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STUDIES ON THE EXCITATION OF AURORA BOREALIS

I. THE HYDROGEN LINES

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Summary. Intensity measurements on the $H\beta$ line and the N_2^+ band $\lambda 4709$ have been made in Tromsø with a new photo-electric filter photometer, which is described in some detail. It is found that the intensity ratio $H\beta/\lambda 4709$ is always very low, usually less than 0.1. $H\beta$ is virtually absent from homogeneous as well as rayed arcs and bands, and from pulsating aurorae, whereas $H\beta$ is usually associated with rays and diffuse aurorae. The results of some earlier observations at Yerkes Observatory are described. At this low latitude $H\beta$ is always present in homogeneous arcs, but less intense in rayed aurorae. One observation of the break-up period of an arc is described. An attempt has been made to relate the various observations available and to form a consistent picture of the behaviour of the hydrogen lines.

The total energy carried into the atmosphere by the primary particles producing the aurora has been computed, and it is concluded that the influx of energy required to maintain an aurora of international brightness III in the zenith is about 6 × 10^{13} eV/cm^2 sec. Some new computations on the emission of $H\alpha$ and $H\beta$ quanta from a H^+/H beam in air, versus the velocity of the particles, are also presented. The total emission of $H\alpha$ and $H\beta$ quanta per incident proton with initial energy above 200 keV is found to be about 60 and 15 respectively. The possibility of collisional deactivation of the excited *H*-atoms is discussed. During the period when the particles are neutralized (*H*-atoms) they are not bound to a magnetic field line, and this may be of importance for the diffusion of a narrow beam of primary particles. The angular distribution of protons which move from near the equatorial plane to the auroral zone is discussed, an electric field being taken into account. One may expect that the angle which the paths of the fastest protons make with the magnetic lines of force is rather small, but that this angle increases with decreasing energy.

The rôle of the protons in the auroral displays is discussed on the basis of the observations and the theoretical results. It is shown that protons cannot regularly be responsible for the main excitation of any of the discussed types of aurora. It is not possible from the intensity of $H\alpha$ and $H\beta$ to derive the absolute flux of protons. From the Doppler profiles it is at present not possible to derive the dispersion in initial velocity of the particles, but it is evident that a rather large fraction of these have quite low velocities. If we consider all emitting atoms whose directions have an azimuth within an infinitesimal small interval $d\varphi$, then the average velocity vector for these atoms makes an angle of about 24° with the magnetic lines of force. There is evidence that the angular distribution of the incident protons varies with the energy as theoretically predicted.

A. INTRODUCTION

1. Summary of earlier work on the hydrogen lines.

1.1. The hydrogen lines in the auroral spectrum were first detected by Vegard in 1939 (Vegard 1939). He found that the α and β lines of the Balmer series ($H\alpha$, $\lambda = 6563$ Å and $H\beta$, $\lambda = 4861$ Å) occasionally appeared in the spectrum of the aurora and concluded that showers of hydrogen atoms or protons occasionally enter the earth's atmosphere during aurorae. Later, he found that on one occasion the $H\beta$ line was displaced about 5 Å towards shorter wavelengths and interpreted the line as due to emission from neutralized protons approaching the earth with considerable velocity (Vegard 1948).

In 1951 Meinel (Meinel 1951) found the hydrogen lines in spectrograms of aurora appearing in the zenith over Yerkes Observatory, and he was the first to make a detailed study of the profile of these lines, which showed a considerable Doppler shift and broadening. At the same time good spectra, which gave results in agreement with Meinel's observations, were obtained by Gartlein (1950, 1951) and by Vegard and Kvifte (1951).

The hydrogen lines in the auroral spectrum were until very recently the only direct evidence of the nature of the particles which enter the earth's atmosphere during aurorae. The recent discovery by Winckler and Peterson (1957) of *X*-rays from an aurora also probably gives direct evidence for incoming electrons. Since many workers believe that the particles responsible for aurorae are accelerated to their maximum energy by electric fields in the neighbourhood of the earth, there has been some tendency to assume that the particles could be of only one sign, and that aurorae are entirely due to protons or other positive particles. Consequently the hydrogen lines received very much attention. As we shall see later, this view is not supported by the evidence, and there is good reason to believe that the protons supply only a minor part of the energy necessary to produce an aurora. But even so, the protons raise problems which are of fundamental interest. Since the hydrogen lines prove that protons enter the earth's atmosphere with considerable energy, a study of these lines may give a clue to the origin of the protons and thus to cosmic and solar phenomena.

1.2. The variation of the intensity of the hydrogen lines relative to the other auroral emissions has been studied in some detail by many authors. Vegard and Kvifte (1954) published a study on the latitude effect of the $H\beta$ line utilizing spectrograms taken with similar spectrographs in Oslo (geomagnetic latitude $\varphi = 60°$) and in Tromsø ($\varphi = 67°$) in Norway. They find that relative to the N_2^+ band $\lambda 4709$ Å, the $H\beta$ line is on the average more than six times as strong in Oslo as in Tromsø. The average of the intensity ratio between $H\beta$ and the $\lambda 4709$ band (here up on denoted $R(H\beta)$), is about 0,7 in Oslo but less than 0,12 in Tromsø. Studies on type effects have been made by Vegard (1955, 1956) with spectrograms from Tromsø. From these investigations it seems that there is a better chance of obtaining the hydrogen lines when the aurora is weak and shows ray structure or is of type A, i.e. with a red colour due to the oxygen doublet 6300/64 Å. Vegard finds that there is an altitude effect, the hydrogen lines being mainly emitted from the upper part of the aurora.

The intensity ratio between $H\beta$ and $\lambda 4709$ has also been studied in Saskatoon ($\varphi = 61°$) by Hunten (1955) with a photo-electric spectrometer. He finds that $R(H\beta)$ is always less than 0.15 in bright aurora but it may occasionally be very great, up to 260, in flickering, very active rays. More recently Montalbetti and Vallance Jones (1957) have presented an analysis of a great number of patrol spectrograms obtained at Saskatoon and at Churchill ($\varphi = 69°$) in Canada. This work furnishes valuable information regarding the diurnal variation of the intensity of the $H\alpha$ line. It is found that $H\alpha$ is, on the average, most intense before midnight at Saskatoon whereas the contrary is the case at Churchill. The latitude effect may be similar to that found by Vegard and Kvifte (1954) as the hydrogen lines are always observed at Saskatoon whereas this is not so at Churchill. Since the spectrographs used in the two places differ very much, the investigations do not furnish quantitative information regarding this question.

Petrie and Small (1952), working in Saskatoon, remark that the intensities of the hydrogen lines vary greatly from one display to another and are strongest relative to other spectral features in the early part of a display and in bright displays. These same variations have been noted by Gartlein (1950) in his extensive observations from Ithaca ($\varphi = 54°$).

Spectrographic studies on low latitudes have been made by Fan and Schulte (1954) at Yerkes Observatory ($\varphi = 53°$). They found the hydrogen lines to be present in all quiet auroral arcs, but weak or absent in ray-structured, active aurorae. These results were confirmed by photo-electric measurements made by Omholt (1957b, 1958), also at Yerkes Observatory. It was found that $R(H\beta)$ was 0.3 to 0.7 in arcs, absent or very weak in active rays and pulsating aurorae, but about 0.10 to 0.15 in auroral glow, the diffuse background of auroral light covering larger parts of the sky after a big display. These results will be dealt with in more detail in section 4.

Gartlein and Sprague (1957) have estimated the intensity of $H\alpha$ from spectrograms obtained at Ithaca. The $H\alpha$ emission from a horizontal column through an average aurora observed from Ithaca (presumably low in the north) is found to be about 10^{-4} erg/cm^2 column/steradian/sec.

Romick and Elvey (1958) and Galperin (1958) have very recently found that the hydrogen lines may be relatively very strong in the very first phases of an aurora, before the distinct auroral forms are visible.

The results obtained by the different observers do not agree very well, and the picture is at present rather confusing. Particularly, there is disagreement between the detailed observations in Tromsø and at Yerkes Observatory, and the peculiar high values of $R(H\beta)$ observed by Hunten are not confirmed by any other workers. The observations which will be described in this paper were made as an attempt to throw further light on these questions and to evaluate a consistent picture of the latitude and type variations of the hydrogen lines.

1.3. It is to be expected that much information can also be obtained from the detailed profile of the hydrogen lines. Some information on the profile has been obtained by Meinel (1954) and by Vegard *et al.* (Vegard and Kvifte 1951, Vegard and Tønsberg 1952, Vegard 1956). The state of affairs is not quite satisfactory, however, as Meinel's profiles are density profiles on the plate rather than intensity profiles, and the profiles obtained by Vegard *et al.* do not have the desired resolution. More recently Chamberlain (1958b) has published profiles obtained with a high-dispersion spectrograph.

The first serious attempt to interpret the profiles of the lines in terms of the velocity and direction of the incoming protons was made by Chamberlain (1954). The basic process is, of course, that when the protons enter the atmosphere they capture electrons, mainly from the atmospheric molecules and atoms. Some of the electrons are captured into excited states, from which the characteristic radiation is emitted. The neutral hydrogen atoms proceed with high speed and by collisions these are again re-ionized or, more seldom, excited. Chamberlain calculated the number of $H\alpha$ protons emitted per unit diminution in the velocity of the primary stream and found that if the protons have an initial energy above 90 keV it may be represented by

$$I(v) = c_1 v^2 \, exp \, (- v^2/\beta^2) \tag{1.1}$$

where $\beta = 1700$ km/sec and v is the velocity. The numerical value of c_1 is 23×10^{-9}

when v is given in km/sec and $I(v)$ in photon/incident proton and km/sec. In the case of protons of energy less than 90 keV regard must be given to the cut-off at v_o, the initial velocity. From the intensity ratio between *Hα* and *Hβ* calculated by Chamberlain it may be shown that the emission of *Hβ* may also be described by equation (1.1,) but with $\beta = 2000$ km/sec. and $c_1 = 3.1 \times 10^{-9}$. The collision cross-sections used in these calculations were estimated by Chamberlain from the results of quantal calculations on protons and hydrogen atoms passing through hydrogen (Bates and Griffing 1953, Bates and Dalgarno 1953) compared with experimental data from hydrogen in air (Ribe 1951, Kanner 1951, Massey and Burhop 1952). Though his estimates seem reasonable, they may not be very accurate. Equation (1.1) describes the profile of the *Hα* line one should expect to obtain from observations towards magnetic zenith, provided the protons are mono-energetic and follow the magnetic lines of force exactly. Chamberlain pointed out that this curve fitted badly with Meinel's observations and suggested that the observed profile may be explained if the paths of the protons make angles θ with the magnetic lines of force, and that a suitable angular distribution may in addition account for the observed luminosity curves of auroral arcs (the variation of the luminosity with height within the arc), presupposing that the aurora was excited by protons only. By adopting the distribution

$$(1.2) \qquad N(\theta) = c_2\, exp\,(-\, tan^2\, \theta/a^2)\,;\; (a = 8.5)$$

in which $N(\theta)$ is the number of protons per unit solid angle, he was able to reproduce the profile of the *Hα* line measured by Meinel in magnetic zenith. Moreover, the main luminosity curves computed from this model and the Bragg ionization curve for protons in air, were similar to the curves observed by Harang (1946). Later Omholt (1956a) showed that the angular distribution assumed by Chamberlain gave a much too wide profile of the line observed in the direction of magnetic horizon i.e. at right angles to the magnetic lines of force. Computations were also made on the height distribution of the hydrogen emission as well as the main emission arising from ionization and excitation by the incident protons, again supposing the angular distribution of the protons to be given by equation (1.2). Since, as we shall see later, the main emission from aurorae is most likely not due to proton excitation and the luminosity curves for the hydrogen emissions are not well known, we cannot yet attach much weight to such computations.

In a more recent paper, Chamberlain (1957, 1958a) has reexamined the angular distribution and found from theoretical arguments that it should be given by

$$(1.3) \qquad N(\theta) = c_3 \cos^2 \theta$$

rather than the old formula. Adopting in addition a dispersion in initial velocities of the protons given by

$$(1.4) \qquad \psi(v_0) = \frac{c_4}{(a+v_0)^2}$$

he obtained Doppler profiles which were in satisfactory agreement with Meinel's observations.

Secondary mechanisms due to absorption in the atmosphere of the α and β lines of the Lyman series of hydrogen emitted from aurorae have been studied by Omholt (1956b). These are probably unimportant.

Further discussion of some of the results referred to in this section, will be made in sections 5 and 6.

B. OBSERVATIONAL WORK

2. Instrumentation for photo-electric observations.

2.1. Photo-electric photometry on aurorae utilizing narrow band interference filters was started in Tromsø in 1954 (Omholt and Harang 1955). The first purpose of this photometer was to study the rapid fluctuations in the intensity of the green oxygen line $\lambda 5577$ and the First Negative nitrogen bands. Two types of photometers were tried then, both constructed by Harang. The first type, the "chopping photometer" was successfully applied to studies on the rapid intensity fluctuations and has since been used by Harang for determining the height distribution of different components of the auroral spectrum (Harang 1958). This photometer is described in the papers by Omholt and Harang (1955) and by Harang (1958). In this photometer the aurora is focussed on the photo-cathode and a window in the multiplier-cover cuts out about $1^\circ \times 1^\circ$ of the sky. A rotating disc with interference filters is placed in such a way that it interrupts the ray-path from the objective to the photo-cathode. The disc is rotated at 23 c/sec, and each time a filter passes the ray-path, a light pulse hits the photo-cathode. The resulting electric pulses are recorded by an oscilloscope and a camera with continuously moving film.

In the other type of photometer the light beam from the objective was split up by a semi-transparent mirror and the aurora was focussed on the windows of two different RCA photo-multipliers. In front of these were placed interference-filters. The two windows cut out identical areas of the sky. However, the sensitivity varies very much over the area of the photo-cathodes and two multipliers are always different in this respect. Therefore the auroral light appearing within the selected areas was integrated differently by the two photo-multipliers. Or, if intensity variations appeared within the selected area, the relative response of the multipliers depended on where within this area the variation took place.

2.2. As we shall see later, the «split beam» photometer may have certain advantages over the chopping type and it was felt desirable also to develop this type further. An improved model of this was built by the author at Yerkes Observatory (Omholt 1957b). It was essentially the same type as that which will be described here. The principle of splitting the light beam from one objective has no particular advantage over a double photometer, using two different optical systems. It was mainly a matter of economy and time, as at Yerkes Observatory we had at our disposal an old 6″ telescope, and in Norway an Askania photo-theodolite. This photo-theodolite can easily be moved in altitude and azimuth directions and is very convenient for our purpose.

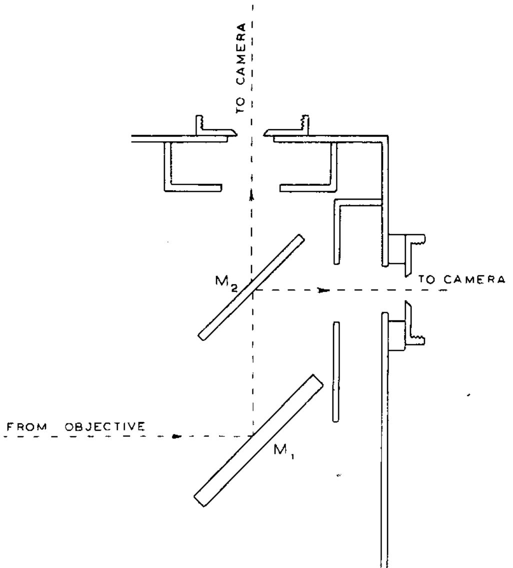

Fig. 1. The split-beam principle.

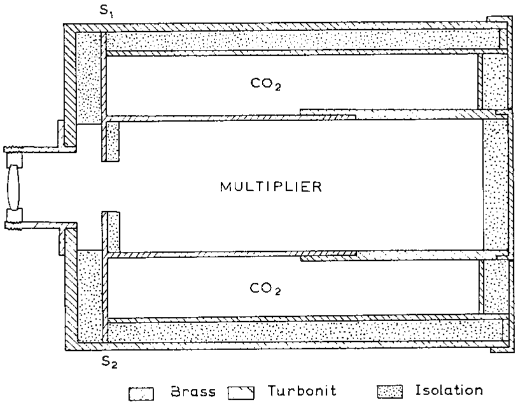

Fig. 2. The photo-electric camera.

The main features of the photometer are shown in Fig.s 1 and 2. The aurora is focussed on two diaphragms through the semi-transparent mirror M_2. The first mirror M_1 serves only to fold up the ray-path to get the necessary room for the multiplers. For the $H\beta/\lambda 4709$ observations we used as transparent mirror a "Transflex" mirror from Gerätebauanstalt, Baltzers, Lichtenstein, with about 27 % reflection and 73 % transmission. Since $H\beta$ is much weaker than $\lambda 4709$, the transmitted light was used for measuring $H\beta$. For work on other spectral components which are sufficiently spaced in wavelength, one may use «dichroic» mirrors with dielectric coatings. These have a high reflection coefficient in one wavelength region and a high transmission coefficient in another. This enables us to make more efficient use of the light. The mirrors can be tilted around axes through the mirror surface and the positions of the diaphragms can be adjusted. This ensures that the two diaphragms cut out exactly the same area of the sky, and that the optical axes intersect the planes of the diaphragms at right angles.

The positions of the diaphragms can be adjusted to exact correspondence and this may be obtained simply by looking through the centre of the objective and moving the two diaphragms until they are seen overlapping each other. From time to time the positions of the diaphragms were also checked by pointing the photometer towards a bright star. When the photometer was moved in height or in azimuthal direction, the images of the star passed across both diaphragms and the two images should appear and disappear simultaneously. This was checked by the response from the multiplier. This was also a test of the evenness of the sensitivity within the field, which was found to be very good.

Interference filters can be inserted in the slides in front of the diaphragms. On the diaphragms are screwed two "photo-electric cameras", which contain the photo-multipliers. In the front of the camera is an achromatic field lens which focusses the opening of the objective on the photo-cathode. The objective is, of course, evenly illuminated by the aurora, so that the light from any point of the aurora will be evenly distributed on the photo-cathode within the image of the objective. The photo-cathode will thus be equally sensitive to any aurora appearing within the area selected by the diaphragms. The focal length of the objective is 60 cm and the diameter of the diaphragms is 8 mm, so that these select a circular area with a diameter of 0.76 degrees in the sky, or less than half a square degree.

The multipliers can be cooled with solid CO_2. The outer walls and the back lid of the camera are double, with 8 mm Styropor as insulation. One filling of CO_2 lasts 4—8 hours, depending on the outer temperature. The resistance chain for the multiplier is mounted directly on the socket and is thus inside the inner container. The lens holder and parts of the inner container are made of brass; otherwise turbonit is used. The construction is such that the field lens will never be very cool, being thermally insulated from the CO_2-reservoir and in contact with the main body of the photometer. The brass wall S_1—S_2 is in contact with the CO_2, and will be cooled down rapidly, so that water vapour in the space between the lens and the photomultiplier will be condensed on the surface of this wall. The lid to the inner container, where the photo-multiplier is placed, is intersected by 3 cables, for high tension supply, signal out and grounding. The lid is sealed very simply with tape. Leak currents on the socket or resistors due to condensing of water vapour have never been experienced.

This system makes the photometer very flexible, which is desirable because it will serve several purposes besides that described in this paper. Photo-multipliers and filters can be changed in a few minutes, since each multiplier is permanently mounted in its own camera. For the work reported in this paper, two *EMI* photo-multipliers 6094 *B* were used (end-on type with flat photo-cathode). In this case it is not necessary to cool the multipliers as the signal from the night sky alone gives a photo-current ten times or more higher than the dark current. After the photo-electric cameras were built, it turned out that a rather high voltage of period 50 *c/sec* was induced from the main power net. This was avoided by simply wrapping the cameras in very thin aluminium foil which was grounded.

The currents from the multipliers are fed into two cathode-follower type pre-amplifiers. These are battery operated and mounted inside the main housing of the photometer, again to avoid annoying induction from the main power net. The input circuit resistance can be varied by a selector switch between $\frac{1}{2}$, 1, 2, 4 and 10 $M\Omega$. During the work reported here capacitors of 0,01 μF where shunted over the input terminals, so that the shot noise was partly short-circuited. Without this, the shot noise was particularly annoying in the signal from the $H\beta$ channel, where the 10 $M\Omega$ resistor was always used. The time constant of the input circuit was thus 0,1 sec for this channel. The voltage gain in the pre-amplifiers was about 3.

Fig. 3. The photometer.

During the work reported in this paper the signals from the pre-amplifiers were fed into two Phillips D.C. amplifiers *GM* 4531 (amplification usually 12 to 50 times), and then into a two-beam Cossor oscillograph with full deflection for 10 *V*. The *X*-sweep was turned off and the deflection filmed with a Shackman 35 mm camera with continuously moving film. The speed of the film could be continuously regulated from less than 5 mm/sec. and upwards. A synchronous motor with a relay broke the connection from one of the channels to the oscilloscope for about 0,1 sec every two seconds. In this way time marks were obtained on the film and the two curves could easily be distinguised. The linearity of the whole system was checked and found satisfactory.

The *HT*. power supply is stabilized and can be regulated through 11 steps from 850 to 2075 Volts. During one recording of an aurora which fluctuates in intensity, it may be desirable and necessary to change the sensitivity of the photometer, as the intensity of the aurora may fluctuate greatly during a short time. The change in sensitivity was most easily done by changing the *H.T.* while keeping an eye upon the oscilloscope screen. One step in the *H.T.* corresponded to a factor close to 2 in sensitivity, and the variation in sensitivity with *H.T.* has been carefully calibrated. Thisvariation is of course characteristic of the individual photo-multiplier.

The filter slides are constructed for square filters of size 2 × 2 inches, and up to 15 mm thick. Thinner filters can be tilted by blocking them up on one side. Thus the transmission maximum can be displaced towards shorter wavelengths. The filters are kept in position by springs. Since the objective has an opening ratio of $F : 4.5$, the convergence of the beam will tend to widen the effective transmission profiles of the filters towards shorter wavelengths. Therefore, when the effective transmission curves for the filters were measured, the illumination and filter angles had to be reproduced exactly as they were in the photometer. The light was then thrown upon a piece of alabaster glass in front of the slit of a spectrograph instead of the photo-cathodes of the multiplier. The effective transmission curves for the two filters used for the work reported in this paper, are shown in Fig. 4. The filters are of the multi-layer type and produced by Baird Atomic Co.

The sensitivity of the photometer may vary slightly from one night to another, owing to variations in temperature and battery voltage. The sensitivity was measured by placing a standard lamp in front of the photometer. This lamp has been described earlier (Omholt 1955). It has been calibrated on an absolute scale by comparing it with a tungsten standard lamp in the Physics Department of the University of Oslo, but owing to the difficulties involved in such comparisons the absolute values may not be very accurate.

The absolute value of the emission from the standard lamp was also checked by comparing it with the star Capella (α Aur.). This star is bright enough to be measured fairly accurately with the photometer. The spectral distribution resembles that of the sun and the energy per unit wavelength was taken to be that of the sun divided by 6.9×10^8 (corresponding to a magnitude difference of 27.1 between the sun and Capella). This gave a value of the absolute emission of the standard lamp which was 14 % lower than that obtained earlier. If we take into consideration that the effective temperature of Capella is somewhat lower than that of the sun, we arrive at a figure about 25 % lower than the earlier value. This agreement is satisfactory, and may of course be accidental, but any correction factor to the absolute values given in this paper should be less than 1.5.

2.3. The first extensive photo-electric measurements of the auroral spectrum were made by Hunten with a scanning spectro-photometer (Hunten 1953, 1955). It may be of interest to compare the important features of Hunten's spectrometer with those of the chopping photometer developed by Harang (1958) and the photometer described here.

The most obvious difference between a scanning spectrometer and a filter photometer is, of course, that the first records the whole spectrum within a certain wavelength range whereas the filter photometer records on fixed wavelengths. The resolution of a scanning instrument may be very good (Hunten reports to have used about 10 *Å*, but this is certainly not the lower limit), whereas that of a filter photometer is limited by the properties of the filters. Although filters of half-width 10 *Å* can be obtained, these are very expensive and have a low transmission coefficient. The use of filters is therefore limited to lines and bands which are strong compared to those close by. The main advantage of the filter photometers is that they record simultaneously the intensity of two or more spectral lines or bands, whereas the scanning spectrometer needs a certain time (of the order of seconds) to move between two wavelengths. With the filter photometers we can follow rapid intensity fluctuations which may frequently occur, particularly in the auroral zone where the aurora frequently is very high up in the sky. We can also scan very rapidly through an auroral form. It seems to the author that the scanning spectrometer would be very difficult to apply to the most luminous auroral forms at high latitudes, since they move and fluctuate in intensity very rapidly.

We may also compare the numerical light powers of the instruments. The photometer described in this paper gathers light from an area in the sky of 0.48 square degree with a lens area of 135 cm^2. The product of these two quantities, 65 cm^2 square degree, gives the geometric light power of the instrument. Harang's photometer has a comparable light power. From the details given by Hunten it appears that with a resolution of 10 Å the slit width must be about ½ mm. From this follows that his instrument gathers light from an area of about $3 \times 0.05 = 0.15$ square degrees and that the effective lens area is about 115 cm^2. The light power of the spectrometer is thus not bad compared to the filter photometer (about $^1/_4$), but the form of the area (3° long and very narrow) may be rather awkward for some applications to aurorae. The efficiency of blazed gratings and the transmission coefficients of ordinary multilayer interference filters are comparable.

Of equal importance is the fraction of the light that the instruments utilize. In the split-beam photometer light is lost by the splitting technique, but if we use dichroic mirrors or favour the weakest of the two radiations, this disadvantage may be considerably reduced. The chopping photometer is open for each wavelength only a small fraction (about 0.15) of the time, so that a considerable amount of light is lost. A scanning spectrometer uses very little of the total amount of light. The efficiency will be approximately equal to the slit width in wavelength units divided by the range of scanning. With 10 Å resolution and 1000 Å scanning range, it will thus be about 1 % only. Since the accuracy that can be achieved depends on $i\triangle t$ where i is the intensity and $\triangle t$ is the time we use the light, it is clear that the split beam photometer is superior to the chopping photometer, which again is superior to the scanning spectrometer. In the case of the slit-beam photometer $\triangle t$ is limited by the rapidity of the variation we want to study, and in the instrument described, time constants of 0,01 to 1 sec have been used. We may also base these considerations on the shot noise rather than the effective use of the light for which the reader is referred to the appendix.

The chopping photometer is, however, in some respects more advantageous than the split beam photometer. The chopping photometer has a much simpler amplifier, as an *AC* amplifier can be used. It is cheap and simple in construction and three to four different filters may easily be used simultaneously. For stronger aurorae, when the intensity is ample in any case, this type may therefore be preferable to the split-beam type, except if we want to study very rapid fluctuations. The chopping photometer in the present form records only 23 pulses per sec per spectral component, which limits the time resolution.

Hunten's spectrometer is obviously superior in all cases when high time resolution is not required, whereas the filter photometers are superior when rapid fluctuations are to be recorded. These fluctuations in the intensity of the light falling on the photocathode may, of course, be due either to fluctuations in the aurora or to a rapid scan through the auroral form.

Some alternations of the instruments may be suggested. It should not be too difficult to fit a scanning spectrometer with two detectors, so that it can also record the intensity on two fixed wavelengths. Also, it may be suggested to chop the light in the split-beam photometer. In this case light is lost, but the stability of an *AC* amplifier is superior to that of a *DC* amplifier. One may even suggest replacing the half-transparent mirror M_2 with a rotating mirror disc, which would alternate the light beam between the two photo-multipliers. This would minimize the light loss, as all the light will be thrown on either of the two detecting systems.

3. Observations in Tromsø February—March 1958.

3.1. Observations were made of the $H\beta$-line and the $\lambda 4709$ (0—2) band of the First Negative band system of N_2^+. $H\beta$ is much more isolated in the spectrum than is $H\alpha$, and it is thus easier to isolate with a filter. The $\lambda 4709$ band was chosen because it is close to $H\beta$ in wavelength, which makes corrections for atmospheric extinction in the relative intensity of the two emissions superfluous. So we preferred this band although the $\lambda 4278$ (0—1) band would give a much higher response in the photometer. The $\lambda 4709$ band had sufficient intensity, as the accuracy in the measurements of the relatively intensity was limited by the accuracy in the intensity of $H\beta$, which was always much weaker than the $\lambda 4709$ band. A N_2^+ band was chosen because we wanted to compare the ionization in an aurora with the proton flux.

3.2. The observations were made either by scanning through quiet auroral forms in height or in azimuthal directions, or by keeping the photometer in a fixed position, recording the intensity variations with time.

By the scanning method it was possible to scan horizontally across auroral rays at different heights or to scan through a patchy and rayed, diffuse aurora. Further, it was possible to scan vertically through arcs, bands and auroral glow. (To scan along a ray is almost impossible, because its angle with the horizon varies with azimuth.) By this method one could easily eliminate the contribution from the night glow or the auroral glow which acts as a background for more distinct forms. The records of the intensity variations with time were made when the aurora varied notably in intensity or moved across the sky. The intensities were deduced from the records by subtracting the minimum from the maximun value, thus eliminating the contribution from the night glow or more permanent auroral glow.

3.3. As mentioned in sec. 2.2 the sensitivity of the photometer was measured by placing a standard lamp in front of the photometer. Since we know the energy emission from the lamp, the filter transmission curves and the geometry of the photometer, it is easy to calculate the sensitivity. The relative sensitivity for the two channels was also checked by placing the 4709-filter in the light beam in front of the mirror M_1 and removing the $H\beta$-filter.

To deduce the sensitivity of the photometer to the $H\beta$ line and the $\lambda 4709$ band, we need to know the effective transmission coefficients of the filters for these rather broad emissions, which means that we need to know their detailed profile. For the $\lambda 4709$ band a profile corresponding to a temperature of 220° K was adopted. This gave an effective transmission, T_{eff}, of 39 % for the whole band[1]). Other auroral emissions do not contribute significantly to the signal from the photo-multiplier.

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[1] T_{eff} is, of course, $\int I\lambda \; T\lambda \; d\lambda \, / \int I\lambda \; d\lambda$.

The *Hβ*-line raises further problems, since its profile varies with the direction of the observation and perhaps with the height in the atmosphere and from one aurora to another. The *Hβ* filter has its maximum transmission at 4867 *Å* for vertical incidence of the light. The tilting of the filter and the convergence of the beam in the photometer alter the transmission profile in a suitable direction, its maximum being close to the undisplaced *Hβ*-line and the curve being somewhat asymmetric in the same way as the *Hβ* profile itself (cf. Fig. 4). The effective transmission coefficient of the *Hβ*-line was computed for four different profiles. The first two are those published by Vegard and Kvifte (1951) and by Vegard and Tønsberg (1952). Thanks to the asymmetric transmission profile these two *Hβ*-profiles give nearly the same value for T_{eff}, 22 % and 23 % respectively, despite the fact that they are appreciably different. The two other *Hβ*-profiles used were derived from Meinel's (1954) horizon and zenith profiles for *Hα*. The difference in wavelength between *Hα* and *Hβ* was taken into account and the units of the velocity scale for *Hα* were increased by the ratio $\frac{2000}{1700}$ in accordance with Chamberlain's results (cf. sec. 1.3). This procedure gave T_{eff} = 24 % for the horizon profile and 16 % for the zenith profiles.

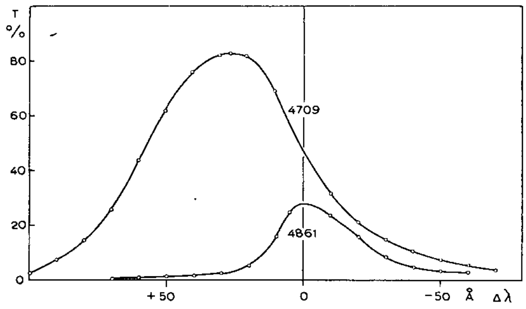

Fig. 4. The transmission curves for the filters.

Meinel's profile for magnetic zenith shows a larger displacement and a broader velocity distribution than any other profile measured, and 16 % should be a safe lower limit for T_{eff}. On the other hand the profiles measured by Vegard *et al.* may be slightly too wide because of the line width of the spectrograph. A correction for this would increase T_{eff} slightly. A recent high dispersion spectrogram obtained by Kvifte at Ås near Oslo, of a diffuse arc low in the north, yields a half-width of about 18 *Å* for *Hα*, in agreement with Meinel's horizon profile.

At present our knowledge of the *Hβ*-profile is not sufficient to introduce a T_{eff} which varies with the direction of observation. As most of the observations have been made at moderate elevation angles (20° to 50° above the horizon), we tentatively adopt $T_{eff} = 22\%$ but should bear in mind that the derived intensities of *Hβ* should be slightly corrected.

When the *Hβ*-filter was received from the manufacturer the transmission profile was measured and found satisfactory. During the work on aurorae, however, it became evident that the filter had a very slight, previously undetected, leak in the green region, and a careful calibration gave T_{eff} = 0.11 % for the wavelength 5577 *Å*. This is not much, but owing to the high intensity of the [*OI*] line λ5577 it proved to be annoying.

A series of measurements of the [*OI*] line, with a filter for 5577 *Å*, and the λ4709 band gave the necessary data for correction, since the response of the *Hβ*-channel of the photometer to the [*OI*] line could be computed from these measurements. We shall deal with these measurements in another paper, as they were interesting in themselves, and we shall here only give the correction term to $H\beta$. It turned out that for the average intensity ratio between the $[OI]$ line and the λ4709 band the response of the photometer due to the $[OI]$ line equals that from a $H\beta$-line with an intensity approximately 0.09 times that of the λ4709 band. The departure from the average was in all cases less then 30 %. This correction will be further discussed in the next section.

It is of course likely that also other, weak radiations leak through the filter, but as far as can be judged from spectrograms of high latitude aurorae these should not be important.

3.4. The main results of the quantitative measurements are summarized in Table 1 and Figs. 5a to f. The intensities Q are given relative to the emission E_λ from the standard lamp at 4709 Å, integrated over 1 Å. $R(H\beta)$ is the intensity ratio $I(H\beta)/I(\lambda4709)$, supposing all the light recorded through the $H\beta$-filter to be due to the hydrogen line. The correction for the filter leak in green has thus not yet been made.

The intensities are not corrected for atmospheric extinction. This does not significantly affect the value of $R(H\beta)$, which is the most important quantity. The correction for extinction will not effect the distribution in absolute intensities very much, and since this correction always is somewhat dubious[1], it has been omitted. The unit

Table 1. *Averages of 100 × R (Hβ). The figures in ( ) give the number of observations.*

Group	a	b	c	d	e	f	g	a—g
1	10.4(26)	9.2(29)	12.7(27)	12.9(15)		15.9(7)	8.5(2)	11.3(103)
2	9.3(7)	8.9(13)	12.9(26)	11.9(14)	6.3(3)	16.8(11)	9.0(3)	11.9(77)
3	10.0(4)	9.7(10)	11.6(14)	14.6(14)	7.3(4)	19.3(8)	10.7(3)	12.5(57)
2+3	9.5(11)	9.2(23)	12.5(40)	13.2(28)	6.9(7)	17.8(19)	9.8(6)	12.1(134)
1+2+3	10.1(37)	9.2(52)	12.6(67)	13.1(42)	6.9(7)	17.3(26)	9.5(8)	11.8(237)

Mean b + e : 8.9(59)
Mean a + g : 10.0(45) Mean quiet forms: 12.7 (178)
Mean c + d : 12.7(107)
Mean f : 17.3(26)

Groups: a: Homogeneous arcs and bands
b: Rayed arcs and bands, moving bands.
c: Isolated rays
d: Diffuse aurorae with rays
e: Pulsating aurorae
f: Diffuse, patchy aurorae, veil and glow.
g: Broad arcs with sharp structure, elongated in *E-W* direction (cf. Størmer 1955 figure 3).

1: Before 22.00	Norwegian time	(21.00 G.M.T.)
2: 22.00—00.00	— —	(21.00—23.00 G.M.T.)
3: After 0.00	— —	(23.00 G.M.T.)

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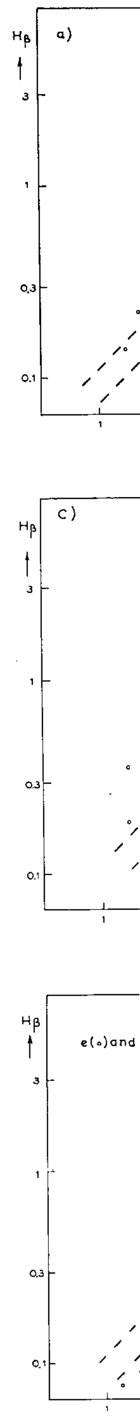
[1] This is because Rayleigh scattering is the most important factor in the attenuation of the radiation. The available extinction tables are for point sources only, and exact corrections for aurorae would include rather complex integrations over the emitting surfaces similar to those encountered in the work on the air glow.



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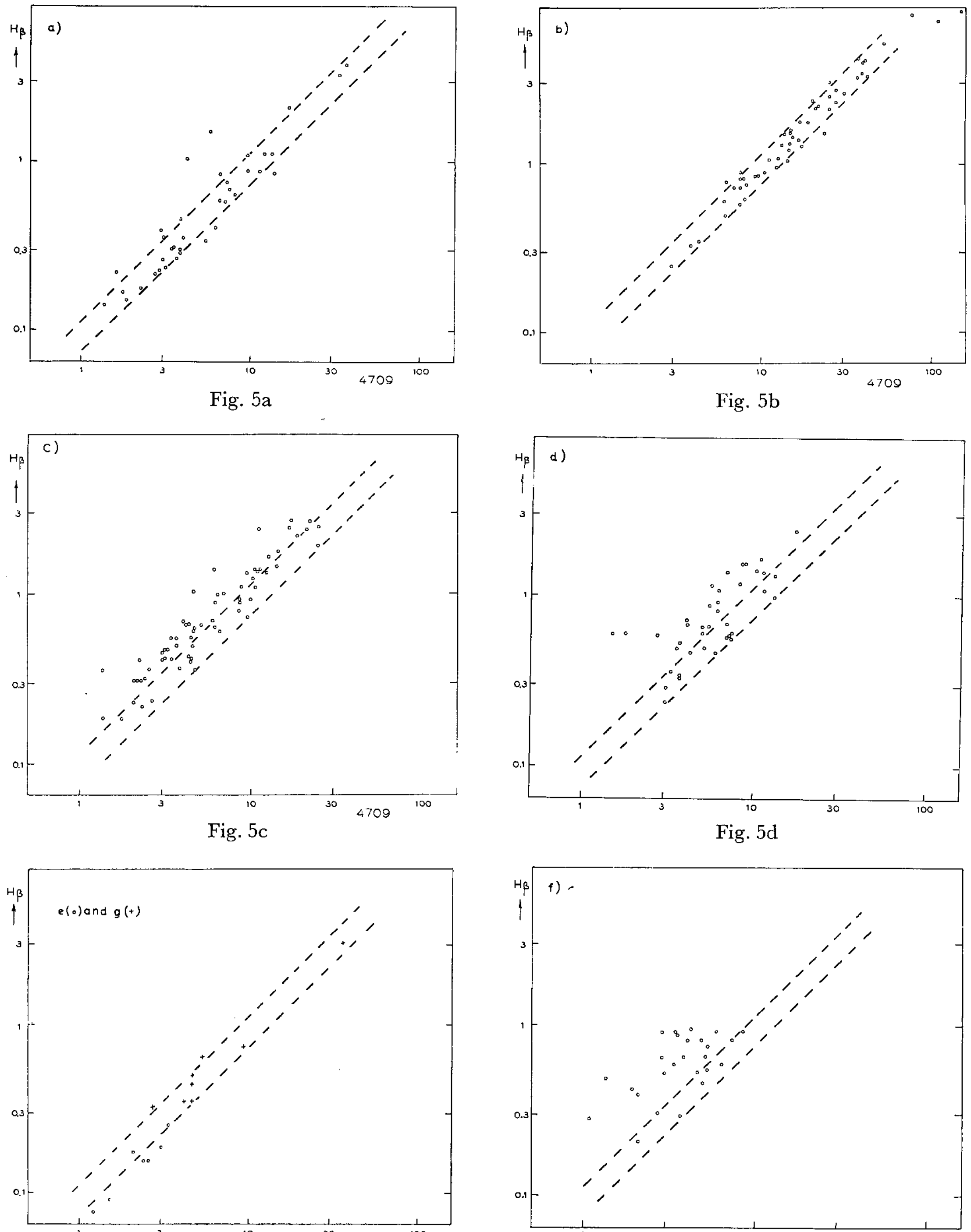


Fig. 5a

Fig. 5b

Fig. 5c

Fig. 5d

Fig. 5e

Fig. 5f

Fig. 5. Apparent intensity of $H\beta$ versus the intensity of the $\lambda 4709$ band.

for Q ($E_\lambda \times 1$ Å for the standard lamp) is about 6×10^{-4} erg/cm^2 (column)/sec or 1.4×10^8 quanta/cm^2 (column)/sec. If we take an average correction for extinction into account we get about 2×10^8 quanta/cm^2 (column)/sec or 0.2 KR as unit for Q used in Fig. 5 (cf. Hunten, Roach and Chamberlain 1956). As said in sec. 2.2 this value may be slightly wrong by a factor which probably does not exceed 1.5.

The emission ratio between the [*OI*] line λ5577 and the λ4709 band was measured to be about 25, in reasonable agreement with earlier results. Values of $Q = 2$ and 20 for the λ4709 band should therefore correspond to 10 and 100 KR for the green line, and international brightness II and III for the aurora (cf. Hunten *et al.* 1956).

The values of Q measured are usually the maximum values in the auroral form. Only in a few cases was there noted any appreciable change in $R(H\beta)$ within a form.

3.5. The observations were divided in 7 groups according to type as specified in Table 1. The values of $R(H\beta)$ for groups b, e and g are very close to the estimated correction for the filter leak in green, and it seems justified to assume that the correct value of $R(H\beta)$ is zero or of the order of magnitude 0.01 for those groups. In Fig. 5b we have drawn two lines between which 80 % of the observed points lie. These two lines are drawn on all Figs. 5a to f, and we will assume that when a point lies above the upper of the two lines, it indicates $H\beta$ to be present in the aurora, and take the correct value of $R(H\beta)$ to be the measured one less 0.09.

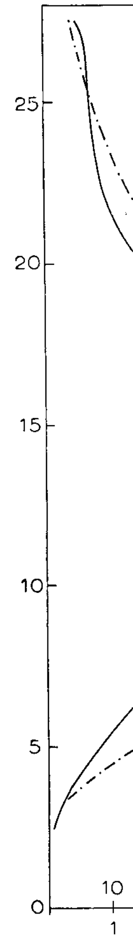
The scatter of the points between the two lines in Fig. 5b is probably partly due to scatter in the true intensity ratio, but is also due to random errors in the measurements. These are again partly due to the statistical nature of the photo-current (shot noise) and partly due to random errors in the reading of the curves. It is difficult to make any accurate estimate of these errors, but it is conceivable that they are the major cause of the scatter in Fig. 5b.

One might think that part of the systematic variation of $R(H\beta)$ may be due to variations in the intensity ratio $I(5577)/I(4709)$. The observations of this intensity ratio contradict this assumption, as aurorae belonging to groups c, d and f showed a slightly lower (≈ 10 %) value for this ratio than did draperies and bands (a and b). It may therefore be possible that all the observed aurorae in these three groups do show $H\beta$, although some of them very weakly.

Each of the seven groups has been divided into three sub-groups according to the time (Norwegian S.T. = G.M.T. — 1 hour). The purpose of this was to see if there were any significant diurnal variations in the appearance of the hydrogen lines. 22.00 N.S.T. is close to magnetic midnight and this point was therefore chosen as partition besides standard midnight.

The results given here will be further discussed in section 5.

In addition to the intensity records which have been treated here, a great number of observations was taken between the records, but with only visual inspection of the deflection on the oscilloscope screen. This was to search for parts of the aurora where $R(H\beta)$ might be particularly high and to find out if parts of the sky showed a detectable $H\beta$-line without showing noticeable aurora. These observations failed to give positive results.



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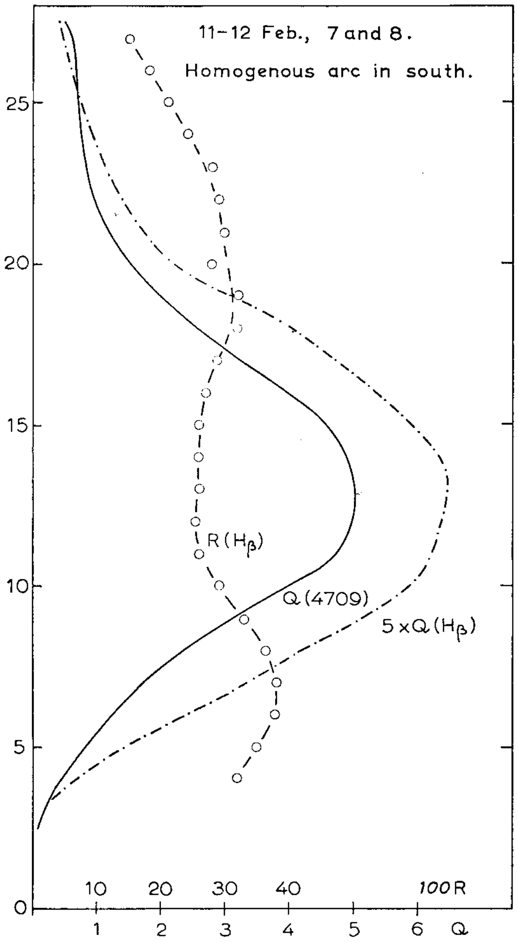

Fig. 6. Vertical scan through a homogeneous arc.

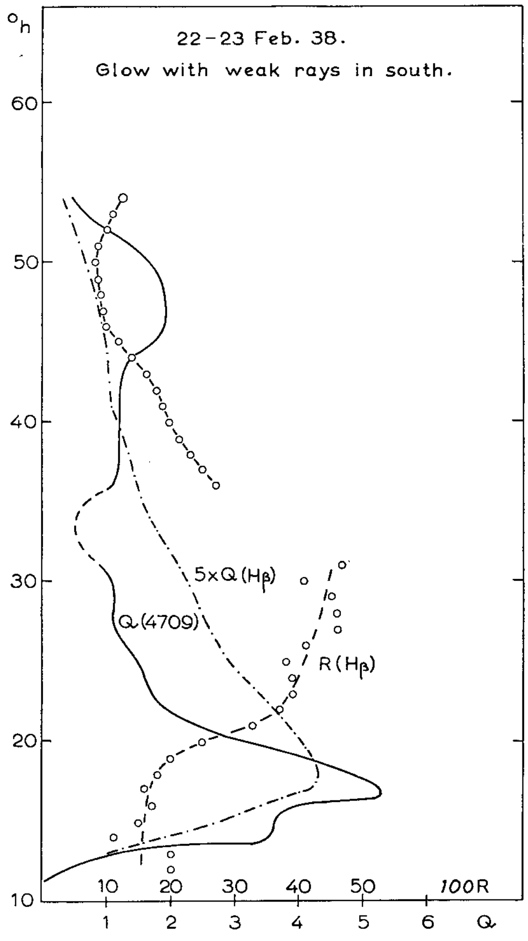

Fig. 7. Vertical scan through glow with weak rays.

It is also necessary to emphasize that because of the observational technique (semi-manual) the total number of observations of each group is by no means representative of the frequency of appearance. It was attempted only to get a sufficient number of records to make the results significant for each group. Therefore, and because of the variation in the average intensity of the different groups, the averages over all groups are not representative and show only qualitatively what would be found with a patrol spectrograph.

3.6. Successful vertical scans of auroral forms showing the *Hβ*-line with sufficient intensity to be of significance were obtained only on two occasions. The intensity variations with elevation angle above the horizon were derived for these two cases and are given in Figs. 6 and 7 together with *R*(*Hβ*). Fig. 6 represents the mean value of two successive scans (with two minutes' interval) of a homogeneous arc in the south and Fig. 7 one scan of a glowlike, patchy aurora with long, weak rays above, also in the south. The plotted intensities and $R(H\beta)$ are not corrected for extinction or for the contribution from the green line.

In Fig. 6 the maximum of $R(H\beta)$ around 7°h is most likely due to the increased relative intensity of the green line, since this suffers less from atmospheric attenuation than do the other two emissions considered. Above 15° the correction to $R(H\beta)$ is for all practical purposes constant (= — 0.09) and it does not vary very much between 10° and 15°h. The variation in $R(H\beta)$ higher up is not significant and it is most reasonable to assume that $R(H\beta)$ varies only very little with elevation angle.

In Fig. 7 the picture is very different, $R(H\beta)$ being relatively high around 30°h, where weak rays were seen. It is difficult to say whether this is an altitude or type effect, since one may say that the aurora consisted of two partly overlapping forms. The altitude effect may then be said to be of secondary nature, i. e. associated with the different average height in the atmosphere of the two forms. The heights of patchy, cloud-like aurorae have been measured by Størmer (1955) who finds an average altitude of about 100 km, whereas rays usually are much higher. Further discussion will be given in section 5.

4. Observations at Yerkes Observatory.

4.1. In March, April and May 1957 some photo-electric records of the $H\beta$ line and the λ4709 band were obtained at Yerkes Observatory, of the University of Chicago, Wisconsin. The photometer and some of the results have been briefly described earlier (Omholt 1957b, 1958), but we shall elaborate a little more on some of the results here. However, the photometer used at Yerkes was less sensitive than the one used in Tromsø, and the observations were less systematic, as they were the first attempts of photo-electric filter photometry of the $H\beta$-line. We shall therefore not deal with any further details of the instrumentation, inasmuch as it was in prinsiple similar to that described in this paper, but give only the results to the extent they are significant and have a bearing upon the other work presented herein. This will include only the results obtained with the filters of high quality (cf. Omholt 1957b). Both the $H\beta$-and the 4709-filter had an effective half-width of about 45 Å.

4.2. Seven different homogeneous auroral arcs were observed on four different nights. These all showed $H\beta$, $R(H\beta)$ being 0.25, 0.25, 0.7, 0.7, 0.5, 0.4 and 0.3. On three occasions observations of the break-up period of aurorae were obtained. When the homogeneous aurorae started to show ray-structure and formed rayed arcs or bands $R(H\beta)$ started to drop. The decrease in $R(H\beta)$ is rather slow, the decay time being 10 to 20 minutes. The best series of observations is given in Fig. 8, which shows the observed intensity of the λ4709-band, $R(H\beta)$, and the variation of the horizontal component of the geomagnetic field at the point of observation. The aurora appeared very low in the north, and the given values are for the maximum point. The elevation angles for this are given in Fig. 8. $R(H\beta)$ did not seem to vary very much with elevation angle. It should be emphasized that part of the increase in intensity may be

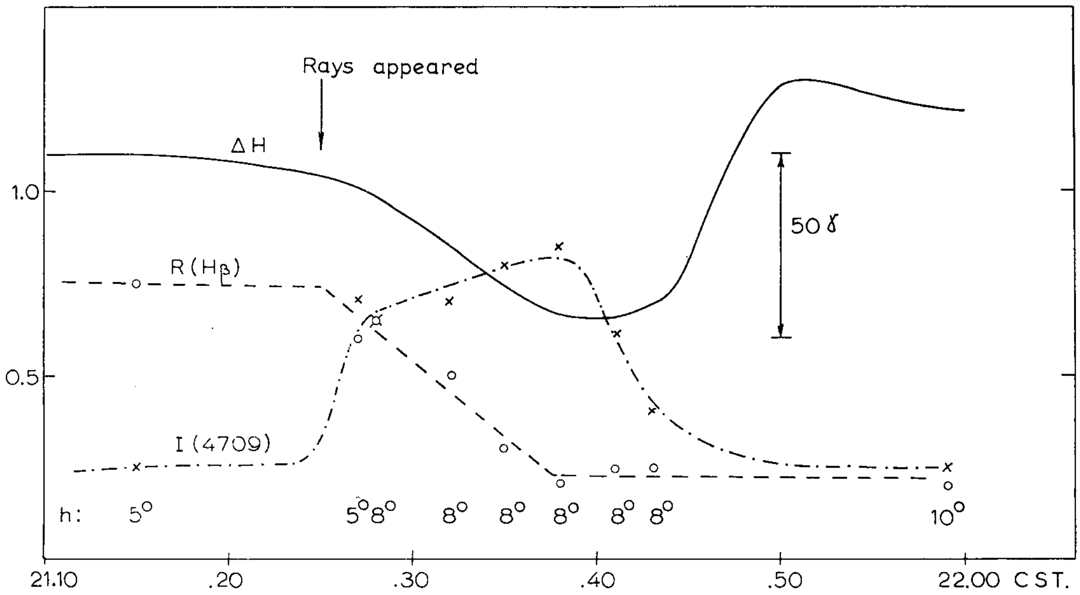

Fig. 8. Time variations when a homogeneous aurora broke up into rays.

due to the increased elevation angle, i.e. less atmospheric absorption as the aurora moved southwards.

4.3. Long rays were observed on two nights. These showed a value of $R(H\beta)$ of about 0.05 only, a value which is probably due to leaks in the $H\beta$-filter similar to that experienced in the Tromsø measurements. The weak glow covering larger parts of the sky after a big display showed a value of $R(H\beta) = 0.15 — 0.2$; this was also the case with the glowlike background of long rays. Pulsating, flaming and flashing aurorae were observed on two nights and all gave values of $R(H\beta) = 0.05$, this again probably being due to filter leaks.

5. The general behaviour of the hydrogen lines.

5.1. We are now faced with the problem of how the observational data obtained by different workers can be reconciled in a general description of the behaviour of the hydrogen emissions from aurora. This is not an easy task, as widely different instruments and observational techniques have been used and the observations include $H\alpha$ as well as $H\beta$. The picture we can draw will therefore to a large extent be of a qualitative nature, although certain quantitative limits can be given. We shall first confine ourselves to the general intensity of the hydrogen lines, then look into the height distribution and finally briefly review the known facts about the line profiles.

5.2. There appear to be type effects as well as latitude effects in the intensity and it seems most instructive to consider the various types of aurorae separately. We shall then start with the homogeneous aurorae, as these forms are the simplest ones and the observations of these are least likely to be ambiguous. One shall bear in mind, however, that when an aurora is observed low in the north, as is often the case south of the auroral zone, it may not be easy to distinguish between homogeneous arcs, bands and glow.

The available observations leave little doubt that there is a latitude effect in $R(H\beta)$ of homogeneous arcs. As shown by Vegard and Kvifte (1954) there is a general latitude effect between Tromsø and Oslo in Norway, but their spectra do not distinguish between different auroral forms. However, from Vegard's recent results (1955, 1956) and from the results reported here, it appears clearly that homogeneous auroral arcs and bands close to the auroral zone show no or extremely weak hydrogen lines, $R(H\beta)$ being usually much less than 0.1. The two cases with a relatively high $R(H\beta)$, plotted in Fig. 5a are both arcs far in the south.

Fan and Schulte's results as well as the observations reported in section 4 show that the hydrogen lines are always present in homogeneous aurorae observed from Yerkes Observatory, with $R(H\beta)$ approaching one in some cases. In the case of auroral glow there is not yet any proof of a latitude effect. As the measurements reported in this paper show, the hydrogen lines are almost always present in glow observed from Tromsø, and this seems also to be the case for glow observed from Yerkes. The observations from the two places yield also the same order of magnitude of $R(H\beta)$, this being always low (usually 0.2 or less).

For homogeneous bands we have no reliable observations from southern stations.

According to the numerous observations reported here, rayed arcs and bands in the auroral zone show definitely no hydrogen lines. From the photo-electric measurements at Yerkes it is evident that rayed arcs and bands may show fairly intense hydrogen lines, particularly just after the breakup of a homogeneous form. This seems also to be confirmed by Petrie and Small's spectra from Saskatoon (1952), which show relatively strong hydrogen lines in the initial and in the brightest phases of an aurora. Also Hunten reports the hydrogen lines to be present in the spectra of type B aurorae. The initial phase is, at least south of the auroral zone, usually the homogeneous arc, and the brightest phase, frequently with type B aurora, appears usually shortly after the break-up of an arc into a rayed arc or band. The decay of $R(H\beta)$ after the break up observed at Yerkes Observatory is probably correct, as Fan and Schulte (1954) find no trace of the $H\beta$ line in their spectra of rayed aurorae. A spectrum can give only an upper limit of the intensity of $H\beta$; this limit is not given in the paper, but may be fairly high. Since the exposure time is usually more than one hour, their spectra do not contradict the photo-electric measurements, which show that the hydrogen lines are partly present in the rayed arcs or bands in southern latitudes.

When we come to the long, fainter rays, which are not associated with an arc or a band, the situation again becomes different. The photo-electric measurements at Yerkes failed to give evidence of emission of the hydrogen lines from the rays themselves, but the measurements are neither extensive enough nor good enough to justify final conclusions. In the auroral zone the hydrogen lines are frequently, but perhaps not always, emitted from ray bundles, but it should be emphasized that the angular resolution of the photometer (0.8 degrees) did not permit a detailed study of the structure of the rays. It may well be that the hydrogen lines do not show the detailed ray structure as the main emissions may show. Indeed, this is very probable from theoretical considerations (cf. section 9).

Pulsating aurorae have been observed with photo-electric photometers both from Yerkes and from Tromsø, and it appeared that the $H\beta$ line was always absent or indeed very weak. This was also the case with flaming and flashing aurorae observed at Yerkes observatory. Hunten reports, however, that on two occasions he had observed unusually high values of $R(H\beta)$ in the faint, very active aurorae which is usually seen just after a big display. The values of $R(H\beta)$ ranged in these cases from 24 to 260, exceptionally high values in view of what other reports give. The absolute intensity of $H\beta$ was of the same magnitude as in bright, normal aurorae. This very high value of $R(H\beta)$ was especially looked for both at Yerkes and in Tromsø, but no significant trace of the $H\beta$ line was ever found. It is therefore likely that the aurorae observed by Hunten are rare exceptions from the normal case. Very recently Romick and Elvery (1958) and Galperin (1958) seem to have detected a type of pre-aurora where $R(H\beta)$ is fairly high. The observations seem to have been made a few degrees south of the auroral zone.

Since the observations from one station include a large variation in latitude and the values of $R(H\beta)$ also vary a great deal for any one station, it is not at present possible to give the latitude effect a quantitative treatment.

5.3. Table 1 does not show any pronounced diurnal variation in the appearance of the hydrogen lines, but there seems to be a slight tendency towards higher $R(H\beta)$ after midnight. This is in qualitative agreement with the results obtained by Montalbetti and Vallance Jones (1957) at Churchill, which lies 2° closer to the magnetic axis point than Tromsø. However, as emphasized in section 3.5 one cannot compare the results quantitatively.

At Saskatoon, well south of the auroral zone, the diurnal variation was found to be opposite to that at Churchill, and this appears at presently to be the only extensive study of the diurnal variation south of the auroral zone.

The diurnal variations may partly follow from the different latitude variations of the various auroral forms, since long rays and diffuse forms are more prominent after midnight. The results given in Table 1 indicate a diurnal variation of $R(H\beta)$ also within single groups, in particular in group *f*, but it is doubtful to what extent these variations are significant.

5.4. The question of the height distribution of the hydrogen emissions from aurorae has been far from satisfactorily investigated. The photo-electric measurements do not indicate any major difference between the height distributions of the $H\beta$- and λ4709-emissions within an auroral form. However, the latitude effect discussed above implies that at low latitudes auroral forms which generally lie low in the atmosphere show the highest value of $R(H\beta)$, whereas in Tromsø the opposite is the case. This may be the reason for the apparent height effects observed by Meinel (1954) and by Vegard

(1955, 1956). Long exposure spectrograms like those obtained by Meinel are particularly difficult to interpret, as the aurora may move and the type and spectrum may change in the course of the exposure. There is therefore no clear correspondence between the elevation angle above the horizon and the height in the atmosphere, although larger angles will generally correspond to greater heights.

The photo-electric measurements in Tromsø revealed that $R(H\beta)$ may vary with altitude within a ray-bundle, but this variation seemed not to be consistent from one aurora to another. The $H\beta$-line could be present or absent in the top as well as in the bottom of rays.

Although we are not able to draw any definite conclusions regarding the height distribution of the hydrogen emission in a particular form, it is likely that, on average, it does not differ drastically from that of the main emissions. This seems also to be confirmed by the very recent work by Galperin (1958).

5.5. The available observations of the profiles of the hydrogen lines are not satisfactory, but they seem to be in reasonable agreement. The profile obtained when the spectrograph is pointed towards zenith is, of course, very different from that obtained when it is pointed towards the magnetic horizon. At intermediate angles it is very difficult to compare the observations, and this complicates a direct comparison between the results of Meinel and those of Vegard *et al.* Chamberlain (1958b) reports that he has measured the half-width of the horizon profile of $H\beta$ to be about 13 Å, corresponding to a half-width in the velocity of about 800 km/sec. A recent high dispersion spectrogram obtained by Kvifte[1] gives a half-width of the horizon-profile of $H\alpha$ of about 18 Å, in agreement with Chamberlain's results, and all the observations indicate a half-width of the horizon profile close to this value.

It is important to ascertain whether the profile varies with height within an aurora (Omholt 1956a). Kvifte's spectrogram was exposed with the aurora focussed on the slit, which covered about 6° of elevation angle. Over this range there was no significant variation in the $H\alpha$-profile, but it is doubtful to what extent this has a bearing on the height variations of the profile. At present, however, all observations favour the view that the half-width of the horizon-profile versus velocity is about 800 km/sec. and that there are no drastic variation of the profile with height within an aurora or with the height in the atmosphere. The zenith profile is indeed more dubious, and more observations on this are urgently needed.

C. THEORETICAL CONSIDERATIONS.

6. General remarks on the theory.

A quantitative interpretation of the hydrogen lines in the auroral spectrum is a difficult task, because our knowledge of the various processes involved is still insufficient. Nevertheless, Chamberlain's work (1954, 1957, 1958a) has shown that some information can be obtained with the present premises.

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[1] The author is indebted to Prof. Kvifte for putting this spectrogram at his disposal.

At present it seems convenient to divide the problem into three parts. First, to what extent do the protons contribute, directly or through secondary mechanisms, to the excitation of the emitted auroral light and to the associated ionization of the atmosphere? Second, what are the flux and velocities of the protons impinging on the upper atmosphere and is there any indication of an electrostatically neutral stream? Third, what angles do the paths of the proton make with the magnetic lines of force in the atmosphere and what are the paths of the protons outside the atmosphere?

These problems are all intimately connected and a proper solution depends on information on the various processes which may occur when the protons enter the atmosphere. The purpose of the next four sections is to present a critical, independent examination of the relevant theoretical and experimental information that is available and on which our interpretation of the observed facts must be based.

7. The energy required to produce an aurora.

7.1. Attempts have been made earlier to answer the first question formulated in chapter 6, the conclusion being that the incident protons supply only a minor part of the energy required to produce an aurora (Omholt 1957b, 1958). To obtain a proper solution to this problem we must first try to make a reliable estimate of the energy which must be supplied through the primary stream to maintain an aurora. Throughout this paper we shall assume that auroral excitation is solely caused by incident fast particles, postponing the discussion of discharge mechanisms to another paper. We shall then try to deduce the total rate of ionization from the intensity of the First Negative N_2^+ bands. These bands are certainly excited by simultaneous ionization and excitation of N_2. Having deduced the total rate of ionization, it is easy to compute the total flux of energy carried by the primary particles, as the formation of one ion pair by fast particles in air requires an energy of about 30 to 35 eV.

Cross-sections for electron excitation of the First Negative bands have been measured by Stewart (1956) and the total cross-section for ionization of N_2, σ_i, by Tate and Smith (1932). For all energies for which measurements have been made (< 200 eV), the two sets of cross-sections are proportional, σ_i being about 440 times larger than $\sigma(4709)$, the cross-section for ionization followed by emission of a $\lambda 4709$ quantum. Since both theoretical (Bates, McDowell and Omholt 1956) and experimental (cf. Landolt—Børnstein 1952, Vol. 1, part 5, page 343) results indicate that most of the total ionization by fast particles is performed by secondary electrons and since fast protons behave similarly to electrons of the same velocity, it seems reasonable to conclude that the cited ratio between the two cross-sections is valid for aurorae. If we take into account that 20 % of the air is oxygen, we obtain a value of 550 for $Q_i/Q(4709)$ in air, where Q_i and $Q(4709)$ are the rate of ionization and the rate of emission of the $\lambda 4709$ band respectively. This figure should perhaps be even higher because the energy distribution of the secondary electrons favours the ground state of N_2^+.

7.2. The high value of this ratio is also supported by spectrographic evidence. The total auroral emission of quanta in the First Negative system is about 25 times that of λ4709-quanta, or approximately equal to the emission of the green [*OI*] line λ5577. If we extrapolate the intensities of the Meinel bands of N_2^+ as measured by Omholt (1957a) to the levels v' = 1 and 0, using transition probabilities given by Nicholls (1958), we arrive at the conclusion that the emission in quanta of the Meinel bands is about 6 times higher than that of the First Negative bands. This result is again supported by recent measurements by Harrison and Vallance Jones (1957), who find a brightness of 360 KR of the 0—0 Meinel band in an aurora of an estimated brightness III and 440 KR of the 1—0 band in an aurora of an estimated brightness II—III. The brightness of the First Negative bands in aurorae of brightness III is about 100 KR.

This leads us to assume that the effective cross-section for ionization of N_2 followed by emission of the Meinel or the First Negative bands is close to 200 times $\sigma(4709)$. Since ionization of N_2 also may form N_2^+ ions in the ground state and in other excited states the figure 550 obtained for the ratio $Q_i/Q(4709)$ is not undue.

For an aurora of brightness III in the zenith this result implies that the total rate of ionization is about 2×10^{12} ion pairs/cm² (column) sec. The influx of energy required to maintain this aurora is about 6×10^{13} eV/cm² sec.

8. The emission of the hydrogen lines and ionization by a H^+ — H beam in air.

8.1. We have now linked the total rate of ionization, and thus the total influx of energy carried by the primary particles, to an intensity which has been measured. Our next step is then to try to deduce the total rate of ionization in the air performed by the H^+—H beam from the other intensity measured, namely the $H\beta$-line. To do this we first have to consider the emission of $H\beta$ quanta from the stream of primary particles. This has already been done by Chamberlain (1954), but since the result necessarily depends on a number of extrapolations and approximations, it is much subject to personal judgement, and it was therefore thought worth while to seek an alternative approach to and solution of the problem. This does not imply that the results presented here are considered to be better than those obtained by Chamberlain, but comparison between the two results may give an indication of the reliability of this kind of work.

We first consider a number of primary particles, N, of which N_p are protons and N_H hydrogen atoms, penetrating through the air. If σ_c and σ_l are the electron capture and loss cross-sections in air, ξ the residual range of the particles in atmos cm[1] and n_o Loschmidt's number, then

$$-\frac{dN_p}{d\xi} = N_H\,\sigma_l\,n_o - N_p\,\sigma_c\,n_o, \tag{8.1}$$

the negative sign on the left-hand side being due to the fact that the particles move towards smaller values of ξ. Adopting the cross-sections measured by Kanner (1951)

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[1] Atmos cm: unit path length equivalent to one cm air at S.T.P.

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it is easy to show that the numerical value of $d\mathcal{N}_p/d\xi$ is several orders of magnitude smaller than each of the terms on the right-hand side of equation (8.1), so that equilibrium is always ensured. We then obtain

$$\frac{\mathcal{N}_p}{\mathcal{N}_H} = \frac{\sigma_\iota}{\sigma_c} \tag{8.2}$$

The number of electron captures or losses per primary particle, per atmos cm, is then

$$\mathcal{J}(\xi) = \sigma_c n_o \frac{\mathcal{N}_p}{\mathcal{N}_p + \mathcal{N}_H} = \frac{\sigma_c \sigma_\iota n_o}{\sigma_c + \sigma_\iota} \tag{8.3}$$

If f_{cy} (ξ) is the fraction of all captures that lead to emission of the line designated by y, and if f_{ey} (ξ) is the ratio between all excitations of the neutral atoms leading to the same emission and the number of ionizations, then the emission of line y, per primary particle, in quanta per atmos cm is

$$\mathcal{J}_y(\xi) = \{f_{cy}(\xi) + f_{ey}(\xi)\} \frac{\sigma_c \sigma_\iota n_o}{\sigma_c + \sigma_\iota} = f_y(\xi) \frac{\sigma_c \sigma_\iota n_o}{\sigma_c + \sigma_\iota} \tag{8.4}$$

This equation is valid only when all the hydrogen atoms are in the $1s$ configuration. As pointed out by Chamberlain (1954) this is not strictly true, because the $2s$ configuration is metastable. However, since the binding energy of this configuration is only one fourth of that of $1s$, and only a small fraction of all captures and excitations leads to an atom in the $2s$ configuration, it is unlikely that any appreciable fraction of the hydrogen atoms is in this configuration. From all the other configurations the transitions downwards are so rapid that at least for high aurorae we can neglect the number of atoms in these configurations. We shall discuss this point further in section 8.2.

If we knew the cross-sections for electron capture into the various configurations and for excitations from the $1s$ configuration, it would be a simple task to compute f_c and f_e, since the transition probabilities between the various configurations are known (cf. e.g. Unsöld 1955). Unfortunately, the relevant cross-section for a H^+—H beam in air is not known, so we have instead tried to estimate f_c and f_e from theoretical work by Bates and Griffing (1953) and Bates and Dalgarno (1953) on H^+—H passing through a gas of atomic hydrogen.

Bates and Griffing investigated the process

$$H(1s) + H(1s) \rightarrow H(1s) + H(2s, 2p, 3s, 3p \textit{ or } 3s) \text{ or } H(1s) + H^+ \tag{8.5}$$

By extrapolating their results to higher quantum numbers f_e was computed for this process, including cascade from higher configurations. In process (8.5) the one atom is left undisturbed, so that all possibilities are not taken into account. Bates and Griffing (1955) have also computed cross-sections for the similar process when one atom is left with a specified quantum number 2 or 3 or ionized and the other at any level or ionized. Unfortunately, to compute f_e we need to know the cross-section for the individual configurations since the transition probabilities also depend on the value of the azimuthal quantum number. Their result indicates, however, that f_e for $H\alpha$ and $H\beta$ should be revised upwards for impact energies above 10 keV, the factors being 2.0 at 30 keV and 2.5 at 100 keV. The result obtained in this way is also in fair agreement with what is found for H—H^+ impact, the atom being excited or ionized.

Bates and Dalgarno (1953) have computed $f_{c\alpha}$ and $f_{c\beta}$ (for $H\alpha$ and $H\beta$) for electron capture from atomic hydrogen. Their results were slightly revised for impact energies below 30 keV before they were used here. The reason for this is that in their case resonance occurs for capture into the $1s$ configuration. Therefore, when computing the revised f_c's, fictitious cross-sections for capture into the $1s$ configuration were used below 30 keV. These were obtained by extrapolation from those for the $2s$, $3s$ and $4s$ configuration. This increases the value of f_c by a factor 1.5 at 10 keV.

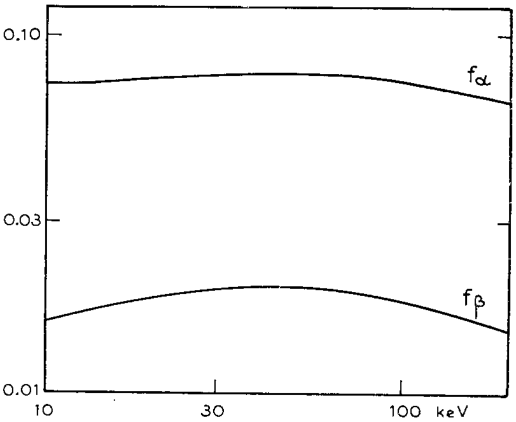

Fig. 9. $f\alpha$ and $f\beta$ versus impact energy.

The sum of f_e and f_c obtained in this way is shown in Fig. 9, where f_α and f_β are plotted against the impact energy. It will be seen that f varies very little with the impact energy. At low energies f_e is much higher than f_c whereas at high energies the contrary is the case. Below 10 keV f_α increases rather rapidly.

Kanner (1951) has measured σ_c and σ_l for impact energies above 30 keV. His values have been adopted, and below 30 keV σ_c and σ_l have been derived from the formulas given by Kanner for the higher energy range. This is certainly not correct, but was done for lack of better data[1]. $J(\xi)$ was computed from equation (8.3), but was arbitrarily bent down towards zero below $\xi = 0.02$ atmos cm. The result is displayed in Fig. 10 together with $J(v)$, the number of captures or losses per unit diminution in velocity. $d\xi/dv$ was derived from the range-energy curves given by Reynolds, Dunbar, Wenzel and Whaling (1953). $J(v)$ does not fit in too badly with the formula

$$J(v) = 4.4 \times 10^{-22}\, v^2 \exp\,(-v/\beta) \tag{8.6}$$

with v in cm/sec and $\beta = 9.5 \times 10^7$ cm/sec.

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[1] After this paper was submitted for publication the author became aware that capture and loss cross sections have been measured down to about 4 keV (cf. Allison 1958, Stier and Barnett 1956). Fortunately the factor $\sigma_c\sigma_l/(\sigma_c+\sigma_l)$ does not differ very much from that computed from the extrapolated values. At energies below 10 keV (v below 1.4×10^8 cm/sec and ξ below 0.03 atmos cm) the values of $J(v)$ and $J(\xi)$ presented in this paper are too large. Stier and Barnett's data yield also significantly higher values for $J(v)$ and $J(\xi)$ at high energies (say above $v = 5 \times 10^8$ cm/sec, $\xi = 0.17$ atmos cm). The total integrals of $J(v)$ and $J(\xi)$ remain almost unchanged, and the effective displacement of the emission curves towards higher values of v and ξ strengthen the conclusions drawn in this paper. Some new measurements by Carleton and Lawrence (1958) also yield cross sections of relevance. Their result fits reasonably well with the data adopted here and are not of sufficient accuracy to justify corrections.

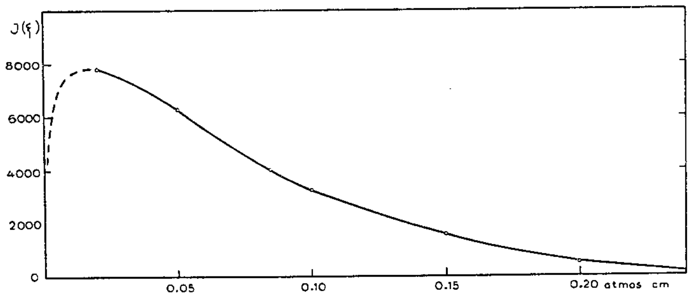

Fig. 10a. $J(\xi)$, the number of charge exchanges per atmos cm, as function of the residual range.

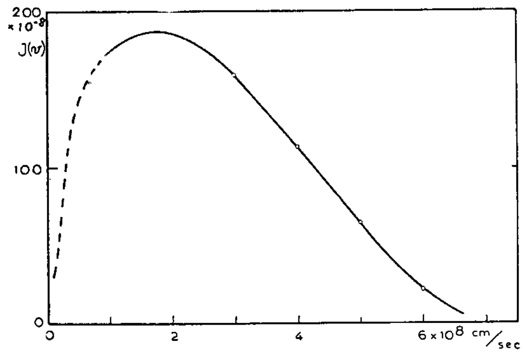

Fig. 10b. J (v), the number of charge exchanges per unit diminution in velocity, as function of the particle velocity.

Since f_{α} and f_{β} are nearly constant we may adopt the curves of $J(\xi)$ and $J(v)$, multiplied by 7.5×10^{-2} for the $H\alpha$ line and by 1.8×10^{-2} for the $H\beta$ line. It is hardly realistic to take the computed variation of f_{α} and f_{β} with ξ into account, but it is likely that $H\alpha$ will show a somewhat more narrow profile than does $H\beta$. This is in agreement with Chamberlain's results.

The form of the function $J(v)$ is somewhat different from that obtained by Chamberlain for $H\alpha$ and $H\beta$, $J(v)$ falling off much less rapidly with increasing v. The main reason for this is that Chamberlain adopted the cross-sections computed by Bates *et al*, multiplied by certain constants to make the total cross-section of the same order of magnitude as those for air. But since the forms of the curves for the cross-sections versus impact energy for H^{+}—H in hydrogen and in air are very different, the final results will be similarly different.

The total integral of $J(v)$ is about 800, this being the total number of capture and loss processes per particles, provided the initial energy is above 200 keV. The total number of $H\alpha$ and $H\beta$-quanta emitted should be 60 and 15 respectively, slightly more than the values obtained by Chamberlain.

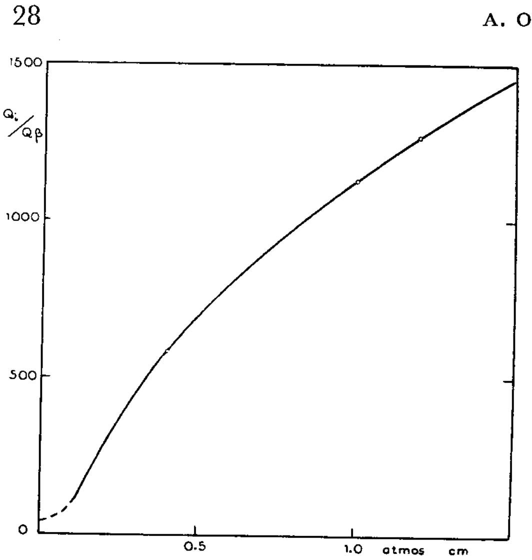

Fig. 11. The ratio between the total rate of ionization performed by protons and the total rate of emission of *Hβ*-quanta versus range of the protons.

In Fig. 11 is given the ratio between the total ionization performed by protons (Jentschke 1940), Q_i, and the number of *Hβ*-quanta emitted, Q_β, as a function of the range of the protons when they enter the atmosphere. The emission of *Hβ*-quanta has been derived from Figs. 9 and 10.

8.2. It should be pointed out that when we consider very low aurorae, the results derived in section 8.1 are perhaps not as valid. If we take the cross-section for collisional transfer from configuration 1*s* to any other state to be about 6×10^{-16} cm², it turns out that with an atmospheric density of 10^{14}/cm³ and a velocity of the primary particle of 3×10^8 cm/sec, the life-time of the *H*(1*s*) atom is less than 10^{-7} sec. Since the life-times of most of the excited states are only an order of magnitude less than this, our assumption that nearly all the atoms are in the 1*s* configuration begins to be dubious. However, an atmospheric density of 10^{14} cm^{-3} corresponds to an altitude of about 90 km (Rocket Panel values, Whipple 1954), and below this height there appear only very few aurorae.

Of even more importance, however, is the collisional disturbance of the excited atoms. The detailed computations show that most of the *Hα* and *Hβ* radiation originates from the 3*s* and 4*s* configurations respectively. The life-times of the atoms in these configurations are 1.6 and 2.3×10^{-7} sec respectively. Since we must assume that the electron loss cross-sections for *H*(3*s*) and *H*(4*s*) atoms are considerably greater than for the *H*(1*s*) atom, electron loss may be serious already at a height of 100 km. With an atmospheric density of 2×10^{13}/cm³ (100 km), an electron loss cross-section of 8×10^{-16} cm², and a velocity of 3×10^8 cm/sec, the life-time against ionization is only 2×10^{-7} sec, about that against radiation for *H*(3*s*) and *H*(4*s*). The average lower limit of aurorae is above this height (Størmer 1955), so that the conclusions which can be drawn from section 8.1 are probably valid, but should the relevant electron loss cross-section prove to be an order of magnitude higher than assumed, the whole problem would have to be reconsidered.

We shall also note that the conclusions reached in this paper will depend to a certain degree on the detailed model of the atmosphere. More recent work by Horowitz and LaGow (1957) and by Byrham, Chubb and Friedman (1956) indicates that the atmospheric density and depth in the altitude range 100 to 140 km is only about one fourth to one third of the Rocket Panel values. This would reduce the importance of the objections raised in this section. On the other hand, the recent measurements on artificial satellites (Mullard Radio Astronomy Observatory 1957, Priester, Bennewitz

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and Lengrüsser 1958, Sterne and Schilling 1958) indicate that the rocket measurements yield densities which are too low by a factor five or so at heights around 200 km. But since rocket measurements obviously are much less certain at this height than lower down, this result may not have implications on the lower ionosphere. In this paper we shall adopt the Rocket Panel values for the atmospheric density between 100 and 150 km as maximum values.

9. The diffusion of a H^+/H beam in the atmosphere.

It has been advocated earlier (cf. Bates 1955) that protons cannot be responsible for rays, because the radius of curvature of the spiralling path around the magnetic lines of force is not consistent with the fine structures of the ray. The horizon profile of the hydrogen lines shows that the paths of the protons do make a certain angle with the lines of force. The radius of curvature is approximately

$$r = r_o \sin\theta = 9.1 \times 10^3 E^{1/2} \sin\theta \text{ cm} \tag{9.1}$$

where E is the proton energy in keV. This equation yields a lower limit for the fine structure of an aurora seen in hydrogen light, provided the energy and the angles of the paths are known.

It is easy to see, however, that for protons of energy less than 100 keV the diffusion due to the neutralization of the protons in the air increases the lower limit of this structure. Protons of not too high energy start to capture electrons as soon as they enter the atmosphere. The density here is so low that the mean path of the atoms before reionization will be considerable. Therefore, because the atoms are not bound to the magnetic lines of force, a narrow bundle of primary particles will diffuse outwards. In Table 2 are given certain data to illuminate this problem. Here E_o is the initial energy of the protons, σ_c the capture cross-section at this energy, ξ_c the average depth of penetration before the first electron is captured, h_c the height where ξ_c is reached provided the paths of the protons are vertical (Rocket Panel values), n the particle density at this height, σ_l the electron loss cross-section, λ_H the mean path of the atoms before re-ionization at density n, and r_o given by equation (9.1).

Table 2.

E_0 keV	σ_c 10^{-17} cm^2 per atom	ξ_c 10^{-4} atmos cm	h_c km	n 10^9 cm^{-3} (atoms)	σ_l 10^{-17} cm^2 per atom	λ_H km	$2r_o$ km
30	21	0.9	235	1.5	25	28	1.0
50	13	1.4	220	3	23	14	1.3
100	4	5.0	190	12	21	4	1.8

The mean distance across the lines for force before re-ionization is

$$\lambda_l = \lambda_H \sin \theta \tag{9.2}$$

It will be seen that for $E_o < 100$ keV $\lambda_H > 2\, r_o$, so that the neutralization of the protons will cause serious diffusion of the H^+/H beam.

The effect of this diffusion will vary much more with θ than equation (9.2) indicates. When θ is low the particles will rapidly proceed into a denser atmosphere, so that λ_H will decrease rapidly from one capture to the next. With high values of θ the particles will remain longer in the higher regions, and λ_H will remain large for a great number of captures. In addition to this effect comes the sin θ factor in equation (9.2).

The mean free path of the atoms should be slightly less than λ_H, but not so much that our arguments are invalidated. The detailed atmospheric model is also not very important for the argument.

10. The behaviour of the protons outside the earth's atmosphere.

10.1. According to the modified Birkeland—Størmer theory, the protons pass directly from the sun to the earth's atmosphere, and in this case it is extremely difficult to make any prediction of the angular distribution of the protons. In Martyn's extension of Chapman—Ferraro's theory and in Alfvén's theory the protons pass along the magnetic lines of force from near the equatorial plane to the atmosphere. For this case the angular distribution has been predicted by Chamberlain (1957), neglecting electric fields along the path between the equatorial plane and the atmosphere. We shall here consider this problem a little more fully, taking electric fields along the magnetic lines of force into account.

To the first approximation we have

$$\frac{\varepsilon \sin^2 \theta}{B} = \frac{\varepsilon_o \sin^2 \theta_o}{B_o} \tag{10.1}$$

where ε is the kinetic energy of the protons and B the magnetic field strength.

We now consider the flux of protons in a tube which runs from near the equatorial plane to the atmosphere along the magnetic lines of force, and whose cross-section is large compared to that of the spiralling paths of the protons. Let $N(\theta)$ be the total flux in a particular direction through the cross-section of the tube, in protons per sec and per unit solid angle and let indices *o* and *1* indicate values at the equatorial plane and at the top of the atmosphere respectively. We then have

$$2\,\pi \sin \theta_1\, N(\theta_1) = 2\,\pi \sin \theta_o\, N(\theta_o)\, \frac{\delta \theta_o}{\delta \theta_1} \tag{10.2}$$

for, provided the protons are not magnetically reflected on their way, the number of protons which enter the tube per sec. within the interval $\delta\theta_o$, must equal that leaving the tube per sec. within the corresponding interval $\delta\theta_1$. From equations (10.1) and (10.2) it follows that

$$\mathcal{N}(\theta_1) = \frac{\varepsilon_1 B_o}{\varepsilon_o B_1} \frac{\cos\theta_1}{\cos\theta_o} \mathcal{N}(\theta_o)\ ^1 \tag{10.3}$$

or

$$\mathcal{N}(\theta_1) = \frac{\varepsilon_1 B_o}{\varepsilon_o B_1} \frac{\cos\theta_1}{\left(1 - \frac{\varepsilon_1 B_o}{\varepsilon_o B_1}\sin^2\theta_1\right)^{1/2}} \mathcal{N}(\theta_o) \tag{10.4}$$

For protons hitting the auroral zone B_1/B_o is about 10^3, provided the deviations from the dipole field are not too large. If there is an appreciable acceleration of the protons, so that $\varepsilon_1/\varepsilon_o > 10^3$, there will be a cut off in θ_1 given by the condition

$$\sin^2\theta_1 \leqslant \frac{\varepsilon_o B_1}{\varepsilon_1 B_o} \tag{10.5}$$

because 1 is the highest possible value for $\sin^2\theta_o$ in equation (10.1).

10.2. Alfvén (1958) has suggested that the acceleration of the protons may take place in a thin sheet between the plasma surrounding the earth and the ionosphere. In this case there may be a much lower cut-off in θ_1. If index s indicates values just above this sheet, we have, since $B_s = B_1$, $\varepsilon_s = \varepsilon_o$ and $\sin^2\theta_s \leq 1$:

$$\sin^2\theta_1 \leqslant \frac{\varepsilon_o}{\varepsilon_1} \tag{10.6}$$

Alfvén (1958) thinks that ε_o may be the order of a few eV, in which case $\varepsilon_o/\varepsilon_1$ may be as small as 10^{-4} and the cut-off in θ_1 at less than 1°. This is certainly not in agreement with observations. The cut-off given by equation (10.5) would be about 20°, a more reasonable value.

Generally, the cut-off will be lower than given by equation (10.5) if the electric field is not strong enough to avoid magnetic reflection of the protons along the path, in which case $(\sin^2\theta_o)max$ will be less than one for the protons which hit the atmosphere. If the energy gain along the path is low, so that $\varepsilon_1/\varepsilon_o \ll 10^3$, then

$$\mathcal{N}(\theta_1) = \frac{\varepsilon_1 B_o}{\varepsilon_o B_1} \cos\theta_1 \mathcal{N}(\theta_o) \tag{10.7}$$

which is equal to the expression derived by Chamberlain except for a factor $\cos\theta_1$.

These considerations are valid only under the following assumption[2]: Collisions which may modify the distribution in directions must be negligible. The sheet (or electric double layer) must be intersected by the magnetic lines of force at right angle or it must be thick compared with the radius of curvature of the orbits of the protons. Finally, the field must be static, i. e. plasma oscillations must not take place.

[1] Equation (10.3) may also be deduced from Liouville's theorem, which states that f, the density of particles in the phase space, is constant along the path. It can be shown that $\mathcal{N}(\theta) = \frac{2}{\mathrm{m}^2} S_0 B_0 \frac{\varepsilon\cos\theta}{B} f$, where m is the proton mass and S_0 the cross-section of the tube at magnetic equator.

[2] The author is indebted to Professor Alfvén for informative correspondence regarding these points.

The first condition is probably fulfilled. The scattering effect is very small for protons, and there is certainly no important change in the distribution in direction between the acceleration and the absorption of the protons in the atmosphere. Particles which are not absorbed but oscillate numerous times in the field may, however, suffer important collisions and this will be of importance to the form of $\mathcal{N}(\theta_0)$. We know very little about the second condition. The thickness of the sheet is probably related to the Debye shielding distance, which is difficult to estimate (Spitzer 1956).

The last condition is also dubious. It is evident that if the fields oscillate with frequencies close to the gyro frequency of the proton, serious complications arise. But it is far from proved that such oscillations exist.

10.3. Our next step is to consider $\mathcal{N}(\theta_o)$. If the particles come from a reservoir where there is an isotropic velocity distribution, then $\mathcal{N}(\theta_o)$ would be proportional to $\cos\theta_o$. However, the reservoir is tapped proportionally to this factor, and in the equilibrium case $\mathcal{N}(\theta_o)$ must equal the supply of protons from the surrounding plasma. It may perhaps seem more natural to assume that $\mathcal{N}(\theta_o)$ is independent of θ_o, but this depends on the mechanism which brings the protons into the space from where they hit the auroral zone.

Since the protons presumably must pass through higher values of θ_o (θ_o being close to $\pi/2$ far from the earth) before they reach the small values, one may even imagine that $\mathcal{N}(\theta_o)$ increases with increasing θ, or that ε_o and θ_o are connected in some way.

Protons which approach the earth in the equatorial plane will start to oscillate around this as soon as θ_o decreases. Protons in a plane parallel to the equatorial plane will also start to oscillate, but if an electric field repels them from the equatorial plane. their final energy ε_1 will then be less than for those originating in the equatorial plane. Thus the cut-off given by equation (10.5) may be higher for particles orginating outside the equatorial plane. One should therefore anticipate that the cut-off varies with the energy ε_1, and that the protons which enter the atmosphere with high energy have a narrower angular distribution than those with lower energy. Certainly, B_o should be replaced by B_o', the value of B in the plane we consider, and since necessarily $B_o' > B_o$ this will lower the cut-off. However, since B varies very slowly near the equatorial plane, this effect will be very small if the electric field is located near this plane.

It is, of course, expected that there is dispersion in ε_o, so that the final beam which enters the atmosphere does not show a strict cut-off, but our rather qualitative arguments may nevertheless be valid[1]. At present it does not seem justified to speculate on the distribution in ε_o.

Altogether, it is important to make it clear that the whole problem is so difficult that our conclusions must not be taken too seriously. It is hoped, however, that this discussion as well as the comparison with experimental results which will be made in the next chapters may serve as a guide for future work.

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[1] For example, if all the protons originate in the equatorial plane and the protons here have a Maxwellian and isotropic velocity distribution with mean energy E, then one can show that the first order solution is $\mathcal{N}(\theta) = C \exp(-B_0\, \varepsilon_i \sin\theta / B\, E_1) \cos\theta$ where ε_i is the energy gain due to the electric field.

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D. INTERPRETATION OF THE OBSERVATIONS

11. The rôle of the protons in the auroral display.

11.1. We shall now examine in detail the possibility that protons alone can maintain an aurora in the sense that they penetrate into the atmosphere and directly or indirectly excite the auroral emissions. There are two reasons for assuming that the protons which enter the atmosphere have a rather low average energy. The first is the relation between the observed profiles of the hydrogen lines and the theoretical results. The emission curves for $H\alpha$ and $H\beta$ computed in section 8.1 are broader than those obtained by Chamberlain, and this emphasizes the need for assuming that most of the protons enter the atmosphere with an energy considerably less than 100 keV (Chamberlain 1957, Omholt 1958), cf. also sec. 1.3. For if we adopt either of the two sets of emission curves it is impossible to bring the much narrower observed profiles in harmony with these unless one assumes that most of the protons have a very low initial velocity. We must bear in mind, however, that the objections raised in section 8.2 may cast some doubt on this argument, but they are not likely to make it invalid.

Further, the average height of the lower border of auroral arcs is about 105 km (Størmer 1955), and if arcs are caused entirely by protons their mean initial energy should correspond to a stopping height of say 110 km or more, or an energy less than 100 keV. Therefore, all evidence favours the view that if aurorae are caused solely by protons, the average energy of these must be less than 100 keV, or their range less than 0.13 atmos cm. From Fig. 11 it then follows that for a pure proton-excited aurora we have

$$\frac{Q_i}{Q_\beta} < 150 \tag{11.1}$$

or

$$\frac{Q_i}{Q(4709)} < 150\, R(H\beta) \tag{11.2}$$

On the other hand it was shown in section 7 that actually

$$\frac{Q_i}{Q(4709)} > 550 \tag{11.3}$$

Since for auroral arcs in Tromsø $R(H\beta) < 0.1$, it appears that these cannot be produced by protons. At lower latitudes, where the average of $R(H\beta)$ is closer to 0.5, the inconsistency between equations 11.2 and 11.3 is less, but it is unlikely that they can be brought into harmony. It cannot be excluded that some particular auroral arcs are caused solely by protons, but there is nothing except the intensity of the hydrogen lines which suggests this, and this intensity is also perfectly consistent with the assumption that protons supply only a minor part of the energy necessary to produce an auroral arc.

For auroral forms which lie higher in the atmosphere the conclusion is obviously the same. Rayed bands, however, lie very low in the atmosphere, their lower border

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being about 95 km, so that the situation for these is somewhat different. But for these it appears to be a latitude effect, the height of the lower border decreasing appreciably with decreasing magnetic latitude (Størmer 1955). This should imply that if rayed arcs were caused by protons $R(H\beta)$ should be higher in Tromsø than further south, since there each proton would have less initial energy. This is contrary to what is observed. But again the objections raised in section 8.2 may cast doubt on our arguments. However, the vertical extension of the form is appreciable, so that the hydrogen lines should in any case be consistently observed in the upper part of the form and this is not the case.

Altogether, it seems safe to conclude that protons regularly supply only a minor part of the energy necessary to produce aurorae.

11.2. If we accept the conclusion reached in section 11.1, that the protons do not carry much of the energy required to produce an aurora, we may enquire further into the properties of the stream of particles that hit the atmosphere during aurora. It seems at present most natural to assume that the dominating constituent is electrons, inasmuch as the work by Winkler and Peterson (1957) and by Winckler, Peterson, Arnoldy and Hoffman (1958) on X-rays from aurorae give a strong indication that fast electrons do enter the earth's atmosphere during aurorae. If electrons and protons hit the atmosphere simultaneously it is difficult to see how both kind of particles can be accelerated in an electrostatic field close to the earth. Alfvéns (1958) proposal, that the electrons gain energy when a neutral beam of particles penetrates into the earth's magnetic field and is compressed, seems more attractive. The electrons are supposed to obtain a much higher temperature than the protons, and according to Alfvén they may easily obtain a nearly isotropic velocity distribution. They will thus leak into the earth's atmosphere very fast, the slow protons lagging behind in this regard and creating a positive potential with respect to the earth. The electric field created in this way will accelerate the protons and, to a certain extent, retard the electrons. The field would have to be such that a sufficient number of protons is driven towards the atmosphere, the large scale movement across the magnetic lines of force being taken into account. Because of these latter movements it is not necessary that the fluxes positive and negative particles which hit the atmosphere at a particular point must be equal. It is also probable that slow electrons will leak out of the ionosphere and partly compensate for the current of fast electrons into the ionosphere.

As demonstrated by Chamberlain (1957) it is necessary to assume that the major fraction of the protons have quite low velocities (cf. equation 1.4). The average emission of $H\alpha$- og $H\beta$-quanta per incident portons may thus be quite low. The theoretical results are particularly uncertain in the low-velocity region, hence it is not at present possible to deduce the total flux of protons from the absolute intensity of the hydrogen lines. The emission curve derived in section 8.1 emphasizes this view when we compare it with the observed Doppler profiles of the lines. The broader emission curve derived here would yield a broader Doppler profile unless we assume that relatively more protons have quite low initial velocities. It is true that we would arrive at the opposite conclusion if we made comparison with the altitude distribution of the luminosity, since a broader emission curve would mean that more hydrogen light would be emitted at greater heights, so that fewer low-energetic protons would be required to fit the curve than in Chamberlain's case. However, as demonstrated in section 5.3 our knowledge about the altitude distribution of the luminosity is still insufficient to draw any conclusions on the basis of these.

It may thus well be that there is a considerable impact of low-energetic protons that give rise to very few or no $H\alpha$- and $H\beta$-quanta. Therefore it is also very difficult to draw any conclusion about the diurnal variation of the proton flux based on the variation in the hydrogen lines' intensities. Montalbetti and Vallance Jones (1957) tried to compare their observations with Martyn's extension of Chapman—Ferraro's theory. One might likewise try to compare their results as well as those reported in this paper with Alfvén's or other theories. For example, the results given in Table 1 particularly for groups *d* and *f*, do indicate that protons are most abundant after standard midnight, or in the morning compared to magnetic midnight. This result is in agreement with that obtained by Montalbetti and Vallance Jones, but its significance to the various theories is doubtful. It appears to contradict Alfvèn's theory, which predicts most protons during the daytime and in the evening (L. Block, private communication), but with reference to what is said above, this result is indeed far from conclusive.

It is perhaps not impossible to imagine that the formation of auroral rays and rapidly moving forms are due to some kind of electro-magnetic instability in the beam of primary particles. The coincidence between the break-up of a homogeneous aurora and the decrease in $R(H\beta)$ observed at low latitudes may point in this direction.

On the other hand, it appears from the observational material that the hydrogen lines at high latitude to a certain extent are associated with long rays. The angular resolution of the photometer is not sufficient to study the detailed ray structure, but it seems from some of the observations that the ray structure is more diffuse in hydrogen light. This is also to be expected from the theoretical arguments advanced in section 9. If the rays are formed by incident electrons, these have relatively low energies[1], whereas rays when viewed end on seem to be quite bright. The electron flux should be approximately proportional to the brightness when viewed along the magnetic lines of force and inversely proportional to the average energy of the electrons, ε_0. The electron density in the beam is then proportional to the brightness and inversely proportional to $\varepsilon_0^{3/2}$. Therefore, even if the proton flux is quite high compared to an arc of the same luminosity, the relative electron flux may be even higher. This may again be a cause for electro-magnetic instability.

It should be emphasized that what is said here is mere speculation, and that a vast amount of careful observational and laboratory work is necessary before these questions can be answered fully. However, it may be useful and necessary to bear these points in mind when a more complete theory for the aurora is considered. At present

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[1] The energy of electrons penetrating to 130 km (a typical lower limit of long rays) is less than one tenth of the energy of electrons penetrating to 105 km (a typical lower limit of arcs).

we can only say that it seems likely that the fast protons are not very important, the dominating role being played by the fast electrons and perhaps the slow protons in the earth's environment.

12. Interpretation of the Doppler profiles.

The great uncertainties in the curves for the emission of $H\alpha$ and $H\beta$ versus the velocity of the H^+/H-particles preclude any accurate determination of the velocity distribution of the incident protons. The uncertainties are particularly great in the low-velocity range and all that can be said with some confidence is that most of the incident protons have a rather low initial velocity, v_o, the distribution on v_o being similar to v_o^{-2} (cf. section 1.3). It seems at present hardly worth while to carry out further detailed computations with the available theoretical and laboratory data.

Some information may be obtained about the angular distribution of the protons. A kind of average value for the zenith distance θ may be obtained by considering the distribution in the velocity space of all atoms which emit within a certain time interval $\triangle t$. We introduce the orthogonal components v_x, v_y and v_z of the velocity of the emitting atoms, v_z being along the magnetic lines of force, positive towards the earth. The distribution in the velocity space will be symmetrical around the z-axis.

If we consider all the emitting atoms whose velocity have magnetic azimuth φ ($\tan\varphi = x/y$) within an infinitesimmally small interval $d\varphi$, then the average velocity vector for these has components $\overline{v}_z$ and $\overline{v}_\varphi$ along the z-axis and in the x—y plane respectively. The angle of this vector with the z-axis is θ_m, given by

$$\tan\theta_m = \frac{\overline{v}_\varphi}{\overline{v}_z} \tag{12.1}$$

and we want to determine this angle. If we consider all the emitting atoms with a positive value of v_x, then the average velocity vector for these atoms has components $\overline{v}_z$ and $\overline{v}_{+x}$. It is elementary to show that

$$\overline{v}_{+x} = \frac{2}{\pi}\,\overline{v}_\varphi \;\; * \tag{12.2}$$

Since v_z and v_x are orthogonal it is not difficult to show that $\overline{v}_z$ and $\overline{v}_{+x}$ are easily derived from the line profiles, $\overline{v}_z$ being the average Doppler displacement derived from the zenith profile and $\overline{v}_{+x}$ that derived from the positive half of the horizon profile. Adopting the recently observed profiles by Chamberlain (1958b) we find θ_m to be about 24°. With an angular distribution proportional to $\cos^2\theta$ as postulated theoretically by Chamberlain we find θ_m to be 38°. It may be shown that for a distribution proportional to $\cos^n\theta$ one has

$$\tan\theta_m = \int_0^{\pi/2} \cos^n\theta \, d\,\theta \tag{12.3}$$

and that $\theta_m = 24°$ corresponds to $n = 7$.

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* The results given here are readily derived by using the analogy with the centre of gravity of a mass distribution in space.

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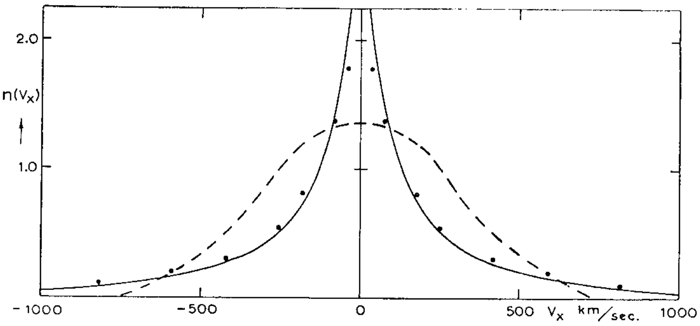

Fig. 12. The horizon profiles of the hydrogen lines.

Since it appears that the directions are fairly narrowly distributed around the z-axis, with cos θ_m close to 1, we may now try a first approximation as follows: We adopt the measured zenith profile as the curve of emission versus velocity of the H^+/H beam, the dispersion in velocities being taken into account. In other words we regard the zenith profile as due to incident protons with $\theta = 0$. If the angular distribution (per unit solid angle) is given by $\mathcal{N}(\theta)$, then the number of emitting atoms within the volume element $dv_x\, dv_y\, dv_z$ centered at v_x, v_y, v_z is

$$n(v_x, v_y, v_z) = \frac{1}{4\pi v^2} n(v)\, \mathcal{N}(\theta) \tag{12.4}$$

where $n(v)$ describes the zenith profile, v being now the total velocity. For numerical integration it is more convenient to make a transformation to an orthogonal v_x, u, v space, where $u = v_x/\sin\theta$ $(0 \leq \theta \leq \pi/2)$. The distribution in this space is given by

$$n(v_x, u, v) = \frac{1}{4\pi} \frac{v_x n(v)\, \mathcal{N}(\theta)}{u\,(v^2 - u^2)^{1/2}\,(u^2 - v_x^2)^{1/2}} \tag{12.5}$$

and the horizon profile, averaged over the whole aurora, will be given by

$$n(v_x) = \frac{v_x}{4\pi} \int_{|v_x|}^{\infty} \frac{\mathcal{N}(\theta)}{u(u^2 - v_x^2)^{1/2}} \int_{u}^{\infty} \frac{[n(v) + n(-v)]}{(v^2 - u^2)^{1/2}}\, dv\, du \tag{12.6}$$

Integration over v is now independent of v_x.

$n(v_x)$ was computed for $\mathcal{N}(\theta)$ proportional to $\cos^7\theta$ ($\theta_m = 24°$), and the result is shown in Fig. 12 together with Chamberlain's (1958b) horizon profile. The points indicate the profile obtained when all the protons have the same value of θ, equal to $\theta_m = 24°$. The profiles are normalized to give the same integrated intensity.

The computed profiles have an infinite amplitude at $v_x = 0$, and very long wings, and it appears that this general characteristic cannot be changed simply by changing $\mathcal{N}(\theta)$ provided we keep θ_m constant. Comparison with the observed profile may indicate, however, that $\mathcal{N}(\theta)$ vary with the initial velocitity of the protons. If the protons with low velocity have a much wider angular distribution than those with high velocity, then the zenith profile as a first approximation to $n(v)$ would be seriously wrong (too high) for small v's. The result of such a variation would be to lower the peak at the line centre (to a finite value if $n(v)$ goes to zero as v^2 for small v's). Further, since then the fast protons must have a narrower distribution (to keep θ_m unchanged) the long wings would be diminished. Such a variation of $N(\theta)$ with the initial velocity (and energy) is actually what was theoretically predicted in section 10.

In these computations we have accepted the zenith profile as published by Chamberlain (1958b). This profile as well as that published by Meinel (1954) shows that some of the photons are emitted with a negative value of v_z (and negative v in our v_x, u, v space). These would have to be emitted by particles moving upwards in the atmosphere, and the question now arises whether these profiles are correct or not. If the low-energetic protons have a very wide angular distribution it may not be surprising that the profiles are correct, because at low velocities it is perhaps not unreasonable to assume that scattering of the protons in the atmopshere may diffuse the angular distribution considerably. This diffusion will also be important to the protons with high initial velocity when these are slowed down in the atmosphere. The available data does not seem to yield sufficient information on these points.

The horizon profile seems to be similar for high aurorae (Tromsø) and low aurorae (Yerkes Observatory), and this may support our conclusions regarding the angular distribution. The lower velocity of the protons associated with high aurorae may be counteracted by a wider angular dispersion. This would also have a bearing on the zenith profiles, which then should be very much different. This question is at present rather dubious but deserves further investigation.

All which at present can be concluded is that θ_m as defined by equation 12.1 is about 24° and that the low-energetic protons probably have a wider angular distribution than those with high energy. Both these results are in harmony with the theoretical predictions made in section 10.

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APPENDIX

Considerations on the shot noice and time resolution of the different instruments.

The shot noise in the current emitted from the photocathode is given by

$$i_s^2 = 2\, e\, I \triangle f$$

where i_s^2 is the mean square fluctuation in the current, e the electronic charge, I the average current and $\triangle f$ the frequency range of the detecting system.

The scanning spectrometer has to respond from zero to quite high frequencies, since it passes rather rapidly over a spectral line. $\triangle f$ will therefore be of the order 100 to 1000 *c*/sec. This determines the accuracy of each reading of a spectral line or band. The accuracy may be increased by averaging over successive scans, but this decreases the time resolution of the instrument correspondingly. The lower limit of this is given by the time between two scans, which is of the order of seconds.

The recording system of the chopping photometer has to read 69 pulses per second (with 3 filters in the rotating disc) without distortion. It therefore has to respond to frequencies from nearly zero to about 500 *c*/sec, and that is the same order of magnitude as the scanning spectrometer. In this case, however, we obtain 23 readings per sec, so that if we average over the same time as with the spectrometer, we obtain a higher accuracy. The lower limit of the time resolution is higher than the time between two pulses from the same spectral line i.e. higher than 0.04 sec.

The amplifier in the split beam photometer has to respond only to the fluctuations in the auroral intensities. The value of $\triangle f$ is approximately T^{-1} where T is the time constant of the input impedance of the pre-amplifier. Practical work suggests T may be as high as 0.1 sec or even 1 sec in some cases. The shot noise is thus considerably reduced although the instrument still has a time resolution comparable to the chopping photometer and superior to the scanning spectrometer.

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