve 5 of the figure was drawn reversed; it should be similar to curve 4. The diurnal storm variation was ascribed to the influence of high flying ions distilled into the auroral regions from the lower latitudes. Neutral atoms and molecules were assumed to be sprayed out from the outer fringe of the atmosphere to distances as great as 50,000 km where they were ionized by the ultraviolet light of the sun. The ions in their descent back to the earth were guided by the magnetic field and accumulated in the auroral zones in the afternoon. By their diamagnetism they caused changes in the earth's magnetic field. The calculated changes agreed with most of the curves of Fig. 4, ref. 1, but not with all of them. Now that more is known about the conductivity of the upper atmosphere[2,3] we see that the diamagnetism is not as important as the gravitational magnetic drift currents of the auroral ion concentration. As shown later, the magnetic effects of these currents agree with all of the facts as embodied in the curves of Fig. 4. In order, however, to calculate the magnetic effects we must examine in detail the course of the high flying ions in their descent into the atmosphere of the auroral regions.

The number of fast moving neutral particles sprayed away from the outer regions of the sunlit atmosphere in a direction θ was assumed to be proportional to $\cos\theta$, where θ is the angle with the line joining the earth and the

[8] Jeans, Electricity and Magnetism, page 479 (1925).

sun.[1] Therefore, if the earth did not rotate on its axis and had no excess electrical charge, the ion concentration in the auroral latitudes from 60° to 70° magnetic produced by the high flying ions would be a maximum at noon. The earth does rotate, however, and we shall assume as was done throughout the earlier papers that the earth is uncharged as a whole. For this case Page[9] has shown that ions beyond an earth's radius away from the outer atmosphere move along the lines of the earth's magnetic field without being influenced by the earth's rotation; that is, their paths are practically the same whether the earth rotates or not. Ions at nearer distances begin to partake of the earth's rotation until in the atmosphere they move with the full rotational velocity of the earth. (I pointed out[10] that the effect of collisions between long free path ions and neutral molecules of the atmosphere might modify Page's calculation, but Page[11] showed that the effect could be included in those which he had already discussed[9] on page 830). From Page's[9] equation (16) it is seen that high flying ions formed on the noon meridian at heights around 30,000 to 50,000 km fall into the auroral zones at about 1 P.M.

Therefore q, the number of high flying ion pairs which descend per cm^2 per sec into the top of the atmosphere of the auroral zones is a maximum at about 1 P.M. and falls off roughly with the cosine of the longitude from the 1 P.M. meridian. q was estimated to be 3×10^7 ion pairs cm^{-2} sec^{-1} (ref. 1, page 421) during solar quiescence, probably a low estimate. During the magnetic storm q is greater than 3×10^7 and during the hours that the solar flare is most active we assume q to be 2×10^{11}. We take the daytime molecular densities in the high atmosphere of the auroral latitudes to be the same as those given by Maris[12] for a summer night in temperate latitudes. At any height z the molecular density n is given by[13]

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

where $p=1.41\times10^{-6}$. The 2×10^{11} ion pairs are probably positive ions and electrons. They fall freely along the lines of the earth's magnetic field into the atmosphere of the auroral zones and continue to descend through the atmosphere by temperature diffusion and electric-magnetic drift.[2] Calculating the temperature diffusion by the method of a former paper, ref. 13, page 1027, we find that the electrons form a bank with a maximum density at about 160 km. Below 160 km the electrons become attached rapidly to oxygen molecules to form negative oxygen molecular ions. The recombination of the electrons with positive ions is small compared to the attachment, and therefore the region above 160 km is a source of 2×10^{11} ion pairs. These form an ion bank as given by the y, z curve 1, Fig. 1. The maximum value of y is 2.35×10^9 at $z=130$ km. 1.23×10^{11} ion pairs cm^{-2} sec^{-1} move downward across the 130 km level (calculated by equation (3), ref. 13) and therefore

[9] Page, Phys. Rev. **33**, 823 (1929), equation (16).
[10] Hulburt, Phys. Rev. **35**, 1587 (1930).
[11] Page, Phys. Rev. **36**, 601 (1930).
[12] Maris, Terr. Mag. and Atmos. Elec. **33**, 233 (1928); **34**, 45 (1929).
[13] Hulburt, Phys. Rev. **31**, 1018 (1928).

their downward velocity is $1.23\times10^{11}\div2.35\times10^{9}=52$ cm sec^{-1}. Since the loss of ions by recombination is small above $z=130$ km the downward diffusion velocity of the ions in these levels is proportional to $1/y$. In particular, the velocity is 250 cm sec^{-1} at $z=140$ km. The electric-magnetic drift velocity v, which is downward in the day hemisphere, has about this same value (section 27 and column 9 of Table 1, ref. 2) throughout the D ion region, i.e. above $z_c=110$ km. Therefore the y,z curve 1, Fig. 1, which has been calculated using gravity diffusion is approximately correct for z greater than about 135 km. Below this level the drift velocity v is more important than temperature diffusion, and hence from 135 km down to z_c we calculate the y,z curve by means of equation (16), ref. 2. This gives curve 2, Fig. 1. Below z_c temperature diffusion is important again, and the curve is found to fall to low values of y below $z=100$ km.

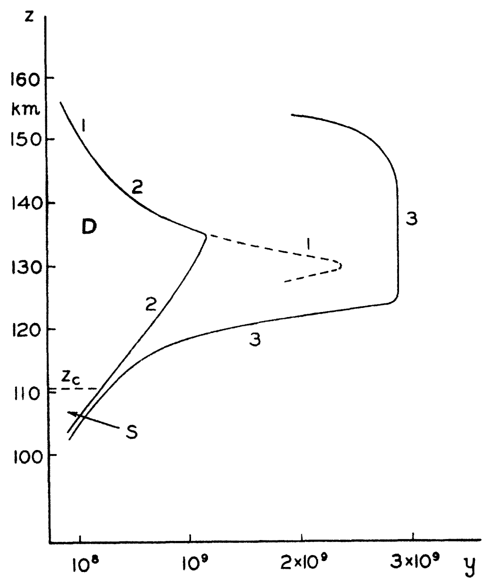

Fig. 1. Ion density y in auroral latitudes; curve 3 for noon on a quiet day, curve 2 the additional ions at about 6 P.M. during a magnetic storm.

Curve 2, Fig. 1, is approximately the ion bank which would be produced by 2×10^{11} ions cm^{-2} sec^{-1} falling down into the atmosphere of the auroral zones and represents the increase in the ionization during a magnetic storm. However, the curve is not entirely correct, the values of y below $z=125$ km being about twice as great as they should be, for two general approximations have entered into the calculations. In the first place we have determined the storm curve disregarding the ionization which was already present. The quiet day ionization at noon is given in curve 3, Fig. 2. This is the y,z curve of Fig. 2(c), ref. 2, with the ordinates lowered to accord with the n,z curve of equation (2). Since the rate of ionic recombination is proportional to y^2 (equations (7) and (9), ref. 13), it comes out that the storm ions produced by $q=2\times10^{11}$ which are added to the quiet day ions of curve 3, Fig. 1 are only about ½ of the ions of curve 2, Fig. 1, in the region below 125 km. In the second place curve 2 is a steady state solution; it is the ion curve which would be formed if the rate of supply q persisted long enough. D, the total number of ion pairs in a 1 cm² column vertically upward through the ion bank of curve 2, is 2.6×10^{15}. With $q=2\times10^{11}$ it would take 1.3×10^4 sec or 3.6 hours to build up the ion bank, if there were no lossess; there are losses of course due to recombination. The solar flare may not persist at full intensity for this length of time. Or even if it did, q is not a constant, because of the rotation of the earth, and varies with the hour angle from 1 P.M. Thus a steady state may never be attained during the magnetic storm.

In spite of the numerous approximations we take curve 2, Fig. 1, as giving a rough idea of the storm ionization in auroral latitudes at 6 P.M. The total time for the ions to descend from the top of the atmosphere at about $z=200$ km to the z_c level at 110 km is 4 or 5 hours. Since q is a maximum at 1 P.M. the ion density at z_c is a maximum at 5 or 6 P.M. The magnetic-gravitational

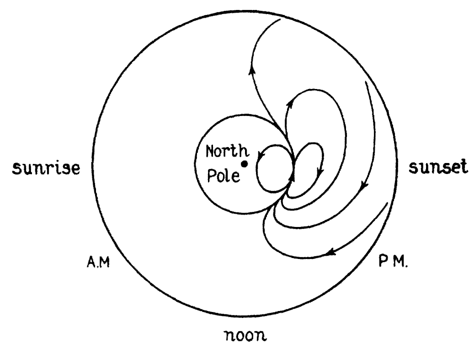

Fig. 2. Theoretical currents in the high atmosphere which cause the diurnal magnetic storm variations. View looking down on the North Pole. Aurorae and magnetic storms.

drift current [1,2] of the D ions is eastward. The current is connected to the S ion region by the D ions which descend across z_c and the circuit is completed in the S region. Using the values of the electrical conductivity σ in the S region (Fig. 2, ref. 3), the lines of current flow are as sketched in Fig. 2; the figure is a view looking down on the North Pole of the earth. This current system causes changes in the earth's magnetic field in entire agreement with the observed diurnal magnetic storm variations in H. With $D=2.6\times10^{15}$ the ion drift current density is 3.7×10^{-5} and 8.5×10^{-5} e.m.u. for atomic nitrogen and molecular oxygen ions, respectively (ref. 2, section 13), and the respective values of H_1 are 23 and 52γ. These values agree with the observed values which are around 40γ for an average storm.

5. The Aurora

The ion storm curve 2, Fig. 1, leads to an explanation of some details of the aurora. It is the energy of these ions which gives rise to the strong auroral displays accompanying magnetic storms. These intense displays occur usually in the evening hours in auroral latitudes.[14] Vegard, Krogness, Störmer and others[15] found that the lower limit of the auroral streamers was at about 100 km and of the clouds and diffuse arcs and draperies was at about 85 km. The z_c level of curve 2, Fig. 1, is at 110 km and if, instead of Maris' n, z curve for summer night which we have used to refer roughly to arctic day conditions, we use his n, z curve for winter night conditions, the ion curve 2 should be lowered about 10 km. This puts the night z_c level at 100 km. In the D region above z_c the free path of the ions is large compared to the radius of magnetic gyration. Therefore groups of D ions are guided by and outline the earth's magnetic field to form the auroral streamers. Below z_c the guidance of the magnetic field is lost, the streamers end at 100 km, and the luminosity in the S region is structureless. The S ionization falls to low values at about 10 km below z_c in accord with the observed lower boundary of the structureless luminosity at about 85 km. Altogether the agreement between the theory and the details of the aurora seems very striking.

6. The Bearing of the Ultraviolet Light Theory on the Charge on the Earth

In general the theory of the ionization of the high atmosphere by solar ultraviolet light, and in particular those portions of the ultraviolet light theory of aurorae and magnetic storms which depend upon atmospheric ions flying at distances up to 70,000 km from the earth, and the recent theory of the zodiacal light[16] would be disturbed by appreciable electric fields in the high atmosphere. Page[9] showed that an excess charge on the earth of 72 coulombs would, if distributed in a certain way, give rise to an electric field which together with the earth's magnetic field would cause the high flying ions to swing around with the rotational velocity of the earth. They would then cause effects contrary to the experimental facts. We may conclude that if the total excess charge on the earth were greater than, say 50 coulombs, the ultraviolet light theories would be untenable, or would require considerable modification.

The earth, however, is observed to have a negative charge of about 10^5 coulombs; there is a positive electric gradient outward from the earth and an outflowing current of negative electricity in the air around us which, totalled over the earth, amounts to about 1400 amperes. The assumption of an earth electrically neutral as a whole was reconciled with these terrestrial electrical phenomena through the thunderstorm theory of C. T. R. Wilson.[17] Wilson suggested, and obtained some experimental evidence in favor of his views, that the outflowing negative current is returned to the earth by thunder

[14] Mawson, Australasian Antarctic Expedition 1911–14, Scientific Reports, Series B, Vol. 2, page 173 (1925).

[15] Wien Harms, Handb. d. Exp. Phys. **25,** 392 (1928).

[16] Hulburt, Phys. Rev. **35,** 1089 (1930).

[17] Wilson, Trans. Roy. Soc. **221,** 73 (1921); Proc. Phys. Soc. London, **37,** 32D (1925); Nature **119,** 502 (1927); Franklin Inst. Jr. **208,** 1 (1929); etc.

clouds. Therefore we assumed (ref. 13, page 1022) that there was a positive charge in the atmosphere below, say 50 km equal to the negative charge on the earth, and approximately no excess charge and no electric field in the high atmosphere. W. Anderson's[18] recent theory of the earth's negative charge assumed that positive electricity is continually annihilated in the earth thereby supplying the earth with the negative electricity necessary to maintain the observed negative charge and outflowing negative current. The theory apparently holds that the earth has an excess negative charge of something like 10^5 coulombs and that there is a strong electric field in the high atmosphere. It is seen that the ultraviolet light theory and Anderson's theory are based on conflicting assumptions and can not both be upheld at the same time.

[18] Anderson, Zeits. f. Physik **42,** 475 (1927); **44,** 376 (1927).