THE TEMPERATURE OF THE AURORAL REGION DETERMINED FROM BAND SPECTRA

BY *L. VEGARD* AND *E. TØNSBERG*

§ 1. Introduction.

The present paper submits some recent results of temperature measurements within the auroral region by means of the energy distribution within the negative nitrogen bands appearing in the auroral spectrum.

The possibility of such measurements was dealt with as early as in 1923 (1), and spectrograms particularly suitable for such measurements were obtained at Tromsø during the year 1924. The temperature measurements based on these spectrograms were dealt with in papers published in Terrestr. Magn. Washington (2) and in Geofys. Publikationer, Oslo (3).

In order to test the validity of the method, a number of laboratory experiments was made with the object of comparing the known temperature of the light source with that derived from the intensity distribution within the rotational band series, and, further, by varying the temperature of the source, a purely emperical relation was found connecting the the temperature with the energy distribution of the R-branch of the negative bands, the bands being photographed with nearly the same dispersion as that of the auroral spectrograms (3).

The temperatures obtained from the first spectrograms varied between $-24°$ and $-43°$ C, the mean value was found to be $-31°$ C.

The observations were continued at the New Observatory at Tromsø. During 1933—1934 we obtained four spectrograms which were dealt with in a paper published in 1935 (4).

During the years 1933—34 experimental investigations were made at Oslo in order to investigate the factors that might influence the energy distribution within the R-branch of the negative bands (5); and

in order to find out how far and with what accuracy the temperature would be determined from spectrograms taken with small dispersion (6).

It was pointed out that the energy distribution of a rotational band might be influenced by the excitation process, and usually in such a way as to make the "apparent band temperature" greater than the true temperature of the gas.

It was shown that excitation with swift cathode rays had no measurable influence on the band temperature, while excitation with canal rays had the effect of making the apparent band temperature considerably larger than that of the gas. In fact the apparent band temperature was on an average about 90° higher than that of the gas. *These results mean that the rotational energy of a molecule is increased by collision with a canal ray, but nearly uneffected by a collision with an electron* (5).

From the laws governing the distribution of light intensity along the auroral ray streamers and from the type of the auroral spectrum (7,8), one of us found that the auroral luminescence is mainly excited by fairly swift cathode rays. Consequently *the apparent band temperature derived from the intensity distribution of the auroral spectrum should give very approximately the true gas temperature existing in the auroral region, when the aurorae are absent.*

From experiments carried out at Oslo (6) it was shown that an approximate determination of the temperature of a light source from the band spectra may be obtained from spectrograms taken with a dispersion considerably smaller than that previously used by the temperature measurements within the auroral region (6).

This result is of importance because it opens up the possibility of determining the temperatures corresponding to fairly short time intervals and of studying possible variations of temperature from time to time (e. g. diurnal or seasonal variations) and possible variations with increasing altitude.

Up to the present we have not obtained spectrograms of small dispersion and short exposure suitable for the study of temperature variations; but it is our intention to continue along these lines. We have, however, continued to take spectrograms with the big glass spectrograph for which the dispersion — in the region of the negative band 4278 — is about 27 Å/mm.

Since we published our previous paper (4) we have obtained two spectrograms, which are suitable for temperature measurements, and with which we deal in the present paper.

In this connection it may be mentioned that one of us has commenced temperature measurements within the auroral region which are based on the measurements of the width of the green OI-line 5577 and the red OI-line 6300 by means of an interferometer method. This method has the advantage that the interference pictures may be obtained with fairly short exposures, and it was shown in a paper recently published that the method can be used with advantage for the determination of possible temperature changes with increase of altitude (9).

Some interference pictures obtained corresponding to considerable differences of altitude, gave the important result that there were no signs of any temperature increase with increasing altitude (9).

§ 2. Remarks regarding the Procedure to be followed by the Measurements of the apparent Band-Temperature.

The basis on which the temperature measurements are founded is well known from the atomic theory of band spectra, and the application of the method to measurements of the temperature of the upper atmosphere from the negative nitrogen bands appearing in the auroral spectrum, has been described in previous papers (2, 3, 4).

For the sake of convenience we shall here briefly mention the procedure and give the equations which are used by the measurements. The intensity distribution within the R-branch of one of the negative nitrogen bands is given by the equation

$$\log_{10}(I_k/K) = -\varkappa \cdot K(K+1)\log_{10}\varepsilon \qquad (1)$$

(I_k) is the intensity of the line corresponding to the rotational quant number (K), $\log_{10}\varepsilon = 0,43429$ and

$$\varkappa = \frac{h^2}{8\pi^2 J k T} \qquad (2)$$

(J) is the moment of inertia of the molecule in the upper state and is equal to $13,410^{-14}$. (T) is the absolute temperature, (h) Planck's and (k) Boltzmann's constant.

We measure (I_k) for a number of (K)-values and we draw the straight line giving the relation between log. (I_k/K) and $K(K+1)$, and the slope of this line gives

$$\varkappa_1 = \varkappa \log_{10}\varepsilon .$$

From equation (2) we find:

$$T = \frac{1,2855}{\varkappa_1} \qquad (3)$$

The temperature may also be found from the rotational quant number (K_m) of the line of maximum intensity. This temperature (T_m) is given by the relation:

$$T_m = 2,96\,K_m(2\,K_m+1). \qquad (4)$$

If we have a Maxwellian distribution of rotational energy the two methods should give the same temperature or $T_\varkappa' = T_m$. Usually we find that T_m is somewhat smaller than $T_\varkappa$. This may be due to deviation from a Maxwellian distribution which may result from the excitation process (cf. paper 5) or from variations of temperature during the exposure.

Some difference between T_m and $T_\varkappa$ may result from inaccuracies in the photometer measurements and the difficulties which we meet in trying to correct for ground fogging of the plate. The ground fogging is likely to make the value of $T_\varkappa$ too large.

The method of temperature measurements here described is an "absolute" one, because we derive the temperature directly from an intensity distribution, and no calibration of our thermometer nor any comparison with light sources of known temperature is wanted.

The method involves that we are able to measure the intensities of the lines corresponding to varying rotational quant numbers. In order to be sure that we measure the true intensity distribution, the spectrograph ought to have such large dispersion that the individual rotational lines appear separated from each other. On account of the small intensity of the auroral

luminescence, we are at present practically prevented from using such large dispersion.

With the spectrograph used by us the band 3914 is very weak so we have based the measurements on the band 4278 where the spectrograph has a dispersion of 27 Å/mm. If we were able to take the band 4278 with a very narrow slit, and under constant laboratory conditions, we might obtain a distinct striation showing that the rotational lines are nearly separated. When we take spectrograms of the aurorae, we have to use a somewhat broad slit, and it is very difficult to keep conditions constant during the long exposures which last for weeks.

As shown in previous papers (2, 3, 4) the method of temperature determination here described may be applied with advantage also in the case when the lines are not separated, but in this case the results ought to be checked by means of spectrograms from light sources of known ·temperature and taken with spectrographs of about the same dispersion as used by the aurorae. By means of such spectrograms we may correct the temperature for the effect of overlapping of the individual rotational components and for other possible systematic errors.

If the individual rotational components are not separated, we may proceed in one of the following two ways:

1. By means of a reference line of known wavelength we find on the photometer curve, the position of a selected number of R-components of known rotational quant number. For each value of K, we measure the corresponding value of I_k and proceed as if the components had been separated.

2. We select on the photometer curve a number of suitably situated points and by means of a reference line of known wave-length, we determine for each point the corresponding K-value, which in this case is no whole number. As the R-branch forms a continuous band, we may consider K as a quantity which varies continuously.

The two methods are equally accurate, the one we use being a matter of convenience.

It has been shown in previous papers (4, 6) that we can find an upper limit for the effect of overlapping on the temperature. Let the true relative intensity corresponding to separated components be I'_k, and the directly measured intensity I_k. Let further d_k denote the interval between successive components corresponding to the quant number K, then:

$$I'_k = d_k I_k. \tag{5}$$

If the interval d_k were constant, I'_k would be proportional to I_k and the overlapping would have no influence on the temperature measurements.

In the case of the R-branch of the negative band 4278, d_k is not constant, but in the interval which interests us, d_k is given by the equation:

$$d_k = d_0 + a K \tag{6}$$

where $d_0 = 0,725$ Å, $a = 0,0615$ Å.

The overlapping will have the effect that the temperature is found too low.

From the corrected intensities (I'_k) we can find the quant number (k'_m) which corresponds to maximum intensity, and from this corrected value of (k'_m), the corresponding corrected temperature T_m is found from the equation (4).

By means of the relation (6), the value of (T'_m) can be found directly by the formula:

$$T'_m = \frac{d_m}{d_0} T_m \tag{7}$$

where (d_m) is the value of d_k at the maximum point.

Laboratory experiments, where the "band temperature" has been compared with the known temperature of the source, have shown that for the dispersion used, a correction for overlapping according to equation (5) or (7) gives a too high temperature. In fact, it was found that the temperature obtained from equation (3) without correcting for overlapping — within the limit of error — was equal to the temperature of the light source (4, 5, 6). The temperature T_m derived from the component of maximum intensity usually came out a little too low.

From laboratory experiments we derived — for the spectrographs used — the following approximate correction formula;

$$T_m \text{ corrected} = 1,057 \, T_m + 38,3°.$$

§ 3. The Spectrograms.

In order to obtain spectrograms of the negative nitrogen bands suitable for temperature measurements, we used a big glass spectrograph, which combines fairly high light power with considerable dispersion. The instrument was described in a previous paper (3) where it is illustrated in Fig. 1 on Plate IV.

The spectrograph was adjusted so as to give the best possible sharpness in the blue and violet
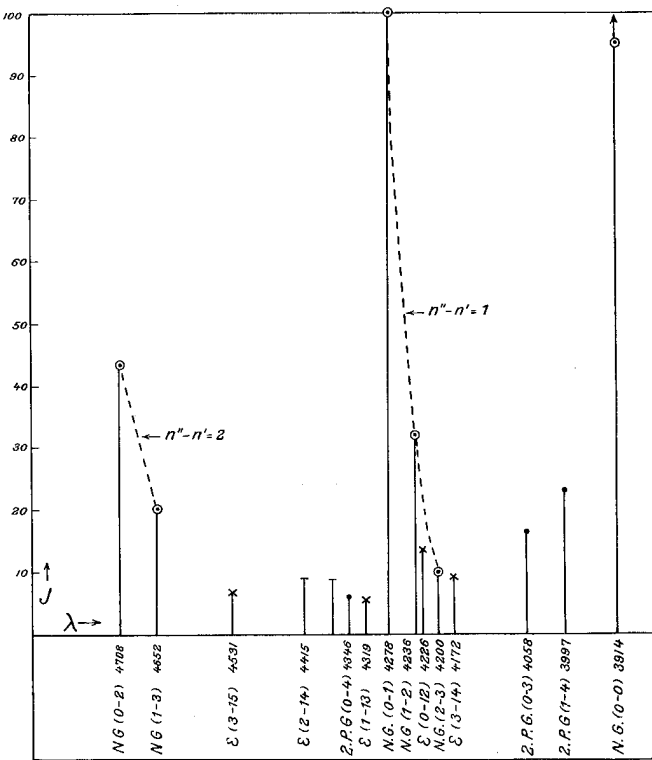
Fig. 1.

region, therefore the green auroral line appears somewhat broad and diffuse.

In order to obtain the R-branch with a suitable density for temperature measurements, an exposure of say 20—40 effective northlight hours will be wanted according to the intensity of the aurorae. That means that we usually have to continue the exposure for several months, or practically during the whole winter season.

Since the previous results were published in 1935 (4), we have only obtained two plates, one for the winter season 1935—36 (Plate A), and one for 1936—37 (Plate B). In both cases we used Ilford double X-press plates.

In the case of Plate A, the exposure lasted from Oct. 15. 1935 to March 28. 1936 with about 37 effective northlight hours, and for Plate B from Dec. 3. 1936 to April 10. 1937 with only 15 effective northlight hours.

In addition to the auroral spectrum, we have on each plate photographed an intensity scale consisting of a series of spectra from an incandescent lamp of known intensity distribution. The spectra were taken with exposures in the proportion $1 : 2 : 4 : 8$. The wave-length for any point of the continuous spectrum

could be found by means of a helium spectrum photographed on the same plate.

By means of the intensity scale and the known intensity distribution of the incandescent lamp, we were able to determine the relative intensities of bands and lines, even if they were widely separated on the spectrogram. A copy of the two plates is shown on Plate I. The auroral spectrum is indicated by (N. L.), the intensity scale by (St. 1) and the helium spectra by (He).

Enlarged copies of the two auroral spectra are given on Plate II, (A') and (B'). The wave-length of some of the more prominent bands and lines are given on the plate.

Plate A for which the exposure was very long, showed considerable ground fog which was somewhat unfavourable for the accuracy of the temperature measurements; but the long exposure had the advantage that not only the band 4278, but a number of weak bands and lines came out quite distinctly. Some of these weak lines and bands had never before been obtained on spectrograms with such a large dispersion.

From this spectrogram their wave-length could be found with such an accuracy, that the error is merely a fraction of an Ångström unit. This result is of great importance because it enables us to fix the origin of these lines with a high degree of certainty.

Table I.

Lines and Bands from Plate A.

λ	Interpretation	I	I_0
4708,7	$NG\ (0—2)\ P$	50,3	43,2
4698,6	$NG\ (0—2)\ R$	26,5	22,8
4650,3	$NG\ (1—3)\ O$	22,9	19,9
4530,6	$\varepsilon\ (3—15)$	7,1	(6,4)
4415,1	$OII\ (4414,9—4417,0)$	9,8	9,3
4368,2	$OII\ (4369,3—4366,9)$	9,4	9,0
4362,1	$OII\ (4359,4)$	4,9	(4,7)
4346,4	$2\ PG\ (0—4)$	6,4	6,2
4317,2	$\varepsilon\ (1—13)$	5,7	(5,6)
4277,6	$NG\ (0—1)\ P$	100	100
4267,9	$NG\ (0—1)\ R$	63,5	63,9
4236,1	$NG\ (1—2)$	31,4	32,1
4226,3	$NII\ (4227,8)—\varepsilon\ (0—12)$	15,7	16,1
4199,0	$NG\ (2—3)$	10,6	11,0
4172,4	$\varepsilon\ (3—14)$	9,2	9,7
4058,6	$2\ PG\ (0—3)$	(20,2)	(22,9)
3997,1	$2\ PG\ (1—4)$	(30)	(35,3)
3914,4	$NG\ (0—0)\ P$	(235,4)	(293,1)
3908,5	$NG\ (0—0)\ R$	(78,1)	(97,9)

The bands and lines measured from Plate A are given in Table I. The first column contains the wavelength values and the second, the interpretations. The column headed (I) gives the relative intensities as directly derived from the spectrograms. (I_0) represents the true relative intensities corrected for extinction. The intensities of some of the bands and lines are shown in Fig. 1.

The two lines 4415,1 and 4368,2 which appear quite distinctly are of particular interest, because — within the limit of error — they coincide with strong lines of the spectrum of ionised oxygen atoms (OII). This result indicates that in the auroral region oxygen is present as ionised O-atoms — in considerable concentration relative to that of molecular oxygen and nitrogen.

§ 4. Results of the Temperature Measurements.

Although the band 3914 is by far the strongest of the negative group, and in spite of the fact that the dispersion of the spectrograph is much larger, we are here prevented from using this band, because its intensity on the plate is reduced on account of absorption in the glass (mainly in the Rutherford-prism). Therefore, with the spectrograph used, we have to base our measurements on the band 4278. Registrams of the band 4278 for the two spectrograms A and B are given in Fig. 2.

The results of the measurements of the intensity distribution of the R-branch are given in Tables II and III for the spectrum A and B respectively.

The first column gives the values of the rotational quant number (K), corresponding to selected points on the photometer curve of the R-branch. (I) represents the directly measured relative intensities, (I') the relative intensities corrected for overlapping according to the equations (5) and (6). Columns (4) and (5) give the corresponding values of log (I/K) and log (I'/K) respectively and the last column gives the values of $K(K+1)$.

The curves log $(I/K) \to K(K+1)$ are represented in Figs. 3 and 4 for the two plates respectively. With the exception of the points corresponding to small K-values for which the intensity measurements are somewhat uncertain, the observations define quite definitely a linear rotation between log (I/K) and $K(K+1)$.
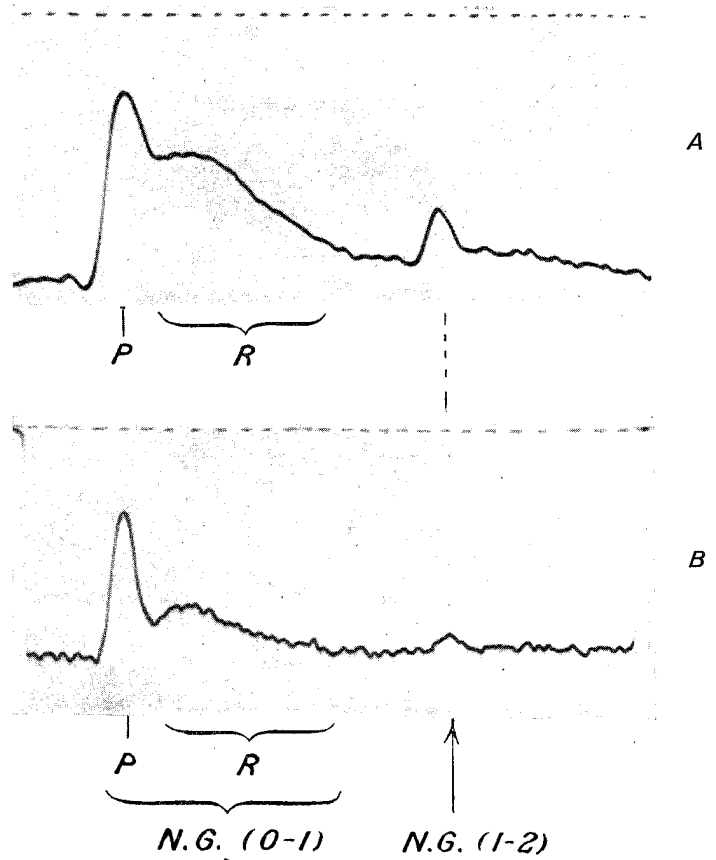

Fig. 2. (A) from spectrogram 1935—36.
　　　(B)　　»　　　　»　　　1936—37.

From the slope of this line we find the values of $\varkappa_1$ and $\varkappa'_1$, corresponding to directly measured intensities and those corrected for overlapping. These $\varkappa$-values and the corresponding temperatures $(T_\varkappa)$ derived from equation (3) are given at the bottom of the corresponding columns of Tables II and III.

From intensity curves $(I) \to (K)$ we determine the quant numbers (K_m) and (K_m'), which correspond to maximum intensity. The values of (K_m) and (K_m') and the corresponding temperatures (T_m) and (T_m') are given at the bottom of the columns headed (I) and (I').

Taking into account the results of our laboratory measurements, the approximate temperature of the auroral region from which the light is emitted, should be given by $T_\varkappa$. It should also be given by the corrected temperature $(T_m)_{corr.}$ derived from equation (8). The temperatures thus obtained for the two plates are given in Table IV.
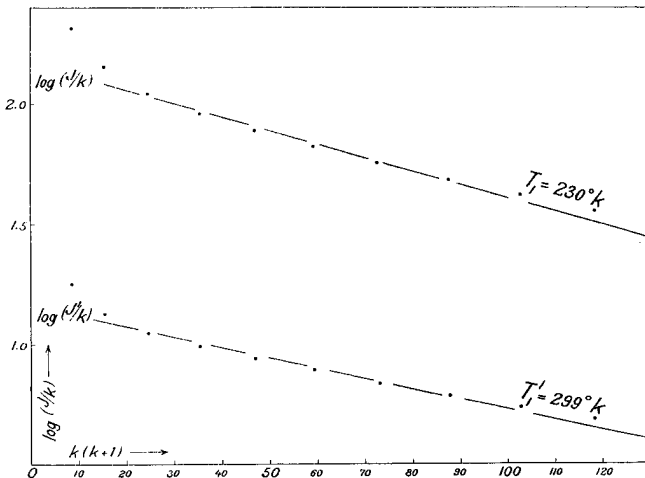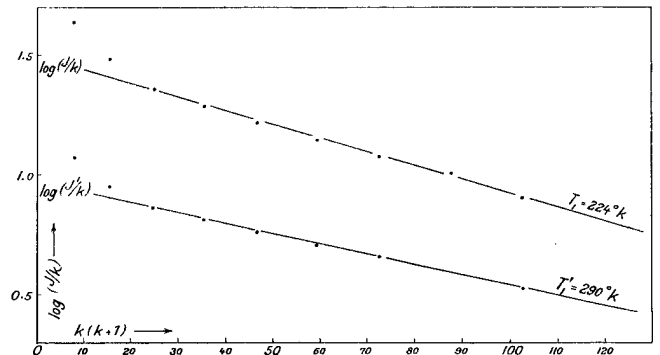
Fig. 3.

Fig. 4.

Table II.

Spectrogram A, Band 4278.

K	I	I'	$\log(I/K)+2$	$\log(I'/K)+1$	$K(K+1)$
1,14	4,68	3,72	2,6129	1,5132	2,44
2,35	4,80	4,17	2,3120	1,2510	7,87
3,44	4,88	4,57	2,1525	1,1240	15,27
4,48	4,93	4,93	2,0426	1,0430	24,55
5,45	4,95	5,25	1,9576	0,9836	35,15
6,37	4,92	5,51	1,8887	0,9370	46,95
7,21	4,78	5,56	1,8209	0,8871	59,19
8,04	4,53	5,52	1,7505	0,8370	72,68
8,88	4,30	5,47	1,6848	0,7889	87,73
9,65	4,05	5.34	1,6232	0'7427	102,77
10,39	3,75	5,12	1,5575	0,6920	118,34
	$k_m = 5,6$	$K'_w = 6,9$	$\varkappa_1 = 0,00560$	$\varkappa'_1 = 0,00430$	
	$T_m = 202\,k$	$T_m = 302\degree\,k$	$T_\varkappa = 230\degree\,k$	$T'_1 = 299$	

Table III.

Spectrogram B, Band 4278.

K	I	I'	$\log(I/K)+2$	$\log(I'/K)+1,5$	$K(K+1)$
2,35	1,014	0,882	1,634	1,073	7,87
3,44	1,028	0,963	1,476	0,947	15,27
4,49	1,038	1,040	1,364	0,864	24,55
5,46	1,059	1,123	1,288	0,814	35,27
6,37	1,040	1,162	1,212	0,760	46,95
7,21	0,995	1,162	1,140	0,707	59,19
8,04	0,952	1,161	1,072	0,658	72,68
8,88	0,896	1,140	1,004	0,607	87,73
9,65	0,778	1,025	0,909	0,525	102,77
	$K_m = 5,5$	$K'_m = 6,6$	$\varkappa_1 = 0,00574$	$\varkappa'_1 = 0,00443$	
	$T_m = 195\degree K$	$T''_m = 277\degree K$	$T_\varkappa' = 224\degree K$	$T'_\varkappa = 290\degree K$	

The temperatures derived from the two spectrograms agree within the limit of error, which means that the average temperature in the auroral region — between say 95—125 km — is the same during both the winter seasons 1935—36 and 1936—37.

Table IV.

	$(T_m)_{corr.}$	$T_\varkappa$
Spectr. A..	252°	230°
Spectr. B..	244°	224°
Mean..	248°	227°

If we put equal weight on the values $(T_m)_{corr.}$ and $T_\varkappa$. we obtain the following mean temperature:

$$T = 237,5:$$

In other words, the average winter temperature in the height interval 95—125 km should be:

$$t = -35,5\degree\ C.$$

The temperature measurements of the auroral region undertaken up to the present have given the following results:

Spectrograms from 1923—1924,

$t = -33°$ C. (Papers 2, 3).

—»—　　»　1933—1934,

$t = -47,6°$ C. (Paper 4).

—»—　　»　1935—1937,

$t = -35,5°$ C. (Present paper).

Mean $t = -38,7°$ C.

List of Papers.

1. L. Vegard: Phil. Mag. 46, 577, 1923. Z. S. f. Phys. 16 367. 1923.
2. L. Vegard: Terr. Magn. 37, 389, 1932.
3. L. Vegard: Geofys. Publ. IX. No. 11. Oslo 1932.
4. L. Vegard and E. Tønsberg: Geofys. Publ. XI. No. 2. Oslo 1935.
5. L. Vegard: Det Norske Vid.-Akad. Avh. I. No. 12. Oslo 1935.
6. L. Vegard, Th. Ringdal and A. Benedicks: Det Norske Vid.-Akad. Avh. I. No. 13. 1935.
7. L. Vegard: Phil. Mag. 42, 47, 1921.
8. L. Vegard: Geofys. Publ. X. No. 4. Oslo 1933.
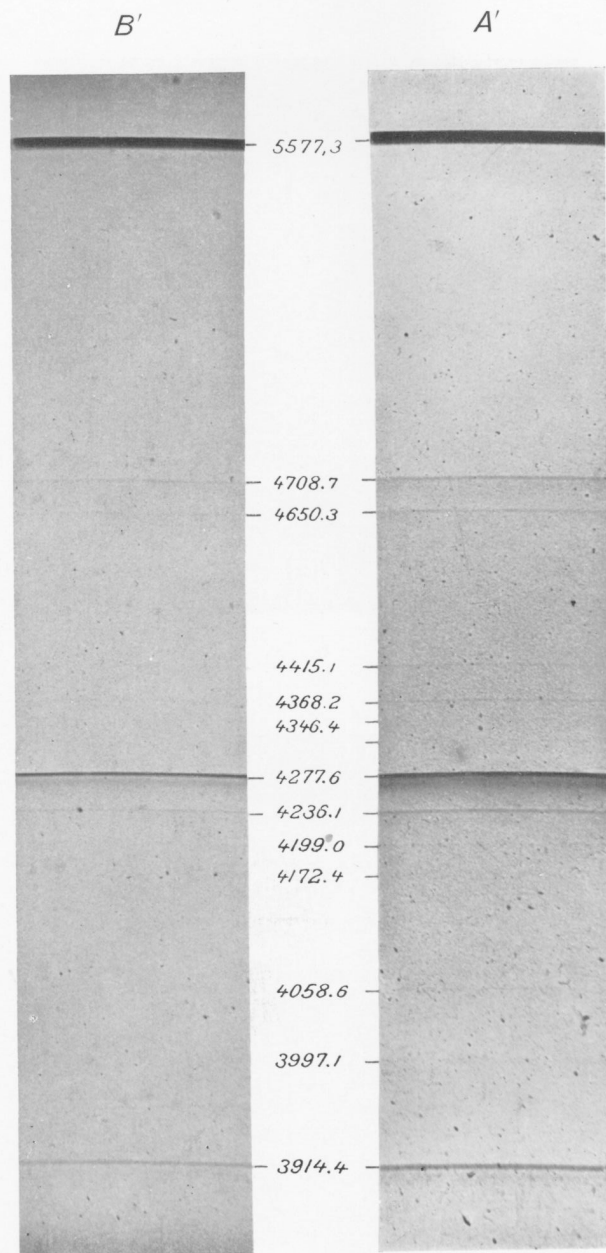9. L. Vegard: Phil. Mag. 24, 588, 1937.

Pl. I.
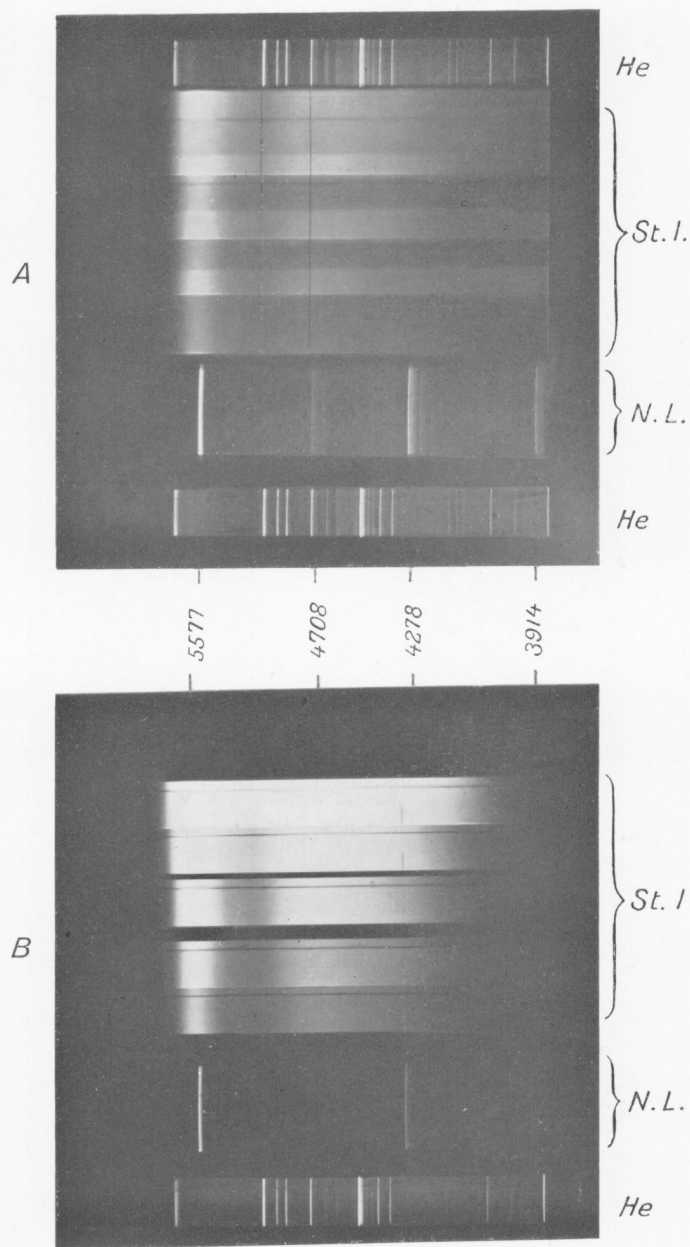
(A) Reproduction of spectra on the same plate as that on which the auroral
spectrum was taken during the winter season 1935—36.
(B) Corresponding reproduction for plate obtained 1936—37.

N. L. indicates the auroral spectrum.
He » a comparison helium spectrum.
St. l. » spectrum from Standard lamp
of known intensity distribution.

Pl. II.

B'   A'

— 5577,3

— 4708.7
— 4650.3

4415.1
4368.2
4346.4
— 4277.6
— 4236.1
4199.0
4172.4

4058.6

3997.1

— 3914.4

Auroral spectrograms taken with large glass spectrograph on Ilford
double X-press plates.
(A′) The exposure lasted from Oct. 15. 1935 to March 28. 1936.
Ca. 37 effective hours.
(B′) The exposure lasted from Dec. 3. 1936 to April 10. 1937.
Ca. 15 effective hours.

The bands and lines measured from Plate A are given in Table I. The first column contains the wavelength values and the second, the interpretations. The column headed (I) gives the relative intensities as directly derived from the spectrograms. (I_0) represents the true relative intensities corrected for extinction. The intensities of some of the bands and lines are shown in Fig. 1.

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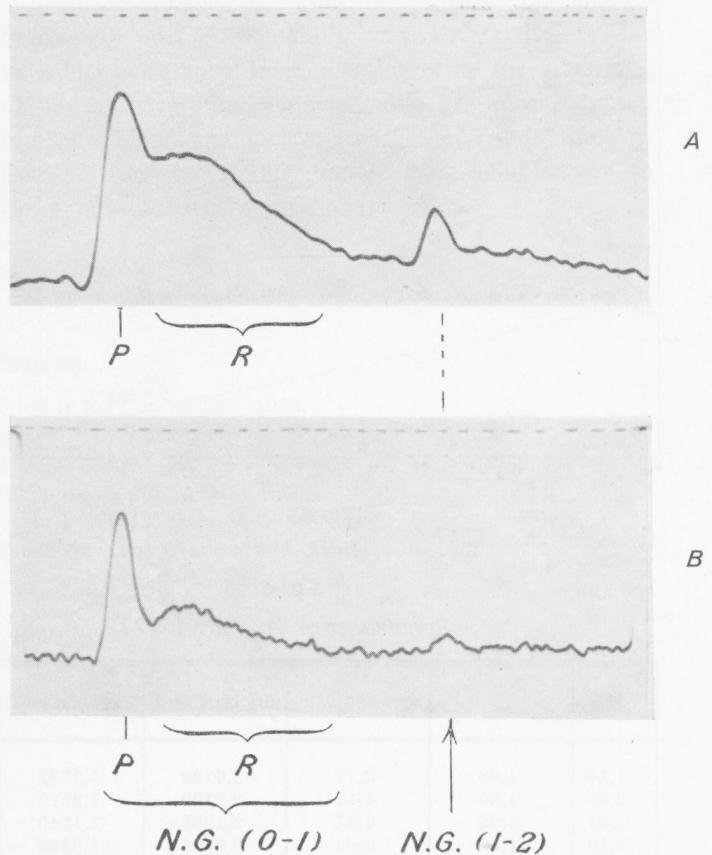

Fig. 2. (A) from spectrogram 1935—36.

(B) » » 1936—37.

From the slope of this line we find the values of $\varkappa_1$ and $\varkappa'_1$, corresponding to directly measured intensities and those corrected for overlapping. These $\varkappa$-values and the corresponding temperatures $(T_\varkappa)$ derived from equation (3) are given at the bottom of the corresponding columns of Tables II and III.

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