DOPPLER DISPLACEMENT OF AURORAL HYDROGEN LINES AND ITS BEARING ON THE THEORY OF AURORA AND MAGNETIC DISTURBANCES

BY

L. VEGARD

(Manuscript received December 7th, 1951.)

1. Introductory Remarks.

According to Birkeland the aurorae and the more prominent magnetic disturbances are caused by bundles of electric rays (cathode rays) from the sun-spot regions on the sun. By the way in which these bundles are acted upon by the magnetic field of the earth, he found by simple reasoning and laboratory experiments, that his hypotheses explained essential features of the auroral display and certain types of magnetic disturbances. Without going further into the question, Birkeland thinks of the ray-bundles as being formed by corpuscles with the same sign of charge.

In his extensive mathematical treatment of Birkeland's hypotheses, Størmer studied the motion of an electrified particle exposed to the deviating force of the magnetic field of the earth. Birkeland's experiments and the results derived from auroral and magnetic observations, as well as Størmer's mathematical theory, were able to explain the typical auroral forms, and the peculiar distribution of aurorae and magnetic disturbances with regard to space and time.

The hypothesis of Birkeland was criticized by Schuster (2) who called attention to the fact, that the formation of limited bundles of rays carrying a charge of the same sign, would be disturbed by electrostatic repulsion.

The possible influence of the mutual electrostatic repulsion between the ray particles of a bundle formed by carriers of the same sign of charge and the possible constitution of the solar electric rays responsible for aurorae and magnetic disturbances, were treated in a paper by Vegard (1) published in 1916. It was shown that the sun must send out streams of electrified particles in such a way that the outward flux of positive and negative electricity taken as the mean over the sun's surface and over a certain time, must be equal.

This state of things does not exclude that within certain solid angles the flux—say of negative particles from the sun—may be greater than that of the positive, because the balance may be restored in other directions, where the flux of positive particles is greatest. Vegard therefore assumes that the aurorae (and certain types of magnetic disturbances) are due to ray-bundles of e.g. electron rays electrostatically neutralized by positive ions. Such a bundle is not subject to Schuster's objection to the Birkeland hypotheses.

In 1918 Chapman (3) proposed a theory of aurora and magnetic disturbances based on the assumption of a stream of electrified particles of one sign evenly distributed in all directions from the sun. The results given in the paper by Vegard referred to, show that this hypothesis must be abandoned, and the same opinion was expressed by Lindemann (4).

Some years later Chapman in collaboration with Ferraro (9) suggested a modified theory of magnetic storms also based on the assumption of a fairly uniform stream of ions from the sun, but it was now assumed that in each volume element the total charge of negative ions was equal to that of the positive and that the radial flux of positive and negative electricity was the same, which means that the current density of the ion stream was equal to zero.

The theory deals with the influence, which the earth's field may have on such a stream of a neutral plasma. It cannot be seen, however, that this theory is capable of explaining the typical forms of aurora and magnetic disturbances or their distribution with regard to space and time.

The properties of limited electrostatically neutralized bundles of electric rays, have been more fully dealt with in a number of subsequent papers e.g. (7), (8), (11), (12), (13), (14), (23), (32).

In fact the geographical and diurnal distribution of aurorae and magnetic storms, shows conclusively, that the ray bundles forming them must be magnetically active and be deflected, in the Earth's magnetic field in a way essentially of the type shown by Birkeland's experiments and by the mathematical theory of Størmer as though they were composed of particles of one sign of charge. This involves that although the bundle is electrostatically neutralized, the negative and positive particles move with different velocities.

If e.g. the bundle is composed of electrons and protons, the current density in a neutralized stream will be (cfr. e.g. paper 12, p. 612):

$$i = ne\ (V_e - V_p) \tag{1}$$

(n) is the number of protons or electrons in unit volume. The electron velocity (V_e) is supposed to be greater than that of the protons (V_p).

The view regarding the constitution of the electrical ray bundles was strongly supported from results derived from the study of the auroral spectrum, which revealed the fact that nitrogen bands predominate in the auroral spectrum to the very top of the highest auroral streamers reaching altitudes of say 800–1,000 km (6). This result together with the fact that the temperature measured from the intensity distribution of the rotational components of the auroral nitrogen bands is very low showed that the density of matter in the auroral region diminishes more slowly than can be accounted for by the ordinary barometric height formula, based on the assumption that the atmospheric gases are only acted on by the gravitational field. Thus in the auroral region, above say 80–100 km, the atmosphere develops into a state similar to that of the solar corona.

The formation of this terrestrial corona was explained as due to photo-electric action of a soft X-radiation from the sun. The upwards moving photo-electrons have a much greater mean free path than those moving downwards. An electric double layer is formed within which the positive ions will be acted on by an upwards directed force which will partly counter balance the effect of gravity on the atmospheric matter.

As the solar X-radiation acts with even much greater intensity on the matter composing the solar atmosphere, the theory of the upper atmosphere was almost directly applicable to the solar corona. This theory of the solar corona has been dealt with in a series of previous papers, see e.g. (7, 8, 10, 11, 12, 14).

In this connection it is of particular interest to mention that according to this theory the corona is composed of fairly swift photo-electrons followed by positive ions of great specific charge (e/m), preferably protons and possibly some highly-ionised atoms of other elements.

This coronal theory was also applied to account for the formation of the ray bundles, which produce aurorae and magnetic storms, cfr. papers (7), (8), (12), (14).

In paper (12) p. 613 the explanation is expressed in the following way: «Through the vortex motion which is attached to the sun-spot activity, masses from the interior are supposed to be brought up to the surface. These masses have a large store of energy and may be highly ionized. *Through the recombination process, which takes place near the surface, light of very short wavelength of the type of X-rays may be formed and electrons of high speed will result from photo-electric action.* The emitted electrons take the form of a narrow bundle because the effective source is very limited and because the electron-rays will have a tendency to follow the lines of force of the local solar magnetic fields which are attached to the sun-spots*). The active masses, pumped up to the surface, may be very large and store much energy and may last during several revolutions of the sun, thus explaining the fact that strong magnetic storms and aurorae appear after 27 days and may continue to do so after several revolutions and after any visible trace of the original sun-spot-group has disappaeared.$_a$

As stated e.g. in paper No. 7 p. 35:

" *The bundles of electron rays must immediately cause an increase of emission of positive rays, which most probably will follow in the track of the negative ones, and in that way they will form bundles with very much the same constitution as the coronal streamers. This constitution of the auroral ray bundles, would have a great influence on the auroral theory and especially on the track followed by the ray-bundles under the influence of the magnetic field of the earth. The attachment of positive particles to the cathode rays would very much reduce the effective specific charge of the whole bundle, and thus we might explain that fairly slow cathode rays with the proper penetrating power, might still have their magnetic deviability so much reduced as to give a diameter of the auroral zone equal to that observed.*"

This view regarding the formation of coronal streamers and ray bundles, originating from sunspot areas, did not merely account for the formation of the soft X-rays, which form the basis of the theory of the terrestrial and solar corona, but it also suggested an interpretation of the coronal emission lines (given in paper 7, p. 33) according to which the coronal lines might originate from forbidden transitions between metastable states of highly ionised atoms.

These consequences of the coronal theory was confirmed through Edlen's interpretation of the coronal lines (1941 (34)), according to which these lines originate from transitions between the metastable ground states of highly ionized atoms. And it is shown e.g. in a particularly convincing way by Waldmeier (35, 36, 37) that the coronal lines are particularly strong in coronal streamers from sun-spot areas, which shows that—in accordance with the coronal theory—highly ionized matter of high energy is brought up to the surface through the activity associated with the formation of sun-spots.

Through the recombination process of the highly-ionized atoms X-rays with photon energies corresponding to 1,000–1,500 electron volts must be emitted. According to my theory of the ionosphere, the soft X-radiation should produce two ionization maxima (6, 10), one corresponding to the height where the ionisation pr. unit length of path is a maximum, and one formed by the accumulation of turning points of electrons higher up in the ionosphere. These were identified with E- and F_2-layer respectively. A third layer in between (F_1) is assumed to be produced by ultraviolet light in the region around $\lambda = 500$–$1,000$ Å (cfr. papers 11, 12, 13, 22).

In these papers it was shown that photons with an energy corresponding to 1,000–1,500 electron volts would give an ionisation maximum at the altitude of the E-layer (ca. 100 km), and this is just the energy to be derived from Edlen's interpretation of the coronal lines.

The correctness of this explanation of the E-layer is also confirmed by Waldmeier (35,36), who found a close correlation between the intensity of the coronal line 5,303 and that of the E-layer.

The constitution of the bundles of the electronic rays producing aurorae and magnetic disturbances, according to which they consist of electron rays mixed with positive ions preferably protons, was supported in a most direct way through the detection and study of the hydrogen lines which occasionally appeared in the auroral luminescence.

2. The Detection of Auroral Hydrogen Lines and their Doppler Displacement.

During the years from 1922 to 1939 a considerable number of spectrograms quite strongly exposed was obtained both at Oslo and Tromsoe, but most of them did not show any trace of the hydrogen lines. Only on a few spectrograms taken with spectrographs of very small dispersion a faint line appeared, which might possibly be identified with H_β.

From auroral displays observed at Oslo during the autumn of 1939, a number of spectrograms was obtained showing the H_α and H_β lines with an intensity of the same order of

---

*) Cfr. also Paper 7 p. 35, from 1928.

magnitude as the prominent negative nitrogen bands 4708 and 4278 (15, 16, 17).

In paper 16 p. 15 the intensities of H-lines from one of the spectrograms relative to other prominent auroral lines, are given and the following conclusion is drawn from the hydrogen effect:

"The numerous strongly exposed spectrograms which were obtained during recent years and where the hydrogen lines are absent, show that *noticeable concentrations of hydrogen are only found in the upper atmosphere on rare occasions. Thus the occurrence of* H*-lines should be due to showers of hydrogen or to a kind of 'hydrogen radiation' occasionally coming from the sun with an unusual intensity*."

These results were confirmed by spectrograms obtained shortly afterwards at the Auroral Observatory, Tromsoe, on Ilf. selo. chrom. pl. with a spectrograph of considerably greater dispersion (18, 19). Two of these (one exposed from 6.2.–10.3. 1940, a second from 21.10–26.11. 1940) showed a fairly sharp line exactly coinciding with the H_β-line of the comparison spectrum, and they showed conclusively that we were observing auroral hydrogen lines.

On a third spectrogram reproduced in paper (19) (exposed from 28.11.40–16.1.41) there was a line coinciding with H_β—of the comparison spectrum, but now it was broad and diffuse.

Such a diffuse line (band) came out even more distinctly on a spectrogram taken at Tromsoe with the same spectrograph from Oct. 14–20, 1941, and in this case the broadening of the line was greatest towards shorter waves.

After having thoroughly considered the possible interpretation of the broad line with the position of H_β—, and by taking into account the composition suggested for the electric ray bundles producing the aurorae, I found that the broadened line was no doubt the H_β-line displaced through Doppler effect and that the hydrogen atoms were in rapid motions (21, 22, 23). Through a rough estimate—directly from the spectrograms—of the magnitude of the displacement, it was found that the average velocities of the emitting H-atoms were of the order of some hundred kilometer a second. The spectrogram from Oct. 1941 further showed that the average velocity of the H-atoms during the exposure on an average had been greatest in the direction towards the observer.

The Doppler displacement of H_β—thus shows—in accordance with the theory previously outlined—*that protons form part of the electric rays which produce the aurorae.*

After my results regarding the detection of "hydrogen showers" and the Doppler displacement of the H_β-line had been observed (15, 16, 17, 19, 20, 21) the appearance of the hydrogen lines in the aurorae has been subject to observations by Gartlein (27, 28).

In his communication to the Oslo Meeting he mentions that the H-lines appear broad, and that "unless other identification can be found for these lines, they indicate the presence of hydrogen in violent random motion during many auroras."

As already mentioned, however, the Tromsoe spectrograms of H_β—obtained in 1941—left no doubt as to the correctness of the interpretation I gave in 1939, and they also showed that the line was sometimes more displaced in the direction of smaller waves which means that the velocities of the H-atoms towards the observer on an average had been greater than in other directions.

On Feb. 23–24 1950 a very successful auroral spectrogram was obtained at Oslo with a new spectrograph which combined a great light power with considerable dispersion and sharpness of lines. On this spectrogram the H_β-line appeared quite strong, but broad and diffuse on account of Doppler displacement.

Some results derived from this spectrogram, including the Doppler displacement of H_β—were given in some preliminary communications (24, 25, 32) and more complete in a paper published in collaboration with G. Kvifte in Geof. Publ. of Oslo (26).

During the exposure of the Oslo spectrogram on Feb. 1950 the spectrograph was kept in a fixed position in such a way that the collimator axis formed a great angle of about 80–85° with the magnetic lines of force (auroral streamers). As is to be expected, the Doppler displacement was only a little greater towards shorter waves than in the opposite direction.

From aurorae appearing in August 1950, spectrograms were taken by Gartlein (28) and by Meinel (29, 30) showing the H_α-line with Doppler displacement in good agreement with the Doppler displacements found for H_β—from the spectrograms taken at Tromsoe in 1941 and at Oslo in Feb. 1950.

In the summer 1950 the new spectrograph was taken to the Auroral Observatory at Tromsoe—and during the winter 1950–51—five successful auroral spectrograms were obtained on various sorts of plates and for various purposes. The numerous results derived from these spectrograms will be dealt with in a subsequent paper. This paper is merely meant to deal with the observed hydrogen lines. One of the spectrograms exposed on a Kodak 103 a E plate from 17.1.–9.2,1951 showed a strong H_β-line, and as the aurora at Tromsoe are very frequent near magnetic zenith, the mean angle between the collimator and the direction towards magnetic zenith had been quite small. Consequently the Doppler displacement towards shorter waves is now much greater than in the opposite direction. The H_α-line was masked by heavily exposed bands mostly belonging to the 1st positive group of nitrogen.

Shortly afterwards a spectrogram was taken on the same sort of red sensitive plates with the collimator directed towards magnetic zenith, and it showed the H_α-line mainly displaced towards shorter waves through Doppler effect. The maximum displacement, however, could not be measured because the end of the Doppler band was masked by a nitrogen band.

3. Detailed Analysis of the Doppler Displacement of H_β.

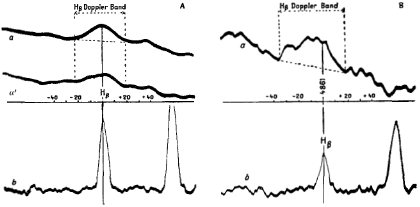
In my first papers (18, 19, 20, 21, 22, 23) dealing with the appearance of the H_β-line on the Tromsoe spectrograms from 1940–41, the broadening due to Doppler effect was merely shown on enlarged copies of the spectrograms, and the order of magnitude of the average velocities was estimated from measurements on the negatives.

The present paper is intended to give a more detailed study of the Doppler displacements shown by H_β on the auroral spectrograms mentioned.

For this purpose photometer curves were taken of the spectrograms of the broadened H_β-line and its nearest surroundings. These curves are shown on fig. 1 A, 1 B, fig. 2 and fig. 3, where the date of the corresponding auroral spectrogram is given.

As the auroral H_β-bands on the two Tromsoe spectrograms from 1940–41 were somewhat weak, we took two registrams along two parallel lines across the spectrograms as shown on fig. 1 A curves (*a*) and (a′). On each of the two fig. 1 A and 1 B is given a photometer curve (*b*) of the undisplaced H_β-line of the comparison spectrum. Although the comparison H_β-line is much more strongly exposed, the auroral H_β-band is seen to be much broader than an undisplaced line would have been.

The spectrograms corresponding to the curves figs. 2 and 3, were taken with the new spectrograph which had much greater dispersion and gave sharper lines than the spectrograph by which the Tromsoe spectrograms from 1940–41 were taken, and the width of the undisplaced H_β-line, compared with that of the auroral H_β-band, would in this case have been much smaller.



Phot.Curves from Tromsö Spectr 28-11-40 - 16-1-41.

Phot. Curves from Tromsö Spectr. Oct 14-20-41
B

Fig 1.

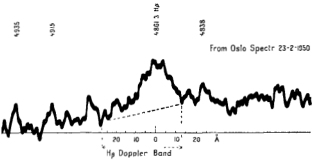


Fig 2

Photm Curve from Spectr. 17 I - 9-2-1951, Tromso.

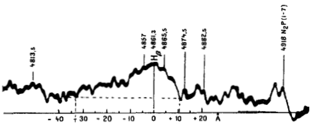


Fig. 3.

From the photometer curves we have drawn smoothed curves, obtained by eliminating the irregularities due to the grained structure of the ground fog on the plate. These curves are shown on fig. 4.

On the upper curve fig. 4 derived from the Tromsoe spectrogram (28.11.1940–16.1.1941) the two dotted curves correspond to the two photometer curves (*a*) and (*a*′) on fig. 1 A. The mean curve is drawn in full. For the three other spectrograms merely the mean curve has been drawn. The dotted curve on each spectrogram indicates the width of the sharp undisplaced H_β-line.

It is seen that the auroral H_β-line is broadened not only towards shorter, but also towards longer waves, showing that the emitting *H*-atoms for reasons to be dealt with later on, are moving in all directions.

The curve from spectrogram (28.11.1940–16.1.1941) shows almost equal displacement in both directions, while the next one from Oct. 14–20 1941—as mentioned in precious papers (21, 22, 23)—shows a considerably greater displacement towards shorter waves, indicating that the motion towards the observer on an average is greater than in the opposite direction. The same is the case for the H_β-bands from the two last spectrograms taken with the new spectrograph.

Doppler Displacement of Hβ

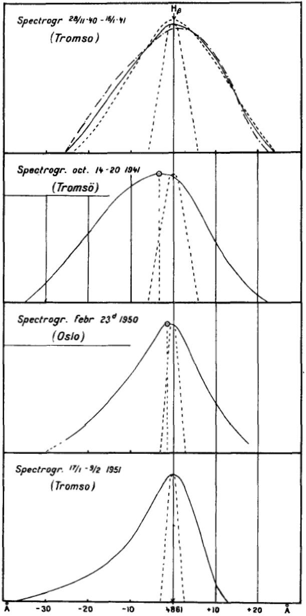


Fig. 4.

From the curves fig. 4 we have calculated the maximum velocity $(V_p^-)_{\max}$ corresponding to displacement towards shorter waves, and $(V_p^+)_{\max}$ corresponding to displacement towards longer waves.

The results corrected for the width of the undisplaced lines are given in table I.

The value we get for the maximum velocities will, especially for weak Doppler bands, depend on the photographic density of the H_β-band.

Taking into account the influence which the earth's magnetic field and the atmospheric matter will have on the motion of the protons in the solar

Table I.

Date of spectrogram	$(V_p^-)_{\max}$ cm/sek.	$(V_p^+)_{\max}$ cm/sek.	Place of observation
28.11.1940–16.1.1941	$1.36 \cdot 10^8$	$1.23 \cdot 10^8$	Tromsoe
14.10.–20.10.1941	1.97 ,,	1.17 ,,	,,
23.2.1950	1.75 ,,	1.05 ,,	Oslo
17.1.–9.2.1951	2.22 ,,	0.68 ,,	Tromsoe

electric ray bundles, the form of the Doppler displacement curve and its variations are easily understood.

When the protons enter into the upper atmosphere they may form different angles with the magnetic lines of force. The absorbtion of proton rays or other electric rays in the atmosphere under the influence of the earth's magnetic field has been treated in a number of previous papers, and in this connection I may refer to paper (5), dealing particularly with the absorbtion of rays forming different angles with the magnetic lines of force and the distribution of light intensity along the auroral streamers. When the ray is not moving parallel to the magnetic lines of force, it will move in spirals round the lines of force, and the number of turns pro unit length along the streamer, will increase with the angle, and as the lines of force converge the number of turns pro unit length will increase downwards.

If the ray is not absorbed a point may be reached where the orbit is perpendicular to the lines of force, and the ray will return into space, but usually with reduced velocity (cfr. paper 5 fig. 6). In the direction of the auroral streamers the proton velocity will on an average be much greater downwards than upwards. The distribution of the velocity components of the protons perpendicular to the lines of force, ought to be equal in all directions.

The part of the H_β-light which is displaced through Doppler effect, is emitted from the proton after they—through some collision process—have captured an electron. In the neutralized state their motion is not influenced by the magnetic field.

The neutralisation process will not essentially change the direction of the moving particle and the velocity distribution of the neutral atoms relative to the auroral streamers will be of the same type as that of the protons just mentioned.

By the exposure of the Oslo spectrogram Feb. 1950 the instrument was kept in a fixed position and pointed in a direction forming a great angle with the magnetic lines of force, and consequently the displacement towards shorter waves is just a little greater than that in the opposite direction. A similar displacement is found for the Tromsoe spectrogram (fig. 1 A), taken 28.11.1940–16.1.1941, showing that the collimator has been mainly pointed towards north nearly perpendicular to the magnetic lines of force.

The H_β-line on the spectrogram from Oct. 1941 (fig. 1 B) and that from Feb. 51 (fig. 3) show by far the greatest Doppler displacement towards shorter waves. This means that at Tromsoe, where the aurorae frequently appear near the zenith, the average magnetic zenith, distance during these exposures has been fairly small.

When the protons move downwards the density increases and the probability for a proton to capture an electron increases too.

This should involve that the relative intensity of the hydrogen lines emitted from the neutralized proton rays (H-atoms) should increase downwards and finally decrease because the protons may be absorbed before the electrons. This is in fact in agreement with results obtained from spectrograms taken in 1939, and e.g. dealt with in paper (17), p. 15 and 16. It was found that while a spectrogram obtained from near the intensity maxim of the aurora showed the H_α and H_β lines with great relative intensity, a spectrogram obtained the same night from near the upper limit of the auroral streamers showed no trace of the Hydrogen lines. Such sets of spectrograms were taken several nights in rapid sucession, and they always showed this altitude effect of the hydrogen lines. See e.g.

the spectrograms reproduced in paper 17 Pl. III A, B, and D.

In the same paper attention is also called to the fact that the yellow sodium doublet (5893) appears particularly strong on the spectrogram taken from the upper limit. This would indicate that the solar electric ray bundle also contains sodium ions, which, however, are neutralized and absorbed at a higher level than the protons. This is in agreement with results derived from the study of the sodium lines in twilight and the explanation given for the formation of the luminous night clouds (cfr. paper 17 p. 14) paper (14) and (38).

4. The Absorbtion of Electron and Proton Rays in the Atmosphere.

a. *Distribution of Matter in the Atmosphere.*

In previous papers (see e.g. paper 5) it has been shown how to determine the height at which an electric ray of given properties will stop, provided we know the distribution of the density of the atmosperic gases.

The study of the auroral spectrum has shown that no permanent layer of the light gases hydrogen and helium dominates on the top of the atmosphere, and this means that we can assume perfect mixing of the components of the atmosphere. We may therefore assume a nearly constant composition to exist below the auroral region or below say 100 km.

Under these conditions the variation of pressure (p) and density (ϱ) with altitude can be found by means of the barometric height formula:

$$\frac{dp}{p} = \frac{d\varrho}{\varrho} = -\frac{dh}{H} \qquad (2)$$

where $H = \frac{RT}{Mg}$ is the reduced height.

In paper No 12 p. 609 table 11 and No 13 p. 11 table IV, we have given the pressure for different altitudes, calculated by means of the barometric height formula (2) on the assumption of constant composition, and that above 10 km the temperature is constant and equal to 223°K or —50°C.

Some values above 60 km taken from these papers are given in table II.

In a neutral atmosphere in equilibrium under the influence of gravity, the amount of matter (m_h) which exists pro cm² above a certain height (h) is given by the formula:

$$m_h = P_h s \qquad (3)$$

where P_h is the pressure at the height (h) in cm Hg and (s) the density of Hg.

Table II.

h (km)	P_h cm. Hg.	m_h gr/cm²
60	8.96 10^{-3}	12.2 10^{-2}
70	1.93 10^{-3}	2.64 10^{-2}
80	4.17 10^{-4}	5.70 10^{-3}
90	9.00 10^{-5}	1.23 10^{-3}
100	1.94 10^{-5}	2.64 10^{-4}
120	9.04 10^{-7}	1.24 10^{-5}
140	4.21 10^{-8}	5.75 10^{-7}
200	5.25 10^{-12}	5.8 10^{-11}

The relation between the mass (m_h) and (h) can be expressed by the formula:

$$\log_{10} m_h = 3.067 - 0.0666\, h \qquad (4a)$$

A ray which is just stopped by a layer of air with a mass pro cm² (m_a) and which enters vertically into the atmosphere, will be stopped at a height (h) given by the equation:

$$h = 46 - 15 \log_{10} (m_a) \qquad (4b)$$

The values of (m_h) given in table II and expressed by equation (4a) may be fairly accurate up to the height of about 100 km (the height of the E-layer), but above this level the values of (m_h) in table II or calculated from eq. (4a) are too small, because the effect of gravity is partly balanced by the action of electric fields. We might express it by saying that the density varies as if the acceleration (g) had been reduced and consequently the reduced mass $H = \frac{RT}{Mg}$ is increased.

If we determine the stopping height of an electric ray from the mass traversed given by equation (4a) the height values—at any rate above 100 km, will be much too small.

For the discussion of the relative influence of the proton and electron rays on the auroral phenomenon, it will be of interest to determine the stopping height of these two types of electric rays on the assumption that the mass (m_h) can be calculated from equation (4a).

b. *Absorbtion of Electron Rays.*

The absorbtion of electron rays in the atmosphere, can be treated in two different ways. Following Lenard we may assume that the intensity varies in accordance with the formula:

$$dI = -\mu I \varrho d\varsigma \qquad (5a)$$

Where μ is the mass absorbtion coefficient. Applying this to an electron radiation entering the atmosphere in a direction $(d\varsigma)$ with a zenith distance Z, the variation of the intensity (I) is expressed by the equation:

$$dI = \mu I \varrho_0 e^{-\frac{h}{H}} \sec Z dh. \qquad (5\,b)$$

Integrating and putting $\mu \varrho_0 \sec Z = a$

$$I_h = I_\infty e^{-ae^{-\frac{h}{H}}}. \qquad (5\,c)$$

The same equation applies to the absorbtion in the atmosphere of light or X-rays.

In dealing with the distribution of light intensity (5) (or the ionisation) it is assumed that the intensity of auroral light J (or the ion density) is proportional to dI_h/dh, which gives:

$$J = \varkappa I_\infty \frac{a}{H} e^{-ae^{-\frac{h}{H}}} \cdot e^{-\frac{h}{H}}. \qquad (6)$$

The position of the maximum of light intensity (or ionisation) is found by putting $dJ/dh = 0$, which gives:

$$ae^{-\frac{h_m}{H}} = 1. \qquad (7)$$

Where h_m is the height of the maximum. This introduced into equation (5c) gives:

$$I_m = I_\infty e^{-1}. \qquad (8\,a)$$

If the rays on their way down to the altitude h_m has passed a mass pro cm² $(m_h)_{\max}$ then we have also:

$$I_m = I_\infty e^{-\mu (m_h)_{\max}}. \qquad (8\,b)$$

From (8a) and (8b) follows:

$$\mu (m_h)_{\max} = 1$$

or

$$(m_h)_{\max} = 1/\mu. \qquad (9)$$

Knowing the mass absorbtion coefficient (μ) we find the mass traversed at the maximum of light or ionisation, and the height of the maximum is found from equation (4b).

This simple method for determinning the height of the maximum has been previously used for cathode rays (5) and for X-rays (cfr. paper 12, p. 605) and paper 22 p. 133.

In order to find the lower limit of an aurora produced by electron rays of known (μ) value, I have calculated the height where the intensity of the ray bundle has been reduced by 95 % which means that in equation (5b) $I_h/I_\infty = 5/100$.

It must be remembered that the equation (5) does not give a true expression of the absorbtion of electron rays. Especially in the atmosphere where the electrons are moving in a magnetic field, the absorbtion is not to be characterized by the mass absorbtion coefficient. The electrons are partly scattered, partly made to turn round the magnetic lines of force. Under these circumstances it is better to consider the electron range, which is measured along its orbit e.g. in air.

As a rule it is convenient to express the range by the mass pr. cm² (m_a) it passes through before it stops. The ranges of electron rays of different velocities in aluminium are given in the textbook of Rutherford, Chadwick and Ellis "Radiations from Radioactive substances" (1930) p. 422.

Assuming the mass pro cm² to be about the same in Al and air, we find the minimum height— which a ray of known range (m_a) can reach, when in equation (4a) we put $m_h = m_a$.

The results of our calculations of the absorbtion of electron rays in the atmosphere are collected in table III.

The first column gives the velocities $\beta = \frac{v}{c}$.

The second the energy W expressed in electron volts.

$H\varrho = \frac{mv}{e}$ expresses magnetic stiffness.

$(m_h)_{\max} = 1/\mu$ is the mass traversed when the intensity max. in the atmosphere is reached.

R_a is the electron range in air.

h_μ is the height where the intensity of the electron rays is reduced by 95 %.

$(h)_{\max}$ is the height of the intensity maximum.

h_R is the stopping height calculated from the electron range R_a.

Table III.

Electron Rays.

$\beta = \frac{v}{c}$	W	$H\varrho = \frac{mv}{e}$	μ	$1/\mu = (m_h)_{\max}$	R_a	h_μ	$h_{\max}$	h_R
	e=Volt	cm x Gauss	cm²/gr	gr/cm²	gr/cm²	km	km	km
0.01	25.4	17	$1.8.10^7$	$5.5\ .10^{-8}$	$(2.5.\ 10^{-9})$	(136)	(154)	174
0.1	2560	171	$8.0.10^5$	$1.25.10^{-6}$	$1.66.10^{-5}$	(113)	(134)	118
0.2	10500	347	$3.6.10^4$	$2.77.10^{-5}$	$2.63.10^{-4}$	108	114	100
0.3	24500	535	$2.9.10^3$	$3.44.10^{-4}$	$1.15.10^{-3}$	92	98	91
0.4	46300	742	$4.9.10^2$	$2.03.10^{-3}$	$3.72.10^{-3}$	78	86	82
0.5	78600	981	$2.2.10^2$	$4.53.10^{-3}$	$9.55.10^{-3}$	74	81	76
0.6	127000	1275	$8.3.10^1$	$1.20.10^{-2}$	$2.04.10^{-2}$	68	75	71
0.7	203000	1660	$2.9.10^1$	$3.43.10^{-2}$	$4.17.10^{-2}$	61	68	66

c. *Absorbtion of Protons in the Atmosphere.*

In order to determine the height which a proton ray of given energy will reach, we shall have to determine its range (R_a) in air of 0° and 76 cm Hg. pressure, or the mass of air pro cm² $m_a = R_a D = 1.25\ 10^{-3} R_a$. The corresponding height, where the ray stops, is found from equation (4b). As shown in paper (5) the range in air is found by means of the relation:

$$R_a = 10^{-27}\, v^3 \text{ cm.air} \tag{10}$$

$$v = 1.39.10^6 \sqrt{V} \text{cm/sek.} \tag{11}$$

where V is the potential in volts or the energy W is expressed in electron volts. The magnetic stiffness of the ray, $H\varrho = \frac{mv}{e} = 1.03\ \ 10^{-4}\ \ v.$ The results of the calculations are given in table IV.

5. The Part Played by the Protons in the Production of Auroral Luminescence.

From the tables III and IV we notice that in order to reach down to an altitude of say 100 km, which is a frequent altitude for the lower limit of an aurora, electron rays would require an energy of about 10,000 el. volts, with a velocity of 6.10^9 cm/sec, while a proton ray would require an energy of about 200,000 electron volts with a velocity 6.10^8 cm/sec, which is ten times smaller than that of the electrons.

The great variability of the intensity of the H-lines does not seem to have any marked influence on the forms and altitude of the aurorae. Even when the H-lines are too weak to be observed on strongly exposed plates, the height and appearance of an aurora is essentially the same as when

Table IV.

Proton Rays,

W	$\beta = v/c$	$H\varrho = \frac{mv}{e}$	R_a	m_a	h
el. volts		Gauss cm	cm	gr/cm²	km
10.10^3	$0.44\ \ 10^{-2}$	$1.43\ \ 10^4$	$2.67\ \ 10^{-3}$	$3.3\ \ 10^{-6}$	128
30 ,,	0.80 ,,	2.50 ,,	$1.40\ \ 10^{-2}$	$1.8\ \ 10^{-5}$	117
40 ,,	0.92 ,,	2.87 ,,	2.13 ,,	2.7 ,,	115
60 ,,	1.13 ,,	3.50 ,,	3.9 ,,	4.9 ,,	111
80 ,,	1.31 ,,	4.05 ,,	6.1 ,,	7.6 ,,	108
100 ,,	1.47 ,,	4.55 ,,	8.5 ,,	10.6 ,,	106
150 ,,	1.80 ,,	5.60 ,,	$1.6\ \ 10^{-1}$	19.8 ,,	102
200 ,,	2.05 ,,	6.40 ,,	2.4 ,,	$3.0\ \ 10^{-4}$	99
7700 ,,	11.8 ,,	36.8 ,,	43.6 ,,	$5.4\ \ 10^{-2}$	65

the H-lines appear with great relative intensity. *This shows that it must be electron rays and not the protons which dominate the production of the auroral luminescence.*

The mutual relation between positive rays and electron rays is governed by the condition that the ray bundle from the sun is electrostatically neutral. And as pointed out in my communication to the Brussels meeting of IUGG in Aug. 1951, this constitution of the solar ray bundles explains the variability of the H-lines and the typical properties of aurorae and magnetic storms.

We consider an electrostatically neutral bundle composed of electrons with velocity (V_e) and protons with velocity (V_p). The number of electrons (ν_e) and protons (ν_p) passing through unit area in unit time will be:

$$\nu_e = n_e v_e, \ \nu_p = n_p v_p \qquad (12a)$$

n_e and n_p is the number of electrons and protons pro cm^3. As the bundle is neutral

$$n_e = n_p = n \qquad (12b)$$

$$\nu_p / \nu_e = v_p / v_e \qquad (12c)$$

Thus the number of protons entering the atmosphere (proton flux) relative to that of the electrons equals their relative velocities. *Therefore the great variability of the relative intensity of the* H-*lines result from a change in the relative proton velocity in the ray bundle.*

The electric current density (i) of the bundle is given by the equation (cfr. paper 11 p. 231, and 12, p. 612)

$$i = en(v_e - v_p) \qquad (13)$$

From the tables III and IV we see that even if we would suppose that the range of the protons is as great as that of the electrons so that the protons are stopped at the same height as the electrons, the electron velocity is much greater than that of the protons. In the case of aurorae giving too weak H-lines to be detected, the proton velocity must be very small compared with that of the electrons, and in most cases not only the velocity, but also the range of the protons, must be smaller than that of the electrons; so the protons will be absorbed before they reach the bottom edge of the aurora.

The maximum proton velocity measured from the doppler effect of the H-lines is found to be $2 - 3 \ 10^8$ cm/sec. Investigations of the Doppler effect from hydrogen canal rays (31) have shown however, that the light emitted from the moving H-atoms decreases with increase of velocity, and seems to vanish when the velocity exceeds about 5.10^8 cm./sec. We are therefore not justified in assuming that the maximum velocities derived from the Doppler effect of the auroral H-lines indicate the maximum proton velocities of the solar ray bundle.

When the proton flux—and consequently the velocity—is small, the maximum Doppler velocity obtained from spectrograms taken nearly in the direction towards magnetic zenith, will no doubt in most cases give the maximum proton velocity.

We know that aurorae is observed down to altitudes of 65 km. In the case of electron rays this requires a fairly moderate energy of about 200,000 e.volt, while proton rays would require an energy of 7.7 million electron volts to penetrate down to this altitude. The magnetic stiffness of the protons would in this case be too great to account for the thin streamers and the distribution of luminosity (cfr. paper 5).

If proton rays of such energy and velocity were engaged in the production of the low aurorae, the proton flux and the intensity of H-lines is unusually large. As a matter of fact, however, spectrograms of such aurorae show strong bands of the first positive group of nitrogen, but no H-lines, in other words, the lower part of these low aurorae are produced by electron rays.

We are then justified in assuming that in equation (13) V_e is much greater than V_p.

In a magnetic field (F) each unit volume of the bundle is subject to a deviating force (K) given by an equation of the form:

$$K = en\,(v_e - v_p)\,F \sin\varphi = i\,F \,.\, \sin\varphi \ldots \qquad (14)$$

Where φ is a kind of average angle between F and V.

In this way the electrostatically neutral bundle will be deviated in the magnetic field in very much the same way as a single electrified corpuscle. *Consequently the theory of Birkeland and Størmer may be applied to the neutralized bundle, and the merits of their theory in explaining the typical features of aurorae and magnetic storms can be transfered to the neutralized bundle composed of electrons and positive ions e.g. protons.*

In fact the neutralized bundle has the advantage that it also explain a number of phenomena, which are not to be accounted for by the Birkeland–Størmer theory:

a. The neutralized bundle accounts for the variability of the auroral hydrogen effect.

b. The positive ions (e.g. protons) in the bundle will excite luminescence in the atmosphere with a spectral composition different from that produced by electrons. In this way we may account for certain variations in the auroral spectrum. Thus investigations on the excitation of nitrogen with positive rays (39) have shown that certain variations in the intensity distribution of the auroral vibrational bands of the system (N_2^+ $1N$) are probably due to proton excitation.

c. As the protons are compelled to follow the electrons, they will have a considerable influence on the way in which the bundle will move in a magnetic field, because it will increase the magnetic stiffness of the bundle.

Suppose that the ray bundle is moving in a homogenous field perpendicular to the magnetic force. Let ϱ_e and ϱ_p be the radius of curvature of the electrons and protons respectively, then:

$$\varrho_p/\varrho_e = \frac{m_p\,v_p}{m_e\,v_e} = 1800\,\frac{v_p}{v_e} \qquad (15)$$

Thus for proton velocities greater than about 10^7 cm/sec. ϱ_p is greater than ϱ_e. This means that although the magnetic field of the bundle and the direction of the deviating force K is due to the electrons, the protons will mainly determine the magnetic deflectibility.

Thus the increase of proton velocity will increase the distance from the aurora to the magnetic axis point, and thus the presence of protons in the ray bundle may—at any rate partly—account for the great radius of the auroral zone, although the auroral luminescence is mainly produced by electrons of moderate energy.

The influx of the protons and the intensity of the H-lines increase with the proton velocity, and thus we should expect the intensity of the H-lines to increase with magnetic polar distance. In fact, a comparison between the auroral spectrograms at Tromsoe and Oslo indicates the existence of such an effect.

My thanks are due to Mr. A. Omholt for valuable assistance in connection with the preparation of the Doppler diagrams given in this paper and to The Norwegian Research Council for financial support of these investigations.

Physical Institute of the University, Oslo. Dec. 1951.

List of Papers.

1. Vegard, L., Über die physikalische Natur der kosmischen Strahlen, die das Nordlicht hervorrufen. Ann. d. Phys. IV, 50, p. 853, 1916.
2. Schuster, A., Proc. Roy. Soc. 85, p. 44, 1911.
3. Chapman, S., Proc. Roy. Soc. A. 95, p. 61, 1918.
4. Lindemann, F. A., Phil. Mag. 38, p. 669, 1919.
5. Vegard, L., Phil. Mag. 42, p. 47, 80, 81, 1921.
6. ,, Det Norske Vid.-Akad. Skr. I, No. 8, 9, 10, 1923. Phil. Mag. 46, p. 193, 1923.
7. ,, Results of Observations from the Solar Eclipse in Norway, June 29, 1927, and the Constitution of the Solar Corona and Sunspots. Det Norske Vid.-Akad. Skr. I, No. 2, 1928.
8. ,, Die Korona der Erde und Sonne und ihre Beziehungen zu kosmischen Erscheinungen. Gerlands Beiträge z. Geophys. 32, p. 288, 1931.
9. Chapman, S., and V. C. A. Ferraro, Terr. Magn. 36, p. 77 and 171, 1931; 37, p. 147 and 421, 1932; 38, p. 79, 1933.
10. Vegard, L., Geof. Publ. (G.P.) Vol. IX, No. 11, 1932.
11. ,, Ergebnisse d. exakt. Nat.wiss. Vol. XVII, p. 229, 1938.
12. ,, Physics of the Earth. (Ed. by J. A. Fleming.) Vol. VIII, p. 573, 1939.
13. ,, G. P. Vol. XII, No. 5, 1938.
14. ,, Coronal Phenomena and their Relation to Solar and Terrestrial Processes. G. P. Vol. XVI, No. 1, 1944.
15. ,, Hydrogen Showers in the Auroral Region. Nature V, 144, p. 1089, 1939.
16. ,, Terr. Magn. 1937.
17. ,, G. P. Vol. XII, No. 14, 1940.
18. Vegard, L., and E. Tønsberg, Gerlands Beiträge z. Geophys. 57, p. 289, 1941.
19. ,, ,, ,, G. P. Vol. XIII, No. 5, 1941.
20. ,, ,, ,, G. P. Vol. XVI, No. 2, 1944.
21. Vegard, L., Phys. Soc., Gassiot Committee, Report p. 82, 1948.
22. ,, Proceed. of the Meeting at Brussels of the Mixed Comm. on Ionosphere, July 1948, p. 111.
23. ,, Transactions of the Oslo Meeting, Aug. 1948, pp. 189 and 484.
24. ,, C. R. Vol. 230, p. 1884, May 1950. Nature 165, p. 1012, June 1950.
25. ,, Ann. d. Geophys. Vol. 6, p. 157, 1950.
26. Vegard, L., and G. Kvifte, G. P. Vol. XVIII, No. 3, 1951.
27. Gartlein, C. W., Trans. of the Oslo Meeting p. 491, 1948.
28. ,, Phys. Rev. Vol. 81, No. 3, p. 463, 1951. Nature, 167, p. 277, 1951.
29. Meinel, A. B., Doppler-shifted Auroral Hydrogen Emission. Astrophys. Journ. Vol. 113, No. 1, January 1951.
30. ,, Phys. Rev. Vol. 80, No. 6, p. 1096, Dec. 15, 1950.
31. Vegard, L., Lichterzeugung in Glimmlicht u. Kanalstr. Ann. d. Phys. IV, 39, p. 111, 1912.
32. ,, Comm. to the Meeting at Brussels 1951 of the I.U.G.G.
33. Størmer, C., Nature 140, p. 1095, 1937.
34. Edlén, Bengt, Arkiv f. mat., astr. och fysik 28, No. 1, 1941.
35. Waldmeier, M., Z.S. f. Astrophys. 22, p. 30, 1942. Helvetia Phys. Acta, Vol. XVII, p. 168, 1944.
36. ,, Terr. Magn. 52, No. 3, p. 333, 1945.
37. ,, Astr. Mitt. d. Eidg. Sternwarte, Zürich, No. 149, 1947
38. Vegard, L., and E. Tønsberg, G.P. Vol. XIII, No. 1, 1940.
39. Vegard, L., and H. Raastad, G.P. Vol. XVII, No. 7, 1949.

Printed March 12th, 1952.
Grøndahl & Søns Boktrykkeri, Oslo.