

INVESTIGATIONS ON THE AURORAL AND TWILIGHT LUMINESCENCE INCLUDING TEMPERATURE MEASUREMENTS IN THE IONOSPHERE

BY *L. VEGARD* AND *E. TØNSBERG*

(Manuscript received March 14th, 1940.)

PART I

Results of Auroral Observations.

§ 1. Introductory Remarks.

The auroral observational material to be dealt with in this paper was obtained at Tromsø mainly during the period from November 1937 to March 1938. Only one spectrogram from the largest of our glass spectrographs was taken during the spring 1939.

The material first of all consists of four very successful spectrograms taken with the largest of our glass spectrographs. By these exposures the instrument was adjusted so as to give the best possible definition of the negative nitrogen band 4278. As the exposure usually lasted for several weeks, it was laid stress on a temperature regulation by means of which the spectrograph was kept at a nearly constant temperature during the exposure.

In addition to the use of these spectrograms for temperature measurements, we also hoped to obtain on them some of the weaker lines with a good definition and sharpness, so as to get reliable wavelength values.

With the large glass spectrograph the band 4278 is to be obtained with a density suitable for temperature measurements.

As stated in previous papers (1—5) a study of possible temperature variations is of great interest. The temperature might vary with the hour of the night, with latitude, and with altitude.

By means of the large quartz spectrograph the band 3914 may be obtained with an exposure much shorter than that required by the large glass spectrograph for obtaining the band 4278 with the same photographic density. In the region of the band 3914,

the quartz spectrograph has a dispersion of about 35 Å/mm, while the large glass spectrograph at the band 4278 has the dispersion 27 Å/mm. It might therefore be of interest to carry out temperature measurements by means of the 3914 band taken with the quartz spectrograph, in order to see how far the results agreed with those obtained with the larger dispersion.

Partly for this purpose we took three spectrograms with quartz spectrograph. On one of these the 3914 band had a too great photographic density for temperature determinations, but the two others gave suitable densities for photometric intensity measurements.

In December 1937 a number of spectrograms corresponding to various conditions were obtained with a small glass spectrograph of considerable light power. Spectrograms from aurorae with a red lower border (red aurorae of type B) — from aurorae situated in an atmospheric layer exposed to sunlight, — and corresponding to different altitudes were obtained. Although the observations here dealt with do not give any essentially new effects, they still are of considerable importance because they furnish us with further confirmation of earlier results and of the existence of effects previously detected and described.

§ 2. The Temperature Measurements.

The procedure to be followed by the temperature measurements from the R-branch of one of the negative nitrogen bands has been described in previous papers (1—4). For the sake of convenience we shall here repeat some of the formulas from which the temperature is calculated.

From the photometer curve of the band we find for the R-branch the intensities I_K corresponding to various rotational quant numbers (K). In the case of a Maxwellian intensity distribution of the lines within the R-branch, theory leads to the following relation:

$$\log_{10} \left(\frac{I_K}{K} \right) = -K(K+1) \dots \quad (1a)$$

where

$$\kappa = \frac{h^2 \log_{10} \varepsilon}{8\pi^2 J k T}, \quad (1b)$$

$\log_{10} \varepsilon = 0.43429$, (h) and (k) are Planck's and Boltzmann's constants respectively. (J) is the moment of inertia of the nitrogen molecule in the upper electronic state and equal to $13.4 \cdot 10^{-14}$. T is the absolute temperature.

From the observed intensities we can draw the curve $\log(I_K/K) - K(K+1)$, which, according to theory, should be a straight line. We draw the straight line (κ -line) which fits the observations in the best possible way, and the slope of this line gives us the value of κ .

From equation (1 b) we get:

$$T_\kappa = \frac{1.2855}{\kappa}. \quad (2)$$

Let (K_m) be the rotational quant number of the strongest line within the R-branch, then

$$T_m = 2.96 K_m(2K_m + 1). \quad (3)$$

If we were dealing with a spectrogram with sufficient dispersion to give separation of the components within the R-branch, and if the intensity distribution corresponded to a Maxwellian energy distribution of the light emitting molecules, then both T_κ and T_m derived from equations (2) and (3) respectively should be equal.

On account of the small dispersion — and possible deviations from a Maxwellian distribution — T_m is not equal to T_κ , but is usually too small. From laboratory experiments where the band-temperatures have been determined from light sources of known temperature, we have found the following empirical equation (1)

$$(T_m)_{\text{corrected}} = 1.057 T_m + 38.3^\circ. \quad (4)$$

When the individual rotational lines of the R-branch are not separated, an error might possibly enter into the results on account of overlapping. An upper limit

of the influence of overlapping may be found in the following way (3, 4):

A new series of intensities (I'_K) are calculated from the equation

$$I'_K = d_K I_K, \quad (5)$$

where d_K is the interval between successive R-components corresponding to the quant number (K). In the case of the negative bands we have for the R-branch:

$$d_K = d_0 + \alpha K \quad (6)$$

For the two bands used d_0 and α have the values:

Band	d_0	α
4278	0.725	0.0615
3914	0.613	0.0455

From the corrected intensities (I'_K) we can draw an ($I'_K - K$)-curve from which we find a (K'_m) corresponding to maximum of I'_K , and from K'_m we find a corresponding temperature T'_m from equation (3). By means of equation (6) the value of T'_m can be found by means of the relation

$$T'_m = \frac{d_m}{d_0} T_m; \quad (7)$$

d_m is the value of d for the value of K for which I'_K is a maximum.

When the dispersion is so large as that of the large glass spectrograph used at the Auroral Observatory, laboratory experiments have shown (6, 7) that the true temperature of the source within the limit of error is equal to the value T_κ , directly derived from the κ -line corresponding to the uncorrected intensities (I_K), and that we get approximately true values from the equation (4).

In the case of spectrograms taken with the large glass spectrograph, we therefore take the mean of T_κ and $(T_m)_{\text{corrected}}$ to represent the true temperature of the light-emitting molecules in the auroral region.

The values (T'_κ) and (T'_m) derived from the intensities (I'_K) are given because they give an upper limit to the temperature values which might come into consideration. We have also in certain cases calculated the values

$$\begin{aligned} \bar{T}_m &= \frac{1}{2} (T_m + T'_m) \text{ and} \\ \bar{T}_\kappa &= \frac{1}{2} (T_\kappa + T'_\kappa), \end{aligned} \quad (8)$$

Table I.

Spectrograph A, November 29th—December 11th, 1937. If. Double X-press.

Plate I, No. 1. Band 4278.

K	I	I'	log I/K+2	log I'/K+1	K (K+1)
1.14	1.88	1.495	2.217	1.118	2.44
2.35	2.065	1.794	1.944	0.883	7.87
3.44	2.175	2.038	1.801	0.773	15.27
4.48	2.25	2.252	1.701	0.701	24.55
5.45	2.26	2.398	1.617	0.643	35.15
6.37	2.215	2.474	1.541	0.589	46.95
7.21	2.115	2.470	1.467	0.535	59.19
8.04	1.935	2.359	1.381	0.467	72.68
8.88	1.765	2.243	1.298	0.402	87.73
9.65	1.58	2.082	1.214	0.334	102.77
10.39	1.47	2.005	1.151	0.285	118.34

$K_m = 5.2$	$T_m = 175^\circ K$	$T_\kappa = 208^\circ K$
$K'_m = 6.6$	$T'_m = 277^\circ K$	$T'_\kappa = 258^\circ K$
	$T''_m = 273^\circ K$	$\bar{T}_\kappa = 233^\circ K$
	$\bar{T}_m = 225^\circ K$	$(T_m)_{\text{corr.}} = 223^\circ K$

Table III.

Spectrograph A, March 9th—April 30th, 1938. If. Double X-press.

Plate I, No. 3. Band 4278.

K	I	I'	1+log I/K	2+log I'/K	K (K+1)
1.14	1.825	1.45	1.204	2.105	2.44
2.35	1.95	1.69	0.919	1.857	7.87
3.44	1.962	1.84	0.756	1.728	15.27
4.48	1.975	1.98	0.644	1.645	24.55
5.45	1.975	2.10	0.559	1.586	35.15
6.37	1.905	2.13	0.476	1.524	46.95
7.21	1.825	2.13	0.403	1.470	59.19
8.04	1.74	2.12	0.335	1.421	72.68
8.88	1.67	2.11	0.274	1.376	87.73
9.65	1.60	2.10	0.220	1.338	102.77
10.39	1.465	2.—	0.149	1.284	118.34

$K_m = 5.15$	$T_m = 173^\circ K$	$\kappa \cdot 10^3 = 5.80$	$T_\kappa = 221^\circ K$
$K'_m = 6.70$	$T'_m = 282^\circ K$	$\kappa \cdot 10^3 = 4.70$	$T_\kappa = 273^\circ K$
	$T''_m = 271^\circ K$	Mean $T_\kappa = 247^\circ K$	
	$\bar{T}_m = 225^\circ K$	$\kappa' \cdot 10^3 = 4.32$	$T'_\kappa = 298^\circ K$
$(T_m)_{\text{corr.}} = 221^\circ K$			$\bar{T}_\kappa = 272^\circ K$

Table II.

Spectrograph A, January 18th—March 9th, 1938. If. Double X-press.

Plate I, No. 2. Band 4278.

K	I	I'	2 log (I/K)	1+log (I'/K)	K (K+1)
1.14	3.42	2.72	2.477	1.378	2.44
2.35	3.82	3.32	2.211	1.150	7.87
3.44	4.08	3.82	2.074	1.045	15.27
4.48	4.20	4.20	1.972	0.972	24.55
5.45	4.18	4.43	1.885	0.911	35.15
6.37	3.95	4.41	1.793	0.841	46.95
7.21	3.70	4.32	1.710	0.778	59.19
8.04	3.42	4.17	1.629	0.715	72.68
8.88	3.13	3.98	1.547	0.651	87.73
9.65	2.87	3.78	1.473	0.593	102.77
10.39	2.51	3.42	1.383	0.512	118.34

From max. point	$\kappa \cdot 10^3$	T_κ in K°	$\kappa' \cdot 10^3$	T'_κ in K°
$K_m = 4.9$, $T_m = 157^\circ K$	6.05	212	5.08	253
$K'_m = 5.8$, $T'_m = 216^\circ K$	5.55	232	4.65	276
$T''_m = 235^\circ K$	6.40	201	5.80	222
$\bar{T}_m = 192^\circ K$	Mean 215		250	
$(T_m)_{\text{corr.}} = 213^\circ K$	$T_\kappa = 233^\circ K$			

Table IV .

Spectrograph A, February 23rd—March 24th, 1939.

Plate I, No. 4. Band 4278.

K	I	I'	2+log I/K	1+log I'/K	K (K+1)
3.44	4.120	3.860	2.079	1.050	15.25
4.48	4.100	4.104	1.962	0.962	24.55
5.45	4.100	4.350	1.876	0.902	35.15
6.37	4.010	4.479	1.799	0.847	46.95
7.21	3.800	4.438	1.722	0.789	59.19
8.04	3.445	4.199	1.632	0.718	72.68
8.88	3.225	4.099	1.560	0.664	87.73
9.65	2.900	3.690	1.478	0.598	102.77
10.39	2.680	3.656	1.411	0.546	118.34

$K_m = 5$, $T_m = 163^\circ K$	$\kappa = 6.35 \cdot 10^{-3}$	$T_\kappa = 203^\circ K$
$K'_m = 6.5$, $T'_m = 267^\circ K$	$\kappa' = 4.85 \cdot 10^{-3}$	$T'_\kappa = 265^\circ K$
$T''_m = 250^\circ K$		$\bar{T}_\kappa = 234^\circ K$
$\bar{T}_m = 211^\circ K$		
$(T_m)_{\text{corr.}} = 211^\circ K$		

1937—38, and one from February to March 1939. Somewhat enlarged reproductions are given on Plate I. The data for each spectrogram are given in the explanation to the plates (at the end of this paper). An intensity scale was photographed on each of the plates containing the spectrograms.

In order to measure the true relative intensities within the spectrum, a light source of known intensity distribution was photographed on the plate.

where equal weight is given to the values derived from the uncorrected intensities (I_K) and those (I'_K) corrected for overlapping.

With the large glass spectrograph (A) we obtained three spectrograms during the winter season

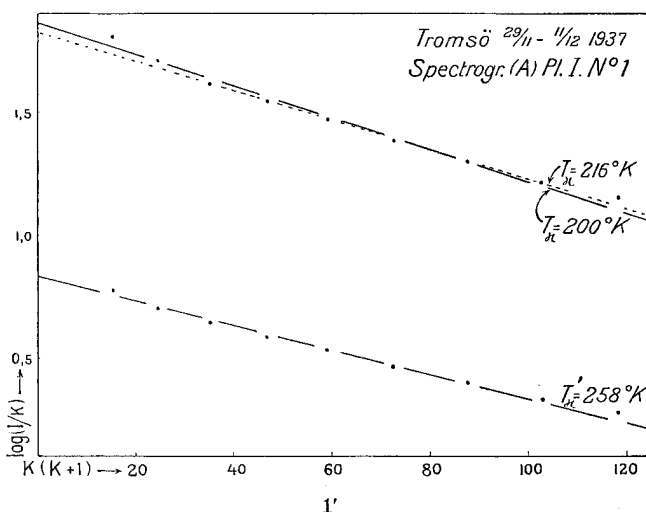
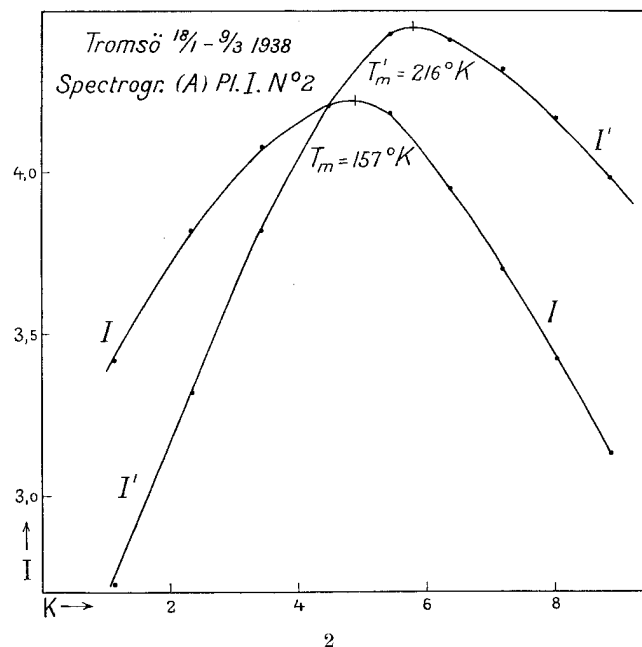
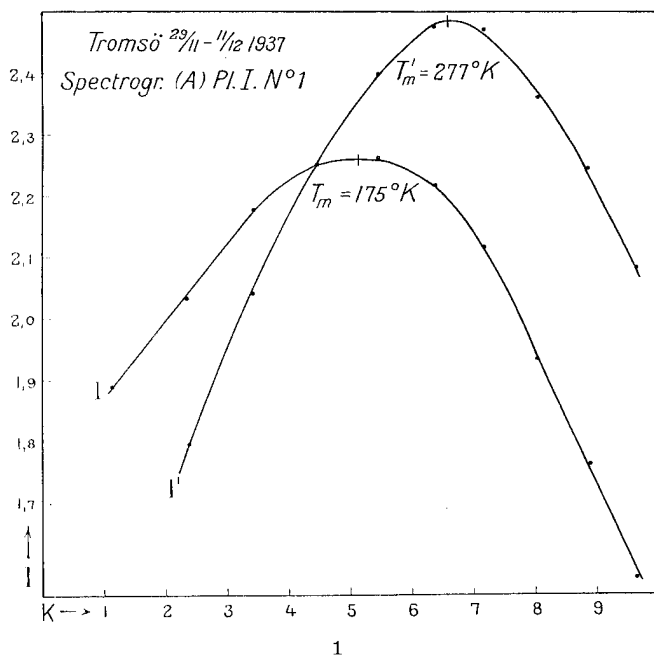


Fig. 1, 1'.

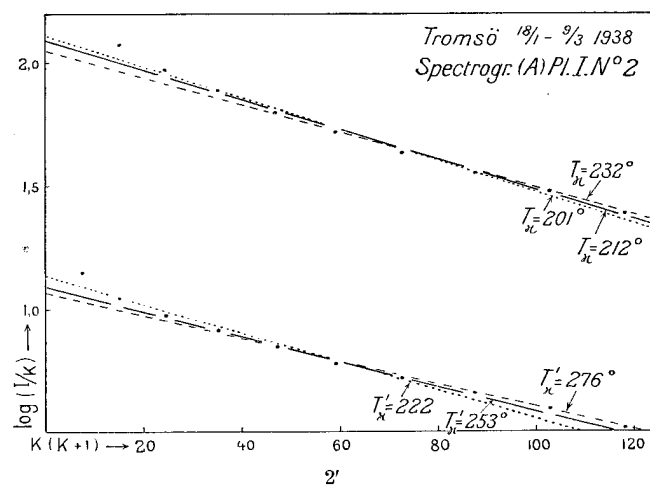


Fig. 2, 2'.

One such spectrogram is shown at the bottom of Plate I. It was taken on the same plate as spectrogram No. 4. The results of our measurements are given in the Tables I, II, III, and IV.

Each table contains six columns for the quantities K , I , I' , $\log(I/K)$, $\log(I'/K)$, and $K(K+1)$ corresponding to the R -branch of band 4278. For each spectrogram we construct the curves (I, K) and (I', K') from which are derived the quantities K_m and K'_m for the calculation of T_m and T'_m from equation (3). These curves are given in Figs. 1, 2, 3, 4 corresponding to the four spectrograms. Further we construct from the tables the curves $[\log(I/K), K(K+1)]$ and $[\log$

$(I'/K), K(K+1)]$ from which are derived the values of κ and κ' and from equation (2) the temperatures T_κ and T'_κ . These curves are given in Figs. 1', 2', 3', 4' for the four spectrograms. Each of the figures contains two curves corresponding to (I) and (I') . For each curve is given the temperature derived from it.

In some cases when the κ -curve departs from a straight line, we have drawn a couple of κ -lines in order to fix the limits within which the true average temperature is to be placed. The temperatures T_m , T'_m , T_m , $(T_m)_{\text{corrected}}$, T_κ , T'_κ , and \bar{T}_κ are given at the bottom of each table. The results are also collected in Table V.

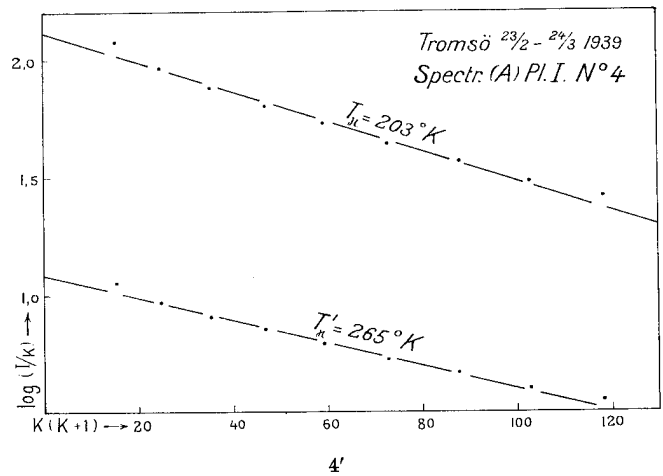
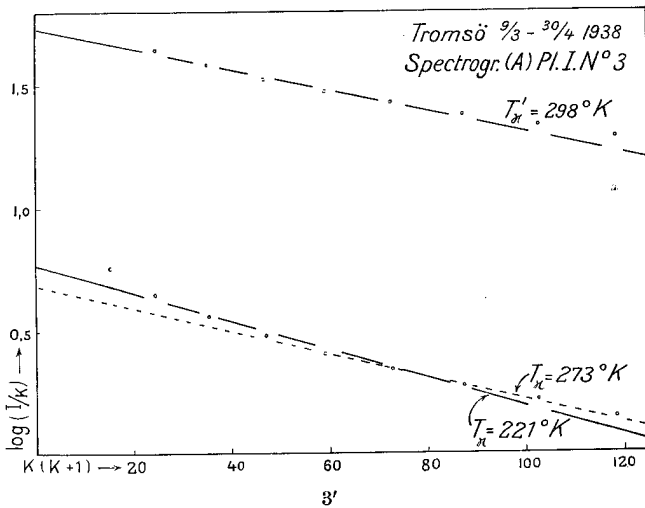
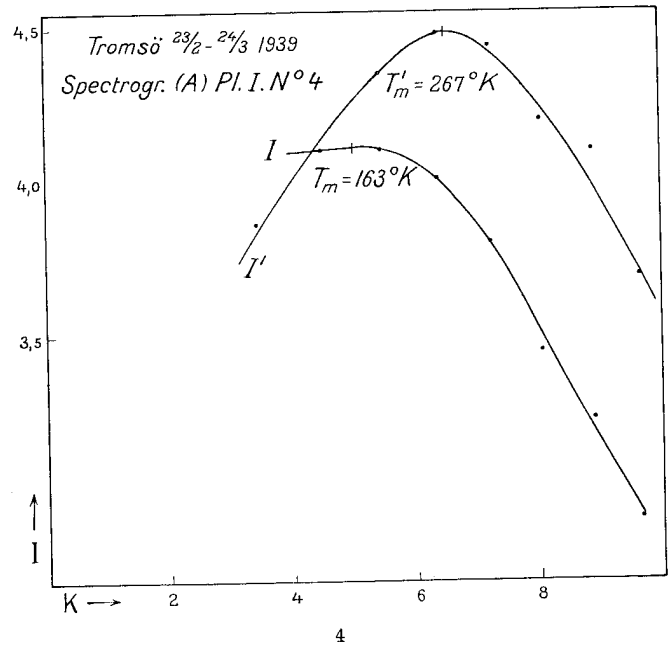
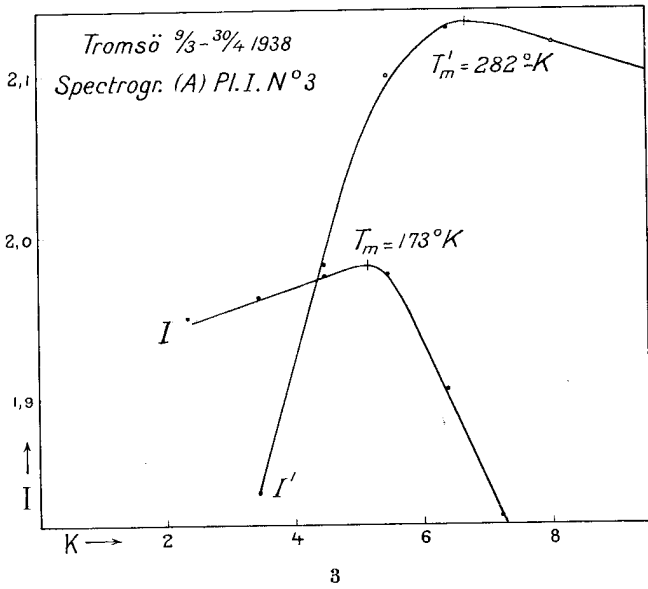


Fig. 3, 3'.

Fig. 4, 4'.

Table V.

Pl. I	T_m	T'_m	T''_m	\bar{T}_m	(T_m) corr.	T_{κ}	T'_κ	\bar{T}_κ
No.	K°	K°	K°	K°	K°	K°	K°	K°
1	175	277	273	225	223	208	258	233
2	157	216	235	192	213	215	250	233
3	173	282	271	225	221	247	298	272
4	163	267	250	211	211	203	265	234
Mean	167	260	257	213	217	218	268	243

During the winter season 1937—38 we took three spectrograms with the large quartz spectrograph. The first one, for which the exposure lasted from November

29th—December 1st, 1937, showed a large number of lines which will be dealt with later on, but the band 3914 was by far too dense for accurate photometric intensity measurements, and was not suitable for temperature determinations.

The second spectrogram (January 19th—28th, 1938) gave only a few bands, but also in this case the 3914 band was too dense to give the best conditions for intensity- and temperature measurements. The R- and P branch was not well separated.

The third spectrogram, for which the exposure only lasted a couple of nights (March 7th—9th, 1938), gave the 3914 band with very suitable density for

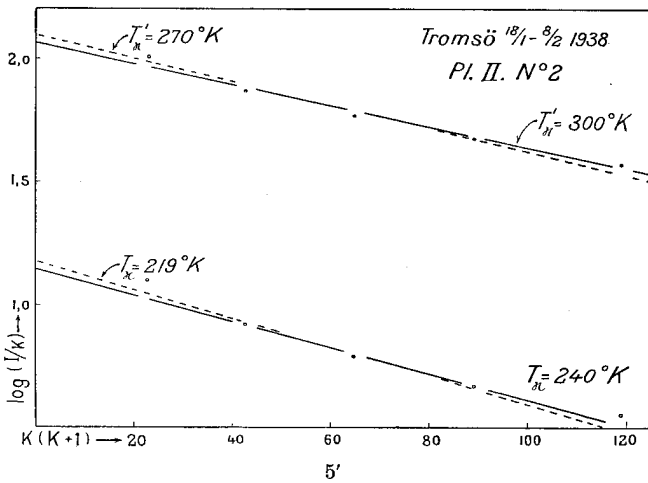
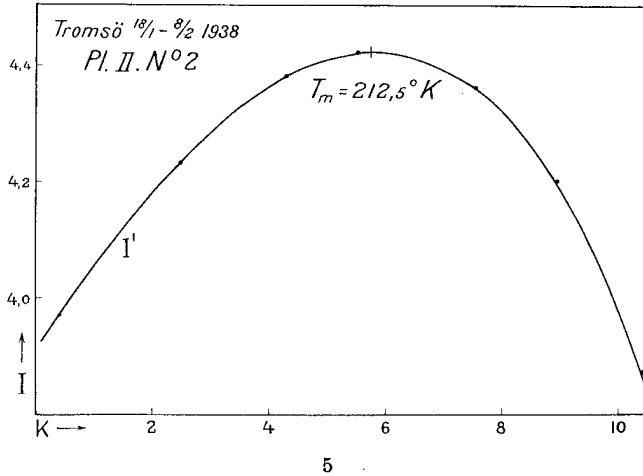


Fig. 5, 5'.

Table VI.

Quartz spectrograph (Q), January 18th—February 8th, 1938. Ilf. Doubl. X-press.

Plate II, No. 2. Band 3914.

K	I	I'	1 + log I/K	2 + log I'/K	K(K+1)
0.43	6.38	3.97	2.172	2.966	0.61
2.50	5.83	4.23	1.368	2.228	8.75
4.30	5.40	4.38	1.099	2.008	22.79
6.04	4.96	4.42	0.914	1.864	42.52
7.55	4.56	4.36	0.781	1.762	64.55
8.95	4.12	4.20	0.663	1.672	89.05
10.42	3.57	3.87	0.545	1.570	119.00
11.63	3.08	3.52	0.423	1.481	146.89
12.80	2.83	3.39	0.345	1.423	176.64
$K_m = 5.75$	$\alpha \cdot 10^3$	$T (K^\circ)$	$\alpha' \cdot 10^3$	$T' (K^\circ)$	
	5.85	219	4.76	270	
$T_m = 212.5$	5.35	240	4.29	300	

Table VII.

Quartz spectrograph (Q), March 7th—9th, 1938. Ilf. Double X-press.

Plate II, No. 3. Band 3914.

K	I	I'	2 + log I/K	2 + log I'/K	K(K+1)
1.80	2.02	1.39	2.050	1.889	5.04
3.55	1.96	1.52	1.742	1.631	16.15
5.12	1.875	1.59	1.564	1.492	31.33
6.60	1.68	1.54	1.406	1.367	50.16
7.97	1.445	1.41	1.258	1.248	71.49
9.25	1.25	1.29	1.131	1.145	94.81
10.50	1.06	1.15	1.004	1.041	120.75
11.62	0.92	1.05	0.899	0.957	146.64
12.71	0.81	0.97	0.804	0.881	174.25
$K_m = 5.7$	$\alpha = 6.28 \cdot 10^{-3}$	$T = 204^\circ K$			
$T_m = 208^\circ K$	$\alpha' = 5.55 \cdot 10^{-3}$	$T' = 230^\circ K$			

temperature measurements. Reproductions of these three spectrograms are given on Pl. II, Nos. 1, 2, and 3. Temperature measurements were undertaken for the two weakest spectrograms. The results are given in the Tables VI and VII. The tables are arranged in the way already described. The corresponding curves are given in Figs. 5, 5' and 6, 6'.

In the case of the weakest spectrogram which gives good conditions for photometric measurements, it was of interest to see with what accuracy the temperature could be measured under very satisfactory conditions with regard to photographic density. We therefore took photometric diagrams at four different parts of the band 3914 and determined the temperature independently for each photogram. The results are given in Table VIII. The values obtained for the different series agree fairly well.

On account of the small dispersion the values of K_m cannot be determined with any satisfactory accuracy. The (I'K) curve, however, usually gives a fairly well defined maximum.

Also the values obtained for the two spectrograms agree fairly well with each other, and we notice that the values obtained for T by means of the quartz spectrograph and the band 3914 agree fairly well with those obtained with the large glass spectrograph and the band 4278. Hence we conclude that the quartz spectrograph may be used with advantage for the study of a possible large increase of temperature with altitude, provided we are able to take spectrograms corresponding to the upper limit of the auroral streamers.

Table VIII.

Quartz spectrograph (Q), March 7th—9th, 1938.
If. Double X-press.

Plate II, No. 3. Band 3914.

Photogram	I	II	III	IV	Mean
K'_m	5.8	5.7	6.2	5.75	5.86
T'_m in K°	215	208	244	212	220
$\kappa \cdot 10^3$	5.94	6.28	5.27	6.49	5.99
T in K°	217	204	245	198	216
$\kappa' \cdot 10^2$	4.88	5.55	4.85	5.50	5.17
T' in K°	262	230	264	235	248

Table IX.

Date and time interval of exposure	T	t	
	$^\circ K$	$^\circ C$	
9 Oct.—31 Dec., 1923 ...	241	-32	N.B. 4278 taken with a large glass spectrograph
7 Jan.—15 Jan., 1924 ...	249	-24	
16 Jan.—12 April, 1924 ...	230	-43	
15 Febr.—20 Febr., 1933 ...	231	-42	
21 Febr.—26 Febr., 1933 ...	228	-45	
17 March—7 April, 1933 ...	218	-55	
3 March—23 March, 1934 ...	219	-54	
15 Oct. 1935—28 March, 1936	241	-32	
3 Dec. 1936—19 April, 1937	234	-39	
29 Nov.—11 Dec., 1937 ...	216	-57	
18 Jan.—9 March, 1938 ...	214	-59	
9 March—30 April, 1938 ...	234	-39	
23 Febr.—24 March, 1939 ..	207	-66	
Mean	228 $^\circ K$	-45	
18 Jan.—8 Febr., 1938 ...	230	-43	N.B. 3914 taken with quartz spectrograph
7 March—9 March, 1938 ..	216	-57	
16 Oct.—28 Oct., 1938	210	-63 L.lim.	
16 Oct.—28 Oct., 1938	210	-63 U.lim.	
5 Nov. 1938—5 Jan., 1939.	235	-38 L.lim.	
Mean	220 $^\circ K$	-53 $^\circ C$	

The results of our temperature measurements from 1923 up to the present are collected in Table IX, which also includes three spectrograms taken with the quartz spectrograph by the assistance of Mr. O. Krogness during the winter 1938—39. One of these spectrograms corresponds to the upper limit of the aurorae, but it shows no increase of temperature upwards.

§ 3. Wavelength and Relative Intensity of Weak Lines from Spectrograms of Great Dispersion.

In addition to the negative bands and the green line some of the spectrograms taken with the large spectrographs mainly for temperature determinations also show a number of other weak lines and bands.

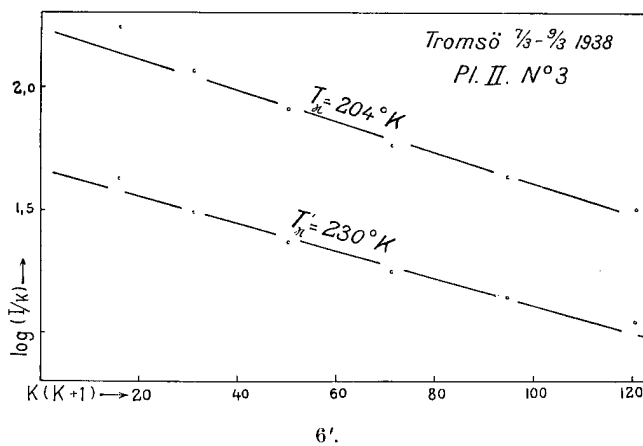
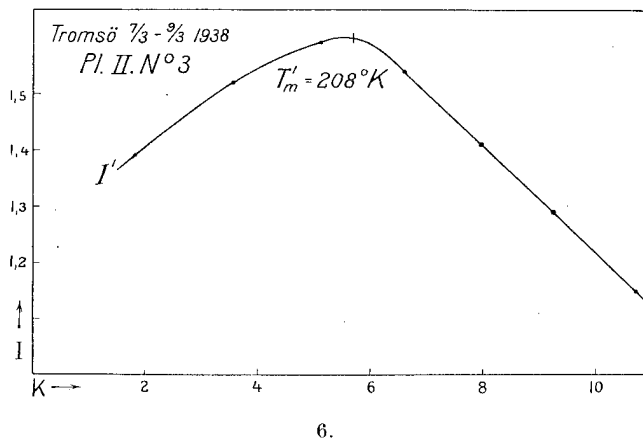


Fig. 6, 6'.

Particular interest is attached to two lines ($\lambda_1 = 4415$ and $\lambda_2 = 4368$), which were obtained very distinctly on spectrograms from the large glass spectrograph and dealt with in previous papers. (4368) was referred to the *OI*-spectrum, the second one to *OII*.

These lines have also been obtained quite distinctly on three of the spectrograms from the large glass spectrograph dealt with in the preceding paragraph (Pl. I, Nos. 1, 2, and 4).

Up to the present these two lines have been obtained very distinctly on four spectrograms taken with the large glass spectrograph. The results of the wavelength measurements are given in Table X.

The wavelength values found for each of the two lines from the four plates differ only with a fraction of 1 Å unit. The mean values are probably correct to within about 1/10 Å unit. The probable origin of these two lines were given in previous papers (8, 9). The line 4415.25 was identified with the *OII*-doublet (4414.9 and 4417.0) from singly ionised oxygen atoms. This doublet is found to appear with dominating

Table X.

Spectr.	Exposure	Reproduced	λ_1	λ_2
<i>a</i>	¹⁵ / ₁₀ 35— ²⁸ / ₃ 36	Paper (4): Pl. II A	4415.1	4368.2
<i>b</i>	²⁹ / ₁₁ * — ¹¹ / ₁₂ 37	This paper: Pl. I, No. 1	4415.5	4368.2
<i>c</i>	¹⁸ / ₁ * — ⁹ / ₃ 38	Pl. I, No. 2	4415.1	4368.3
<i>d</i>	²³ / ₂ * — ²⁴ / ₃ 39	Pl. I, No. 4	4415.3	4368.4
		Mean	4415.25	4368.3
		Interpretation	<i>OII</i> $\left\{ \begin{matrix} 4414.9 \\ 4417.0 \end{matrix} \right.$	<i>OI</i> 4368.3

Table XI.

Wave-length	Interpretation	Relative intensity from spectr.				
		¹⁵ / ₁₀ 35— ²⁸ / ₃ 36	²⁹ / ₁₁ . ¹¹ / ₁₂ 37	¹⁸ / ₁ . ⁹ / ₃ 38	²³ / ₂ . ²⁴ / ₃ 39	Mean
4708	N.G. (0—2)	43	47	33.8	33.8	39.4
4650	N.G. (1—3)	20	20	16.5	19.6	19
4415.25	<i>OII</i> (4414.9, 4417.0)	9.3	13	8.4	9.8	10.1
4368.3	<i>OI</i> (4368.3)	9.0	15	8.2	9.4	10.4
4278	N.G. (0—1)	100	100	100	100	100
4236	N.G. (1—2)	32	29	17.9	19	24.5

strengt in spectra excited by canal rays. The doublet corresponds to the following electronic transitions:

$$OII: 2s^2 2p^2 ({}^3P) \left\{ \begin{matrix} 3p^2 D_2^o - 3s^2 P_1 \\ 3p^2 D_3^o - 3s^2 P_2 \end{matrix} \right.$$

It is evident that with the dispersion used the doublet will appear as a single line.

The second line 4368.3 was identified with a line from neutral oxygen atoms having a wavelength 4368.3 which is in perfect agreement with that found for the corresponding auroral line. This oxygen line results from the electronic transition

$$OI: 2s^2 2p^3 ({}^4S) (4p^3 P_{0,1,2} - 3s^3 S_1^o).$$

At the *University Physical Institute of Oslo* one of us (Vegard) has recently carried out experiments in which we have obtained the spectrum of neutral oxygen atoms under such conditions that the green auroral line appeared with considerable intensity. And in this case the line 4368.3 appeared with dominating intensity. It is therefore to be expected that this line may be observed in the auroral spectrum, while most other *OI*-lines are too weak to appear with noticeable density. Certain weak lines may also be masked by other bands and lines.

As mentioned in previous papers (4, 9) a comparison between spectra obtained at different times suggests that the intensity of the two lines vary in a way similar to that of the sunspot frequency. We have therefore found it to be of importance to measure the intensity of these two lines compared to that of the negative nitrogen bands. Such measurements from spectrograms with about the same dispersion (the best would be to use the same spectrograph) ought to be made each year for a period covering say 25 years.

As a contribution to such an investigation we have measured the relative intensities from the four plates which have been taken with the large glass spectrograph, and which give the two lines with a density sufficient for intensity measurements. The results are given in Table XI.

The greatest relative intensity of the two lines is found for the spectrogram from 1937. The one taken a couple of months later, however, gives much smaller intensities indicating that the relative intensities of the two lines are subject to certain fluctuations of some yet unknown origin.

On the last of our spectrograms taken with the large glass spectrograph (Pl. I, No. 4) a considerable number of other weak lines appear. As most of the weak auroral lines have previously only been obtained on spectrograms of very small dispersion, we have measured the wavelength of all these lines. Some of the lines being too weak to be seen in the microscope, we have fixed the position of the line by means of spectrophotometer diagrams. It should be noticed, however, that only such maxima were measured which correspond to lines distinctly seen on the plate or the photographic reproduction.

The results are given in Table XII.

The first column contains the lines or bands measured from the plate mentioned. The second column gives the corresponding lines from previous measurements, and the third column gives the probable interpretation. It appears that most of the lines appearing on our spectrogram are known from previous observations, but it also contains a new line 4332.3 and a band or group of lines in the region 4466—4476 not previously recorded in the auroral spectrum; we have not yet been able to give any plausible interpretation of these new lines.

On one of the spectrograms from the quartz spectrograph (Pl. II, No. 1), for which the exposure lasted from Nov. 29th—Dec. 11th, 1937, the band 3914

had a too large density for temperature measurements. As the two lines 4415 and 4368 appeared, we found it of interest to measure the relative intensity of some of the lines and bands.

The results are collected in Table XIII.

The relative intensities of the lines 4415 and 4368 are somewhat smaller for the quartz spectrograph than those obtained from the large glass spectrograph. It must, however, be remembered that the intensities are referred to that of the band 4278, the intensity of which is put equal to 100.

On account of the great density of this band on the spectrogram (Pl. II, No. 1) the intensity is uncertain. It would be better to compare the intensities of the lines 4415 and 4368 with some weak negative band in the neighbourhood, *e. g.*, the band 4650. If the intensity of this band is put equal to 20, we get:

λ	Intensity from quartz spectrograph	Intensity from large glass spectrograph
4650	20	20
4415	8.9	10.6
4368	8.8	10.9

Table XII.

Wavelength		Interpretation
Measured from spectr. Pl. I, No. 4	Previously measured	
4708.7	4708.7	N.G. (0-2)
4650.8	4652.2	N.G. (1-3), ϵ (4-16)
4593.9	4596.1	N.G. (2-4)
4570.8	4566.0	
4542.0	4535.0	ϵ (3-15)?
4486.0	Line group (band) not previously observed	<i>OII</i> (4469.4, 4467.9)?
4476.0		
4466.0		
4425.6		
4415.3	4424.0	ϵ (2-14)
	4415.1	<i>OII</i> (4414.9, 4417.0) 2 P.G. (3-8) (4416)?
4376.6	4375.6	<i>OII</i> (4376.2)
4368.4	4368.2	<i>OI</i> (4368.3), (⁴ S) (4 <i>P</i> ³ <i>P</i> _{0, 1, 2} - 3 <i>s</i> ³ <i>S</i> ₁ ^o)
4345.3	4345.6	2 P.G. (0-4)
4332.3	New Line	
4319.5	4319.5	ϵ (1-3)
4277.6	4277.6	N.G. (0-1)
4236.0	4236.0	N.G. (1-2)
4197.9	4200.0	N.G. (2-3)
4059.0	4058.0	2 P.G. (0-3)
3914.4	3914.4	N.G. (0-0)

Table XIII.

Intensity measurements from spectrograph. Nov. 29th—Dec. 11th, 1937.

Pl. II, No. 1.

Wavelength	Interpretation	Relative intensity	
		From Pl. II, No. 1	Previous values
4708	N.G. (0-2)	28	39.4
4650	N.G. (1-3)	16	19
4415	<i>OII</i>	6.8	10.1
4368	<i>OI</i>	7.1	10.4
4345	2 P.G. (0-4)	7.0	12.3
4278	N.G. (0-1)	100	100
4236	» (1-2)	23.2	24.2
4200	» (2-3)	8.8	8.2
4058	2 P.G. (0-3)	11.2	14.0
3998	» (1-4)	15.4	15.2
3943	» (2-5)	12.2	9.0
3914	N.G. (0-0)	221.00	196.00
3883	» (1-1)	9.0	9.0

It appears that the relative intensities of the lines 4415 and 4368 found from the quartz spectrograph within the limit of error agree with those found by means of the large glass spectrograph. It must, however, be remembered that the relative intensities which we measure for spectral lines when compared with those of bands, will depend on the sharpness with which the line appear as well as on the adjustment of the spectrograph and on the width of the slit.

§ 4. Spectrograms Showing Intensity Variations Due to Sunlight and Increase of Altitude.

Early in the evening of Dec. 1st, 1937, a number of spectrograms were taken at Tromsø with the small glass spectrograph (*a*) of aurorae appearing in an atmospheric layer still exposed to sunlight. Later in the evening a spectrogram was taken under usual night conditions. The spectrograms are reproduced on Pl. II, No. 4 (*a-e*). The spectrogram (*f*) on the same photographic plate was taken on Dec. 3 and corresponds to a mixture of polar light and night sky luminescence. On the first spectrograms (*a, b, c*) we observe the negative bands, the green and red *OI*-lines, and the yellow line of the twilight, the intensity of which is seen to decrease rapidly as the sunlight withdraw from the atmosphere. This line, which is identical with the line 5893 measured in the night sky luminescence (10), had also previously been found to appear with considerable strength on twilight spectrograms (10, 15), but we had not ventured to refer it to

sodium, as done by Bernard (11, 12), Cabannes, Dufay and Gauzit (13, 14) in 1938. The wavelength and origin of this yellow line will be dealt with in the Part II of this paper.

In addition to the yellow line the spectra (*a, b, c*) show the negative bands, the green and the red auroral lines superposed on the continuous sunlight spectrum. Comparing these spectra with spectrum (*e*) corresponding to the lower limit of aurorae under normal night conditions, we notice at a glance the large enhancement of the red *OI*-line ($^1D_2-^3P_2$) in a sunlit atmosphere first detected and described by us in 1936 (16).

The spectrogram (*d*) corresponds to the upper limit of auroral streamers so late in the evening that the sunlight effect has practically vanished. Compared with spectrum (*e*) the red *OI*-line and the negative bands compared with the green line, appear enhanced on account of the large altitude.

The measured intensities for the green and red *OI*-lines and the strongest negative bands are given in table XIV for the five spectra (*a, b, c, d, e*). The numbers do not give the true relative intensities (*I*), but a quantity (*I · Q*), where *Q* is a factor which depends on the wavelength, but is the same for all spectra on the same photographich plate.

In order to see how far the intensity of a certain line or band (λ) varies from one spectrum to another, we take for each spectrum the ratio $\left(\frac{I_\lambda}{I_{5577}}\right)$. Let us compare any of the spectra (*a, b, c, d*) with the normal night spectrum (*e*), and form the double ratio

$$D = \left(\frac{I_\lambda}{I_{5577}}\right)_n : \left(\frac{I_\lambda}{I_{5577}}\right)_e \quad (9)$$

where (*n*) stands for *a, b, c*, or *d*. Then (*D*) is independent of *Q*, and (*D*-1), if $D > 1$ and $\frac{1-D}{D}$ if $D < 1$ gives a measure of the change of relative intensity of the line (λ) in spectrum (*n*) as compared with the spectrum of comparison (*e*).

The values found for the double ratio (*D*) are given i Table XV.

The values for the spectra *a, b*, and *c* show the large enhancement of the red *OI*-line in a sunlit atmosphere, and also the negative bands show a small but definite enhancement. The spectrum (*d*) gives similar enhancements due to increase of altitude.

The same effects are also clearly demonstrated by some spectra taken a few days later (on Dec. 8th)

Table XIV.

Small glass spectrograph. Dec. 1, 1937.

Plate II, No. 4.

Spectrum	<i>I · Q</i>				
	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
Direction.	N-W, h = 13°	W, h = 17°	W, h = 17°	W, h = 20-40°	NW, h = 15°
Exposure	1514-26	1528-43	1554-1618	1620-45	1812-27
Form ...	H.A.	R.B.	R.B.	R. upper limit	H.A. weak
Character	Sunlit	Sunlit	Sunlit?	Prob. sunlit	Night
λ					
6300	62	68	49	66	20
5577	100	100	100	100	100
4278			78	71	48
3914	108	107	108	105	79

Table XV.

λ	$D = \left(\frac{I_\lambda}{I_{5577}}\right)_n : \left(\frac{I_\lambda}{I_{5577}}\right)_e, \quad n = a, b, c, d$			
	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>
6300	3.18	3.49	2.51	3.36
4278			1.64	1.49
3914	1.37	1.35	1.37	1.32

and reproduced on Pl. II, No. 5 (*f, g*, and *h*). The sunlight and altitude effects are seen by comparing the intensities for the spectra (*f* and *g*) with those of spectrum (*h*) as they are given in the three last columns of Table XVI.

§ 5. Spectrograms of Red Aurorae of Type (B).

In the case of red aurorae of the (B) type, the red colour is restricted to the region near the bottom edge. This type was observed by one of us in 1912 (17), and in a paper published in 1917 (18) is suggested an explanation of the red colour which has been confirmed by later investigations on the variations of the intensity distribution within the auroral spectrum (15, 19, 20). According to this explanation the red colour of the (B) type should be due to the enhancement of red nitrogen bands (1st positive group) which accompanies the diminution of ray velocity and the

increase of pressure taking place towards the lower limit of an auroral streamer.

In accordance with this view, it was found (20, 15) that the red bands of the 1st positive group appeared enhanced in cases when the aurorae had a redish lower border.

The study of the excitation functions of the various nitrogen bands, when produced by electron bombardment gave the result (21, 22, 23) that the intensity of the 1st positive group compared with that of the negative group becomes dominating when the energy of the electrons falls below say 20 electron volt. According to our view the relative intensity of the 1st positive group ought to decrease upwards because the average energy of the electric rays increases. This altitude effect has in fact been detected and measured (24, 25).

In 1926 one of us (26) showed that the red colour of type (A) was due to the enhancement of the red line, which later has been identified as the *OI*-triplet (1D_2 — $^3P_{0,1,2}$). In certain cases the red colour of type (A) was restricted to the top part of the streamers (27) due to the fact that the relative intensity of the red *OI*-triplet increases rapidly upwards (27, 28).

On a spectrogram from an aurorae with a red bottom edge obtained by Harang (29) not only the 1st positive group, but also the red *OI*-triplet appeared with unusual strength, and Harang is of the opinion that also the red aurora of type (B) is due to the enhancement of the red *OI*-triplet. The conclusion drawn by Harang from his spectrogram is, however, not justified and does not agree with other observations. Extensive studies of the altitude effect of the red *OI*-triplet have shown that *without exception the intensity of the red OI-triplet increases rapidly upwards. The enhancement of the red triplet alone cannot therefore explain that the red colour is restricted to the lowest part of the streamers.*

If the red colour was mainly due to the enhancement of the red *OI*-triplet, then the redness might be rather restricted to the upper limit, as it actually has been observed in the case of red aurorae of type (A). Sometimes the red triplet may appear fairly strong, although not strong enough to change the colour into red. Under such conditions, however, the enhancement of the red bands of the 1st positive group towards the bottom edge, acting together with the red triplet, may change the colour into red near the bottom edge.

A luminescence with a strong *OI*-triplet will, as it were, be more sensitive to the colour changed produced by the enhancement of the 1st positive group. A strong red *OI*-triplet is, however, not at all essential for the production of a red lower border (type B). The correctness of this is shown by intensity measurements from earlier spectrograms of red aurorae of the (B) type (20, 15), and also spectrograms recently obtained at Tromsø by Bernard (30) give results in accordance with Vegard's explanation.

During the evening of Dec. 7th, 1937, we obtained spectrograms of aurorae with red bottom edge (type B) *which showed the red bands of the 1st positive group with unusual strength, while at the same time the red OI-triplet was hardly visible.*

These spectrograms are reproduced on Pl. II, No. 5 (a, b, c).

When we pass on to ordinary aurorae later in the evening (spectrograms No. 5 d, e), the intensity of the 1st positive group gradually diminishes and on spectrogram (e) this group is hardly visible while the red *OI*-triplet — although still weak — can be distinctly seen.

The measured intensities are given in Table XVI.

These spectrograms show conclusively the correctness of Vegard's explanation and that a strong OI-triplet is not essential for the formation of a red aurorae of type (B).

As previously mentioned by one of us (19), mixed types may occur and such a case is the one observed by Harang.

PART II

The Spectrum of the Twilight Luminescence.

§ 6. Remarks regarding Previous Observations and Results.

As twilight gradually passes over to the night sky luminescence, we may expect a certain similarity to exist between the spectra of these two light phenomena. During the night when the atmosphere is not exposed to direct light from the sun or the moon, the continuous light originating from the scattered sunlight is so weak that the emission spectrum of the true night sky luminescence may appear quite distinctly on a fairly unexposed background. A considerable portion of twilight, however, consists of scattered sunlight and if the night sky spectrum during the twilight was emitted with the same intensity as it is in the night, it would be entirely masked

Table XVI.

Small glass spectrograph. Spectrum a—e, Dec. 7th, f—h, Dec. 8th, 1937.

Plate II, No. 5.

Spectrum		a	b	c	d	e	f	g	h
Exposure		1805-08	1811-25	2125-30	2135-45	2200-30	1535-55	1600-15	1620-25
Direction		N.W.	N.W.		W	S	W	W	W
Height (h)		20°	20-30°	16°	15°	30-40°	15-30°	20-30°	27°
Form and character		H.A. Red lower border	H.A. Red lower border	H.A. Red lower border	H.B. Normal	H.A. Normal	Upper limit of sunlit rays	Lower limit of sunlit rays	H.B. Normal
I · Q _λ	λ								
	1 P.G. 6500	25	22	24	Weak				
	6300	Extremely weak	Weak	Weak	15	18.9	68.5	38.4	Faint
	5577	169	262	170	192	100	100	100	100
	4708	13	23	15	Faint				
	4278	100	100	100	100			Weak	47.8
	3914	162	127	169	185		96.8	79.9	

by the relatively strong continuous spectrum of sunlight.

Now we know from the study of the auroral spectrum that certain bands and lines are enhanced when the atmosphere is exposed to sunlight (16, 28, 9). Thus the red *OI*-line 6300 was largely enhanced and also the 1st positive and the negative nitrogen groups were found to appear with relatively greater intensity in an atmosphere exposed to sunlight.

Similar effects might be expected in the case of the night sky luminescence, in other words we should expect that certain lines or bands of the night sky luminescence appeared enhanced in the spectrum of twilight. Such effects have actually been observed.

First of all we shall deal with a yellow line probably first observed in the night sky spectrum by Slipher¹ (31) in 1929, who deduced for it a wavelength of 5892. Later it was observed by Dufay (32), Sommer (33), Cabannes (34), and by Vegard and Tønsberg (10). The latter obtained spectrograms with very sharp lines by using a narrow slit and deduced the fairly accurate wavelength

$$\lambda = 5892.6$$

in good agreement with the measurements of Slipher and Dufay. We were also able to show that the line was too broad to be a single atomic line. It might

¹ V. M. Slipher, Pub. A. S. P. 41, 263, 1929.

either be a very narrow band or a group of at least two atomic lines.

The intensity of this and other lines of the night sky spectrum is very small indeed, and even with the small spectrograph of high light power (camera lens *f*: 2) used by us, an exposure of say 10-15 hours is necessary to obtain the yellow line distinctly. We were therefore surprised to find that in spectra from twilight a line appeared which, as far as could be judged from the dispersion used, was identical with the yellow line of the night sky. Taking into account that in the case of the twilight spectrograms, the exposure only lasted a few minutes, *this means that the yellow line of the night sky is enormously enhanced when the atmosphere from which it is emitted is directly exposed to sunlight.* Two such twilight spectrograms showing the enhanced yellow line were taken at Tromsø in February 1936 and reproductions are given in a paper published in 1937 (15).

Some spectra showing the same effect were also obtained at Oslo on the 13th of January, 1936. Reproductions of these twilight spectra showing very distinctly the yellow line, are given on Pl. IV A, No. 1, 2, 3.

At the same time we also tried to obtain the yellow line with a spectrograph of much greater dispersion. Our first attempts in this direction were, however, not successful and other pressing investig-

ations prevented us from continuing these observations at that time. Later on we found that similar twilight spectra showing the yellow line, were also obtained by Currie and Edwards (34) during the Polar Year. The enhancement of the yellow line in the twilight was shown by Bernard who worked at the Tromsø Observatory during November 1937 (11). By studying the variation of its intensity as the twilight faded away, he was able to make certain estimates as regards the probable height of the emitting layer (12).

With regard to the interpretation of the line we find in the wavelength tables that the value 5892.6 is just about the mean value of the wavelengths of the components of the sodium *D*-doublet.

As it appeared to us to be rather unlikely that a sodium line should be emitted with such an intensity from the atmosphere, we regarded this coincidence as merely accidental and suggested as a possible interpretation, that the yellow line was a narrow band belonging to the 1st positive group of nitrogen, because we know that very sharp bands of this group are emitted from active nitrogen. Acting on the assumption that the yellow line of the night sky might be the (*Na*) *D*-doublet, Dufay in 1932 tried to trace its origin outside the atmosphere, but the increase of intensity with the zenith distance proved its atmospheric origin.

As long as the yellow line was only obtained with spectrographs of very small dispersion, the value found for its wavelength was too uncertain for any definite conclusion to be drawn with regard to its origin or possible identity with the *D*-line of *Na*. There is hardly any help in trying to proceed further by using the *D*-line for comparison — as done by Cabannes, Dufay, and Gauzit (14). They used a spectrograph which near 5900 had the small dispersion of 500 Å/mm which is about the same as that used by us (10) in 1933—35 for obtaining the yellow line from the night sky. Already from previous measurements we know that the *D*-line of *Na* under these conditions is bound to coincide apparently with the yellow twilight or night sky line, but this procedure cannot essentially increase the accuracy.

In order to find further agreements for the identification of the yellow twilight line with the *D*-line of sodium, Bernard (11, 12) and at the same time and independently Cabannes, Dufay, and Gauzit (14, 25) used an interferometer method to investigate the internal structure of the line. The instrument was similar to that used for the determination of the

wavelength of the green and red auroral lines (36, 37). By using thin interferometer plates of different thickness the last mentioned authors were able to show that the yellow twilight line consisted of two components. With a distance of 0.15 mm between the silver coating the two components were separated. With a distance of 0.3 mm the picture showed coincidence of the two components.

From the wavelength values of the two components of the (*Na*) *D*-doublet we can easily calculate that the *D*-line would show the same behaviour. This consequence of the calculation was demonstrated by photographing the interferometer fringes directly from a sodium light source. From these observations we can draw the conclusion that the yellow twilight line has two components, whose difference of wavelength is nearly equal to or a simple rational fraction of that of the components of the *D*-line of sodium.

There was also a certain similarity with regard to the intensity of the two components, but certain interferometer pictures indicated small differences both as regards position and relative intensities of the fringes corresponding to the twilight line as compared with those of the *D*-doublet.

In spite of such differences, however, the interferometer pictures gave a strong argument in favour of the interpretation of the yellow night sky- and twilight line suggested by Dufay.

§ 7. Spectrograms of the Yellow Twilight Line Taken with Large Dispersion.

The interferometer pictures taken by Bernard and by Cabannes, Dufay, and Gauzit do not give any determination of the wavelength of the yellow twilight line and until we have more accurate wavelength-measurements we cannot regard its interpretation as definitely settled. We have therefore tried to obtain the yellow line with a spectrograph, which has a dispersion sufficiently large to separate the two components of the *D*-line of *Na*.

At first we took at the Tromsø Observatory a considerable number of spectrograms with the new large glass spectrograph, described in a previous paper (cfr. paper 19, Figs. 6—12). These spectra are shown on Pl. III, B Nos. 1—8.

The dispersion (255 Å/mm at 5890) was about twice as large as that used by Cabannes, Dufay, and Gauzit, but it was not sufficient to give separation of the *D*-doublet. The accuracy with which the mean

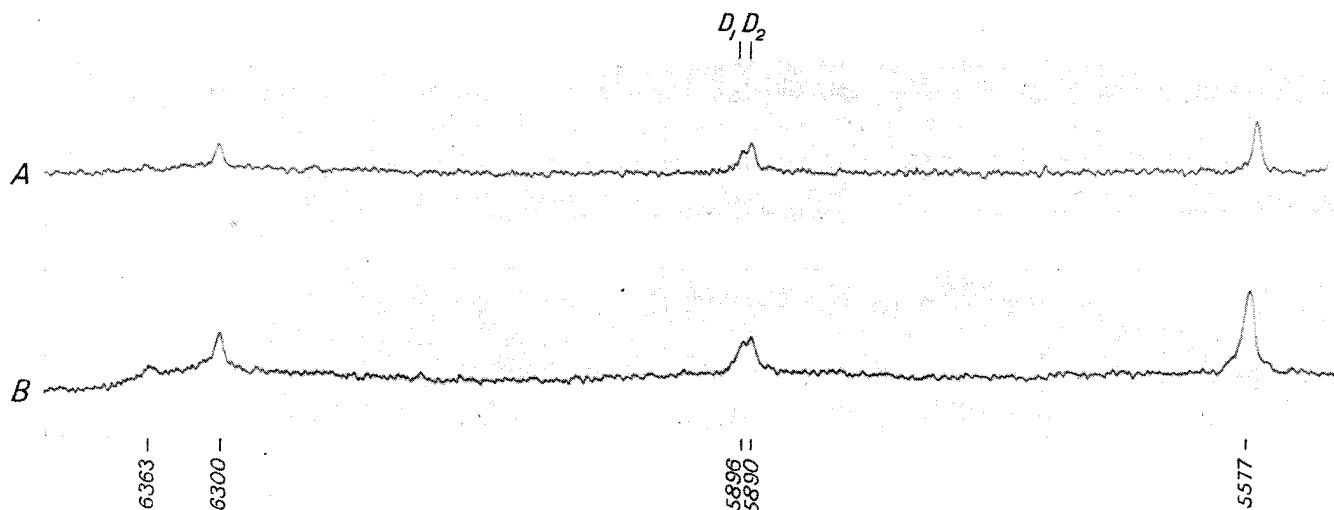


Fig. 7. Microphotometric curves from twilight spectra (mixed with some polar light) taken with our largest glass spectrograph giving separation of the D -line. (A) from spectrogram taken $4^{14/12}$ 1939, (B) spectrogram taken $24/12$ 1939— $22/1$ 1940.

wavelength could be measured was, however, considerably improved. The wavelength values obtained from these spectrograms for the yellow twilight line and for the red OI -lines are given in Table XVII. The accuracy may be estimated from the values found for the OI -lines for which the wavelengths are precisely known.

Table XVII.

Plate III, No.	OI		NaI
	$(^1D_2-^3P_1)$	$^1D_2-^3P_2$	$D_2 D_2$
B. 1	6365.2	6300.2	5892.4
B. 2	6363.4	6301.1	5895.7
B. 3	6365.6	6299.6	5893.6
B. 4	6362.5	6299.3	5892.4
B. 5	6363.1	6299.9	5891.6
B. 6	6363.5	6299.0	5891.9
B. 7	6362.5	6299.6	5893.6
Mean	6363.7	6299.8	5893.0
Probable error	± 0.83	± 0.46	± 0.94

The large glass spectrograph built by one of us in 1922 and described in previous papers has a considerably larger dispersion (99 \AA/mm at 5890), and by using a narrow slit, accurate adjustment, and high degree of temperature-constancy, we should be able to separate the two D -components.

This spectrograph, which was previously described by one of us (paper 1, Pl. IV, Fig. 1), is the one we mostly used for taking spectra of bands suitable

for temperature measurements. With this instrument twilight spectra were taken at Tromsø. It was necessary to keep on with the exposure for several evenings. We have taken two spectrograms which are reproduced on Pl. III A, Nos. 1 and 2. If the doublet structure, which is seen on the original, may not come out in the reproduction, it is clearly seen on Fig. 7, giving reproductions of spectro-photometer curves of the twilight line and the green and red auroral lines for the two spectrograms.

By photographing the sodium D -line, as a comparison spectrum, we see that the components of the yellow twilight doublet coincide exactly with those of the sodium D -doublet. Taking into account the large dispersion the exact coincidence shows that the twilight doublet cannot differ in wavelength by more than about $0.1-0.2 \text{ \AA}$ units from the D -doublet of sodium. Also as regards the relative intensity of the components the twilight doublets agree with that of sodium.

These results taken in connection with those obtained from the interferometer pictures already referred to, show that the yellow twilight line originates from sodium, and our spectrograms thus confirm the interpretation first suggested by Dufay and later essentially supported by the observations of Bernard, Cabannes, Dufay, and Gauzit.

The twilight spectrograms of large dispersion are also interesting by the great density with which the two strongest components of the red OI -triplet appear. Comparing the intensity of the red lines in twilight spectra with those obtained with the same

spectrographs directly from polar light and taking into account the time of exposure, we see that the red *OI*-triplet is considerably enhanced in an atmosphere exposed to sunlight. Such an effect of sunlight is well known in the case of aurorae (16).

It is, however, remarkable that the twilight spectra usually give the green and red *OI*-lines although no aurorae are visible. The idea will naturally suggest itself that the *OI*-lines are excited by the same solar rays as the yellow sodium line. This, however, does not seem to be the case, or an excitation of this kind is at any rate relatively insignificant. When series of twilight spectrograms are taken with small spectrographs of great light power, we sometimes find that the green and red *OI*-lines are absent although the yellow sodium line may appear very distinctly. It seems as if there occasionally should be some kind of radiation different from that which excite the sodium *D*-line and which is capable of exciting the 1D_2 and the 1S_0 -states of the neutral oxygen atoms.

§ 8. The Atmospheric Layer from Which the Sodium *D*-Line Mainly Originates.

Through measurements made at Pie-du-Midi Garrigue (41) found that the intensity of the yellow line (5892) in the night sky luminescence increased from the zenith towards the horizon, showing that the line originated from the atmosphere. Garrigue measured the ratio of the intensity of the yellow line near the horizon and at zenith, and from his ratio it is possible under certain assumptions to calculate the height of the atmospheric layer from which the *D*-line is mainly emitted. Such calculations were carried out by Cabannes, Dufay, and Gauzit (14, 35).

From Garrigue's measurements Cabannes, Dufay, and Gauzit deduce that the average intensity at 10° above the horizon is 2.8 times the intensity at zenith, and applying their formula, they find that the altitude of the layer, emitting the yellow line, should be 130 km.

Bernard (11, 12, 38, 39) observing at Tromsø determines the time when in the twilight the intensity of the yellow line drops down to insignificance. Assuming that the emission of the yellow line is restricted to a layer below a certain maximum altitude (H_B) and that the sodium present below this limit is excited by ordinary sunlight, the disappearance of the *D*-line means that the shadow of the solid earth passes the height limit H_B . From the time at

which the *D*-line disappears, Bernard finds that H_B may be put equal to about 60 km. In other words, according to Bernard the emission of the sodium line in the twilight luminescence should be mainly restricted to a layer below 60 km.

Bernard regards his result to be in contradiction to that found by Cabannes, Dufay, and Gauzit for the *D*-line of the night sky, and expresses the opinion that the calculations of Cabannes, Dufay, and Gauzit are not valid because the intensity measurements are too uncertain. There is, however, not necessarily any conflict between the two results, as the layer of maximum intensity of the *D*-line does not need to be the same for the twilight and for the night sky luminescence. It must be remembered that the altitude at which the *D*-line is a maximum, is a function not only of the way in which the active sodium is distributed, but also of the distribution with altitude of the processes and agencies which produce excitation.

In the case of twilight the excitation is caused by a radiation coming directly from the sun. In the case of the night sky luminescence, the excitation is due to a matter which during the day has been brought to some activated state. But it is only at great altitudes and extremely low pressures that these active states last throughout the night.

As already pointed out by one of us (9, p. 277) the appearance in the night sky of forbidden lines and bands (like the green and red *OI*-lines and bands of the ϵ -spectrum), makes it necessary to assume that the night sky luminescence originates from a layer within the auroral region.

In the following we are going to show that also in twilight the sodium *D*-line is emitted from a layer corresponding to the lower part of the auroral region. In order to determine the position and the extension of the layer which is mainly responsible for the emission of the sodium *D*-line during twilight, we have proceeded as follows:

By means of small spectrographs of great light power, we took series of spectrograms of twilight in rapid succession. From these we determined the time of appearance and disappearance of the yellow line. Such series were taken both at Oslo and at Tromsø, some in a vertical direction, some near the western horizon. Most of them were taken during sunset, a few also before sunrise.

Some of these series of spectrograms are reproduced on Plate IV. Details are given in the explanation to the plates.

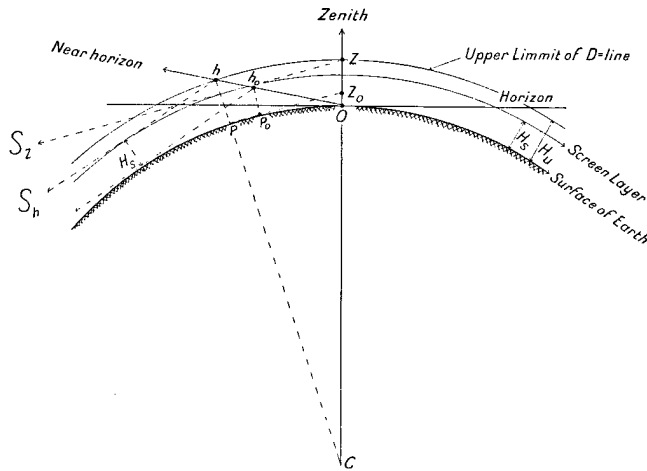


Fig. 8.

If we would follow the view advocated by Bernard, that the *D*-line is excited from ordinary sunlight and that the upper limit of the emission is determined by the shadow of the solid earth, then the observations near the horizon would give a greater upper limit (H_u) of the effective emission layer than the spectra from the zenith.

Assuming, however, that the *D*-line is excited by some easily absorbed, probably ultra violet, solar radiation, and that the atmosphere below a certain height (H_s) acts as a screen for the effective solar rays, this screening height may be found from the condition that spectra from the zenith and from a direction near the western horizon must give the same upper limit for the emission of the *D*-line.

It is easily seen that if we determine H_u for various values of H_s , the values of H_u increase more rapidly for the zenith observations than for those taken near the horizon. The correctness of this will be evident from Fig. 8. Here (S_z) indicates the direction of the sun, when the *D*-line disappears in zenith (direction OZ), (S_h) is the sun's position when the *D*-line disappears in a nearly horizontal direction (Oh). If the surface of the earth is the effective screen ($H_s=0$), then the limiting height of *D*-emission for the zenith observations (OZ_0) is seen to be smaller than ($P_0 h_0$) for the observations near the horizon. Selecting a suitable height for the effective screening (H_s), we may obtain that the zenith value of (H_u) (OZ on Fig. 8) is equal to the horizon value (Ph).

The results obtained from the Oslo series of spectrograms are given in Table XVIII. The upper part *a* contains the observations near the horizon, the lower part *b* the zenith observations.

Table XVIII.

Twilight spectrograms from Oslo, 1939.

Date	Exposure interval of the series	h	H_u in km		
			$H_s=0$	$H_s=80$	$H_s=100$
a. Collimator directed towards W in the evening or E in the morning					
19/1	16 ⁵⁸ —17 ³⁹	15°	69.8	146.9	163.2
>	16 ⁵⁵ —17 ³³	16°	66.2	144.1	158.8
31/3	19 ³⁹ —20 ³⁰	20°	50.2	130.9	146.5
25/4	2 ²⁸ —3 ¹⁰	22°	51.2	133.8	149.6
25/4	21 ³³ —22 ¹⁵	12°	57.5	130.9	145.2
26/4	21 ⁰⁰ —21 ³⁵	13°	59.5	134.1	148.6
28/4	21 ³⁷ —22 ³²	10°	56.2	127.4	141.4
	Mean ...	15.4°	58.7	135.4	150.5
b. Collimator directed towards zenith					
25/4	2 ²⁷ —3 ⁴¹	90°	43.2	139.4	159.6
25/4	20 ³⁵ —21 ³³	90°	45.9	142.7	162.9
26/4	21 ⁰⁰ —21 ³⁵	90°	46.4	143.3	163.5
28/4	20 ⁴⁷ —21 ³⁷	90°	44.8	141.4	161.6
	Mean ...	90°	45.1	141.7	161.9

The three first columns contain dates, exposure intervals, and height above the horizon (h) of each series. In the evening the instrument is directed towards West, in the morning towards East.

The last three columns contain the upper limit of the *D*-emission for three different values of the screening height, $H_s=0$, 80, and 100 km.

For $H_s=0$ the observations near the horizon give an upper limit $H_u=58.7$ km which is considerably greater than the one (45.1 km) corresponding to the zenith observations. For a screen height of 100 km, the value of (H_u) is seen to be the greatest for the zenith observations. For a certain value of (H_s) the limit height must be the same for both zenith and horizon.

The Tromsø observations are given in Table XIX a and b. In this case we have given the upper limit corresponding to $H_s=0$ and also the lower limit at which the *D*-line could be seen on our spectrograms.

We see that at both localities the morning observations give about the same upper limit H_u as those from sunset. This means that there is no time lag in the emission process. As soon as the effective sun rays leaves the effective layer in the evening, the *D*-emission stops, and as soon as the effective sun rays in the morning come down into the effective layer the *D*-emission sets in.

Table XIX.

Twilight spectrograms from Tromsø, 1939.

Date	Exposure interval of the series	In km	
		H_e	H_u
a. Collimator directed towards zenith. $H_s=0$			
2/2	15 ⁵⁰ —16 ³⁰		45.5
4/2	16 ⁰³ —16 ⁴⁸	2.9	46.0
11/2	16 ¹¹ —16 ⁵⁵		38.0
17/2	17 ⁰² —17 ²⁶	31.0	48.5
22/2	16 ⁴⁸ —18 ⁰⁰	28.0	49.5
24/2	17 ¹⁸ —17 ⁵⁶	30.5	45.0
28/2	17 ²⁵ —18 ¹¹	29.5	46.0
1/3	5 ⁴⁷ —6 ¹³	29.5	39.0
2/3	5 ²⁸ —6 ¹⁹	28.0	46.0
2/3	17 ⁴² —18 ¹⁴	29.0	45.0
3/3	5 ⁴¹ —5 ⁴⁹	29.0	42.0
3/3	17 ⁴⁵ —18 ¹⁸	29.0	47.0
8/3	18 ¹² —18 ⁴⁵	30.0	50.0
24/3	19 ¹⁴ —19 ⁵⁰	28.0	47.0
25/3	19 ¹⁷ —19 ⁵⁴	29.0	48.0
26/3	19 ²⁰ —20 ⁰⁰	29.5	45.0
Mean . . .		29.2	45.5
b. Collimator directed towards W; elevation = h			
Date	Exposure interval of the series	h	H_u km
27/1	16 ⁰⁰ —16 ²⁰	(23°)	(41.0)
28/2	18 ³¹ —19 ¹¹	10°	58.0
2/3	18 ⁴⁴ —19 ⁰⁴	10°	59.2
8/3	18 ⁴⁶ —19 ²⁰	10°	58.3
24/3	19 ⁵⁰ —21 ⁰⁰	10°	57.5
25/3	19 ⁵⁴ —20 ³⁴	10°	59.8
Mean . . .		10°	58.5

The values of (H_u) for various values of the screening height (H_s) are given in Table XX.

For both the zenith and the horizon we draw a curve giving the relation between the (H_u) and (H_s). The curves reproduced in Fig. 9 correspond to the mean values for Oslo and Tromsø.

The intersection point between the two curves gives us the true effective screening height (H_s) and the true height (H_u) of the layer, where the D -emission rapidly vanishes.¹

As seen from Fig. 9 the mean values derived from our observations are:

$$H_u = 116 \text{ km,}$$

$$H_s = 56 \text{ km.}$$

For the height (H_l) of the lower limit at which the D -line appears on our spectrograms, we get $H_l = 85 \text{ km.}$

¹ A brief account of the determination of the screening height (H_s) from the Oslo observations was given by one of us (Vegard) in the letter sent to Nature March 11 this year.

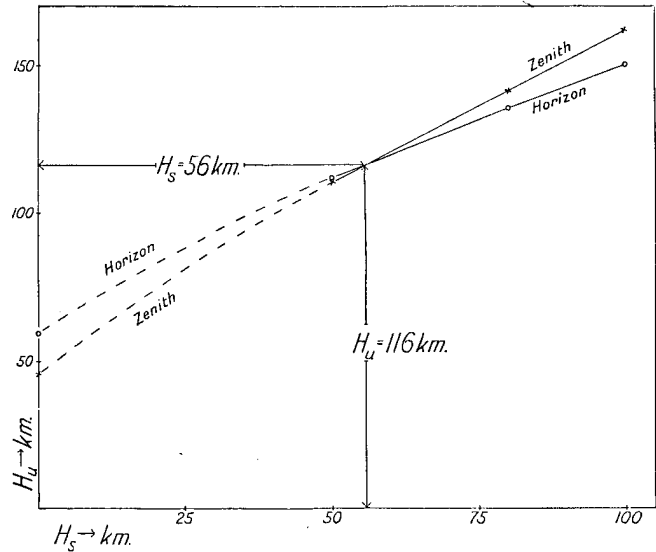


Fig. 9.

With regard to the physical significance of this lower limit it should be remembered that it does not indicate that the concentration of sodium drops down to insignificance below that altitude; for when the active solar radiation in the observed direction passes the atmosphere below 85 km, the effective atmospheric layer between 85 and 116 km is still exposed to effective solar radiation and will emit the yellow sodium doublet.

The disappearance of the yellow emission line below 85 km is due to the effect of scattered sunlight, which give the sodium (D_1D_2) doublet as absorption lines. When, with the spectrograph used, the yellow (D_1D_2)-lines are of the same intensity as the adjacent continuous spectrum, then the yellow doublet can no longer be observed on the spectrogram. If this is the explanation the lower limit should depend on the spectrograph used and diminish as the dispersion increases.

Table XX.

H_s	H_u					
	Near horizon			Zenith		
	Oslo	Tromsø	Mean	Oslo	Tromsø	Mean
km	km	km	km	km	km	km
0	58.7	58.3	58.5	45.1	45.0	45.1
50	113.7	109.4	111.6	111.4	109.3	110.3
80	135.4	130.6	133.0	142.0	139.0	140.5
100	150.2	143.6	147.0	162.0	160.0	161.0
$h =$	15°	10°	12.5°	90°	90°	90°

$$H_s = 56 \text{ km gives } (H_u)_{\text{horizon}} = (H_u)_{\text{zenith}} = 116 \text{ km}$$

§ 9. Specification of the Solar Rays Which Excite the Sodium D_1D_2 -Lines in Twilight.

The solar rays which excite the yellow line in the twilight luminescence must be of a kind which is absorbed by the atmosphere below the screening height 55 km. If the radiation is of the photon type its wavelength must be shorter than that of visible light.

We shall first consider the possibility that the effective radiation is to be found in the near ultra violet. The effective screening is limited by a sphere concentric with the earth and with a radius $(R_E + H_S)$, where R_E is the radius of the earth. A solar ray which passes as a tangent to the screening sphere will traverse a certain amount of matter given by the expression

$$m_s = \sum \varrho_h \Delta s, \quad (10)$$

where ϱ_h is the density at the height considered and Δs is an element of the line traversed by the ray. The value of ϱ_h as function of the altitude is known and the minimum screening mass (m_s) can be calculated.

For the altitude 55 km we find

$$m_s = \sum \varrho_h \Delta s = 5765 \varrho_0 \text{ g/cm}^2,$$

where ϱ_0 is the density of air at 0° C and 760 mm pressure. The screening mass is equivalent to a thickness of air under normal conditions of 5765 cm or 57.65 meters.

If the atmosphere was essentially composed of oxygen and nitrogen, ultra violet light for which the wavelength is smaller than about 1950 Å would be completely absorbed by a layer of thickness 58 meter of air at atmospheric pressure.

Thus if the effective radiation is to be found in the ultra violet, it must have a wavelength greater than say 1950 Å. The existence of a screening layer up to 55 km means that the effective component must be completely absorbed below 55 km. This absorption cannot be referred to ordinary nitrogen and oxygen, but to a substance which have absorption bands in the ultra violet region 3900—1950 Å. The only substance which may come into consideration is ozone, and we come to the following conclusion:

If the radiation responsible for the excitation of the yellow Na -line is ultra violet light, it must be a sort of light strongly absorbed by ozone. This is also in accordance with the fact that the screening height 55 km is situated far above the maximum of ozone concentration and corresponds to a layer

in the atmosphere where the ozone content is extremely small.

The ozone absorption sets in when the wavelength falls below say 3100 Å and has a maximum absorption coefficient at 2550. Minute layers of ozone will be sufficient to absorb a radiation at or near this wavelength. The ultra violet radiation producing the excitation of the yellow line should thus have a wavelength somewhere in the interval 3100—1950 Å. As the screening height is far above the height of maximum ozone concentration, the effective wavelength should be somewhere near the one for which the ozone absorption is a maximum or near 2500 Å.

It is of interest to notice that the light which has just sufficiently large energy quanta to ionize a Na-atom, has a wavelength of 2412 Å which is indeed near to the wavelength for which the ozone absorption is a maximum.

If the ultra violet light effective in exciting the yellow sodium line is strongly absorbed by ozone, we may conclude that the amount of ozone present in the atmosphere above 55 km is extremely small and this would have important consequences for the excitation processes which may account for the auroral spectrum and its variations. Any process including a reaction with ozone might then be put out of consideration.

It must, however, be kept in mind that the solar radiation effective in producing the yellow sodium line might not be situated in the near ultra violet, but might have a much shorter wavelength. From the screening height we may calculate approximately the absorption coefficient of such a soft X-radiation.

Let $\left(\frac{\mu}{\varrho}\right)$ indicate the mass absorption coefficient which at an altitude of 55 km would reduce the intensity of a solar ray to half its original value, then

$$\frac{I}{I_0} = \frac{1}{2} = e^{-\left(\frac{\mu}{\varrho}\right)_s 5800 \varrho_0}. \quad (11)$$

This gives

$$\left(\frac{\mu}{\varrho}\right)_s = \frac{\log 2}{\log e 5800 \varrho_0} = 0.093 \text{ cm}^2/\text{g}.$$

This absorption coefficient corresponds to a wavelength of about 0.04 Å. It is, however, not likely that such hard X-rays are emitted from the sun. The great intensity of the yellow line in the twilight luminescence involves that the effective solar radiation ought to be fairly strong. X-rays with a wavelength 0.04 Å, which falls vertically into the atmosphere

would produce an ionization maximum far below 55 km.

If such an ionization layer existed, it might be detected by investigations on the absorption and reflection of electric waves in ionized atmospheric layers.

§ 10. The Origin of the Sodium in the Upper Atmosphere.

The sodium atoms which emit the yellow line observed in the twilight spectrum, are to be located in an atmospheric layer between 85 and 115 km. Temperature measurements by means of the auroral bands show that the temperature within this region is about -40°C . At this temperature no sodium compound would give noticeable quantities of sodium atoms due to thermal agitation. If the luminescence is excited by ultra violet light, we have either to assume sodium to be present in a compound, which is dissociated through the action of ultra violet light, or the sodium in these regions must partly exist in the form of free atoms. It would be of interest to make experiments with the object of finding out whether and under what conditions the yellow *D*-line may be excited, by exposing various sodium compounds to ultra violet light of the sort which should be effective in producing the yellow line in the twilight luminescence. The sodium present at these great altitudes can hardly have a terrestrial origin.

To explain the emission of the yellow line in the night sky spectrum at an altitude of about 130 km, Cabannes, Dufay, and Gauzit (35) assume that the sodium originates from meteorites which contain traces of sodium and, as they usually evaporate in the higher strata of the atmosphere a kind of meteoric dust containing sodium may be spread out in the atmosphere.

This meteoric dust, however, will probably fall fairly rapidly and it is very questionable whether such dust may be excited to luminescence by the action of ultra violet light. I therefore think we have to consider the possibility that atomic sodium may enter into the atmosphere.

Some auroral spectrograms recently obtained at Oslo by one of us (43, 44) showed two enhanced lines which within the limit of error coincided with the two strongest lines of the Balmer series of hydrogen (H_{α} and H_{β}). As these lines are usually absent in the auroral spectrum, the observations indicate that every now and then hydrogen showers enter into the atmosphere. These showers are probably due to a kind of hydrogen radiation from the sun. It would therefore seem legitimate to assume that similar showers of sodium atoms — coming from the sun — might enter into the earth's atmosphere.

Some years ago one of us (19) proposed an explanation of the luminous night clouds according to which they were due to hydrogen occasionally coming in from space. The hydrogen atoms then combined with oxygen probably in the form of atoms — and at a height of about 80 km, and with the presence of suitable condensation nuclei the water vapour thus formed might condense to droplets and form the thin clouds which are seen when illuminated by the sun.

As stated by one of us¹ the sodium atoms might combine with oxygen to form very effective nuclei for the condensation of water vapour. This would mean that the particles forming the luminous night clouds consist of a concentrated aqueous solution of sodium hydroxyde.

¹ Dealt with in a paper read by Vegard in the Norwegian Academy of Science on January 19th, 1939.

LIST OF PAPERS

1. L. VEGARD: Geofys. Publ. IX, No. 11, 1932.
2. L. VEGARD: Terr. Magn. 37, 389, 1932.
3. L. VEGARD and E. TØNSBERG: Geof. Publ. XI, No. 2, 1935.
4. L. VEGARD and E. TØNSBERG: Geof. Publ. XII, No. 3, 1938.
5. L. VEGARD: Phil. Mag. 7, 24, 588, 1937.
6. L. VEGARD: Det Norske Vid.-Akad. Oslo, Avh. I, No. 12, 1935.
7. L. VEGARD and K. G. DØRUM: Det Norske Vid.-Akad. Oslo, Avh. I, No. 1, 1936.
8. L. VEGARD: Geofys. Publ. XII, No. 8, 1938.
9. L. VEGARD: Ergebnisse d. exakt. Naturwiss. XVII, 229, 1938.
10. L. VEGARD and E. TØNSBERG: Z.s. f. Phys. 88, 709, 1934, 94, 413, 1935.
11. R. BERNARD: C. R. 206, 448, and 928, 1938, Nature 141, 788, and 142, 164, 1938.
12. R. BERNARD: Z.s. f. Phys. 110, 291, 1938.
13. J. CABANNES and J. DUFAY: C. R. 206, 221, 1938.
14. J. CABANNES, J. DUFAY, and J. GAUZIT: C. R. 206, 1525, 1938, Nature 141, 1054, 1938. The Astroph. Journ. 88, 164, 1938.
15. L. VEGARD and E. TØNSBERG: Geof. Publ. XI, No. 16, 1937.
16. L. VEGARD and E. TØNSBERG: Nature 137, 778, 1936.
17. L. VEGARD: Chra. Vid.-Selsk. Skr. Kl. I, No. 13, 1916.
18. L. VEGARD: Jahrb. d. Radioakt. u. Elektr. 14, 1917.
19. L. VEGARD: Geof. Publ. X, No. 4, 1933.
20. L. VEGARD: Transact. of the Amer. Geoph. Union 1935.
21. R. SEELIGER: Phys. Zs. 16, 55, 1915.
22. R. BERNARD: C. R. 207, 488, 1935.
23. B. RYPDAL and L. VEGARD: Geof. Publ. XII, No. 12, 1939.
24. L. VEGARD: Nature 141, 200, 1938.
25. L. VEGARD: Geof. Publ. XII, No. 5, 1938.
26. L. VEGARD: Det Norske Vid.-Akad. Oslo, Avh. I, No. 2, 1926, Nature, 117, 356, 1926.
27. L. VEGARD: Nature, 138, 930, 1936.
28. L. VEGARD: Z.s. f. Phys. 106, 108, 1937.
29. L. VEGARD: Gerlands Beiträge zur Geoph. 48, 1, 1936.
30. R. BERNARD: C. R. 208, 824, 1939.
31. V. M. SLIPHER: Publ. A. S. P. 41, 263, 1929.
32. J. DUFAY: C. R. 194, 1897, 1932.
33. L. A. SOMMER: Z.s. f. Phys. 77, 374, 1935.
34. B. W. CURRIE and H. W. EDWARDS: Terr. Magn. 41, 265, 1936.
35. J. CABANNES, J. DUFAY, and J. GAUZIT: C. R. 206, 1525, 1938.
36. L. VEGARD and L. HARANG: Geof. Publ. XI, No. 1, 1934.
37. L. VEGARD and L. HARANG: Geof. Publ. XI, No. 15, 1936.
38. R. BERNARD: The Astrophys. Journ. 89, 133, 1939.
39. G. DÉJARDIN et R. BERNARD: C. R. 207, 81, 1938.
40. P. M. DIFFIEUX: Bull. de la Soc. sci. de Bretagne XV, 7, 1938.
41. GARRIGUE: C. R. 205, 491, 1937.
42. J. CABANNES: J. de phys. 5, 601, 1934.
43. L. VEGARD: Nature 144, 1089, Dec. 1939.
44. L. VEGARD: Det Norske Vid.-Akad. Oslo, Avh. I No. 8, 1939.

Printed October 7th, 1940

A. W. BRØGGERS BOKTRYKKERI A/S

Explanation to Plate I.

Spectrograms taken with large glass spectrograph (A) on Ilford double X-press plates.

Spectrogr. 1. Exposure from $29/11$ to $11/12$, 1937.

» 2. » » $18/1$ » $9/3$, 1938.

» 3. » » $9/3$ » $30/4$, 1938.

» 4. » » $23/2$ » $24/3$, 1939.

At the bottom of No. 4 is a continuous spectrum from a standard lamp.

Explanation to Plate II.

Spectrograms Nos. 1—3 are taken with large quartz spectrograph (Q) on Ilford double X-press plates.

No. 1. Exposure from $29/11$ to $11/12$, 1937.

» 2. » » $19/1$ » $28/1$, 1938.

» 3. » » $7/3$ » $9/3$, 1938.

Nos. 4 and 5 contain spectrograms from two photographic plates (Ilf. hypersens. pan.) taken with one of the small glass spectrographs (α).

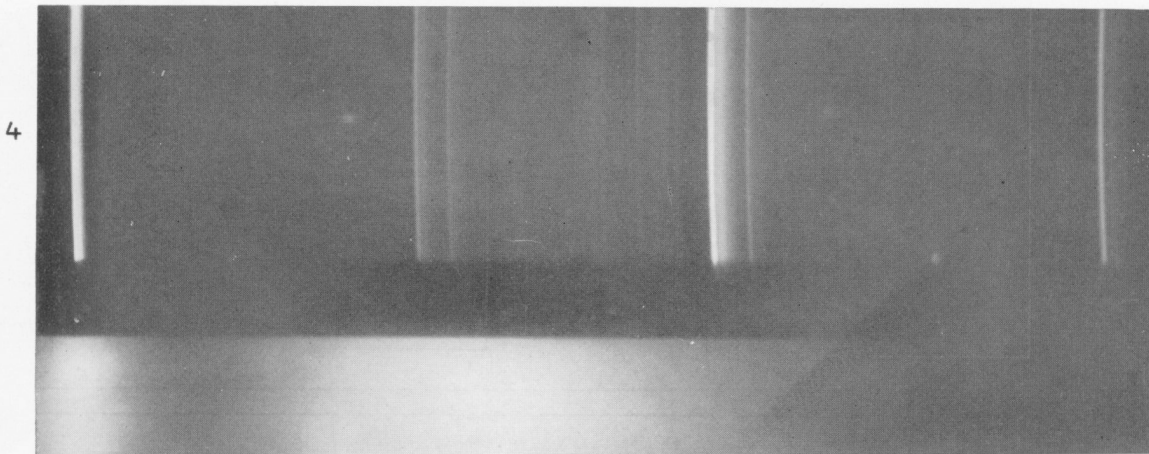
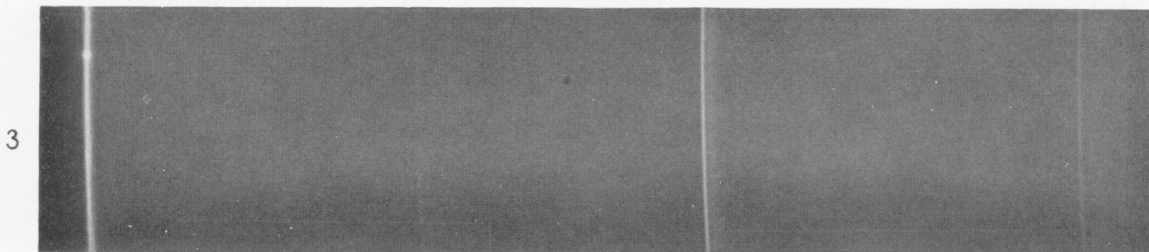
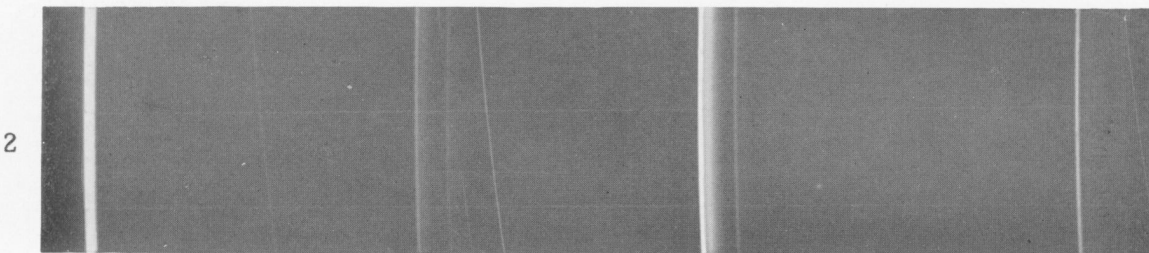
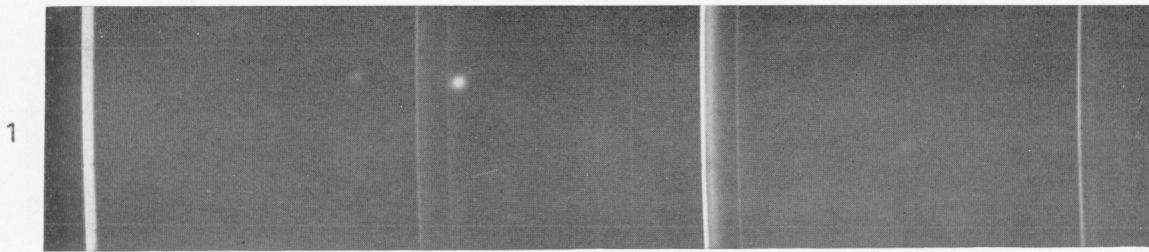
Specification of spectra from small spectrographs (Nos. 4 and 5, Pl. II).

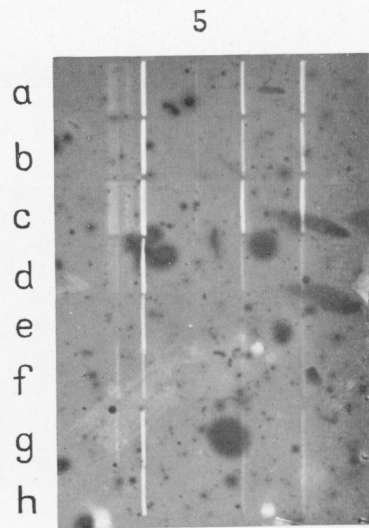
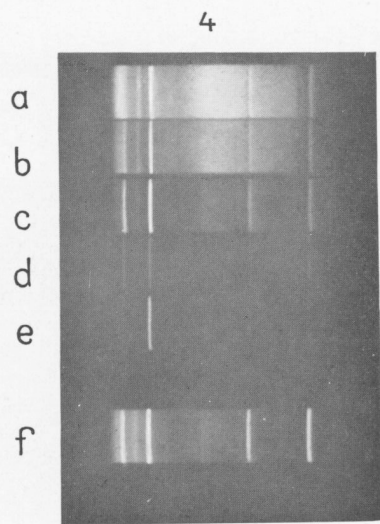
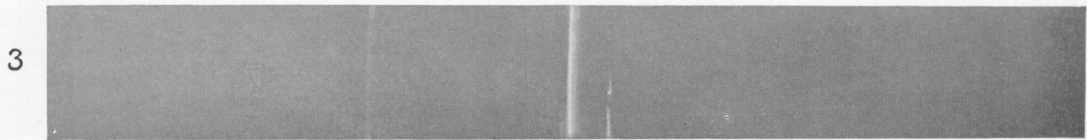
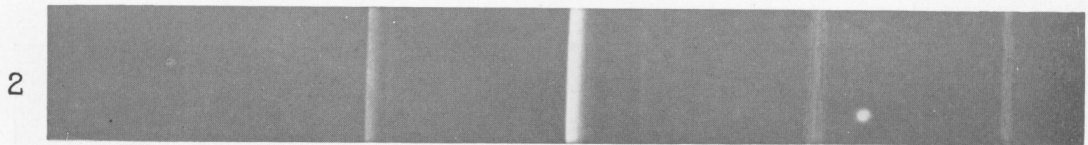
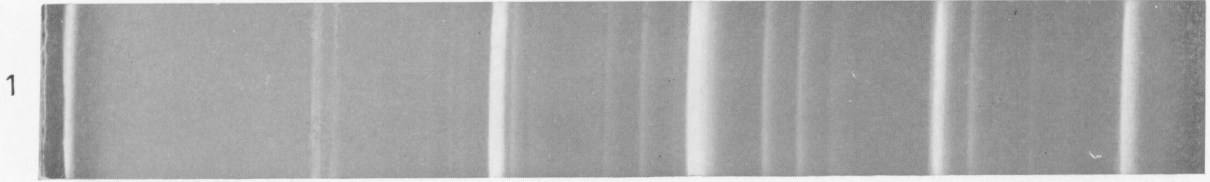
Spectr. No.	Date	Time of exposure	Auroral form
4 a	$1/12$ 1937	15 ¹² —15 ²⁶	H.A. sunlit
» b	» »	15 ¹⁸ —15 ⁴³	» »
» c	» »	15 ⁵⁴ —16 ¹⁸	A + D »
» d	» »	16 ²⁰ —16 ⁴⁵	R. U. limit.
» e	» »	18 ¹² —18 ²⁷	H.A.
» f	$3/12$ »	19 ⁰⁰ —24 ⁰⁰	Night sky + aurora
5 a	$7/12$ »	18 ⁰⁵ —18 ⁰⁸	H.A. + red lower border
» b	» »	18 ¹¹ —18 ²⁵	» » » » U. limit.
» c	» »	21 ²⁵ —21 ³⁰	» » » » L. limit.
» d	» »	21 ³⁵ —21 ⁴⁵	H.B. normal type
» e	» »	22 ⁰⁰ —22 ³⁰	H.A.
» f	$8/12$ »	15 ³⁵ —15 ⁵⁵	R. sunlit (L. limit)
» g	» »	16 ⁰⁰ —16 ¹⁵	R. » »
» h	» »	16 ²⁰ —16 ⁴⁵	H.B. normal

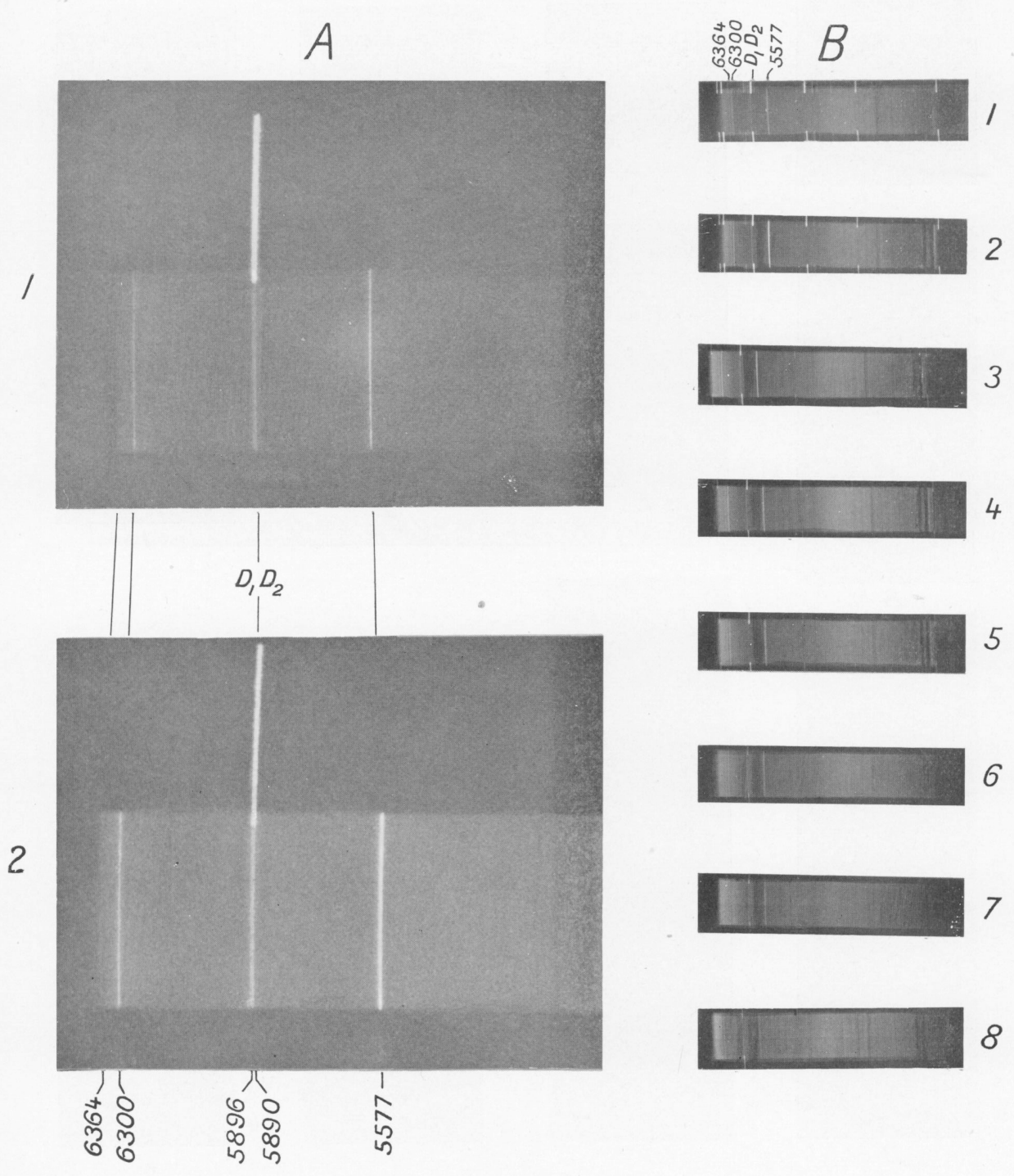
Explanation to Plate III.

Twilight spectra.

Spectrograph	Spectr. No.	Date	Exposure
A	1	$4-10/12$ 1939	8 evenings
»	2	{ $24-30/12$ 1939 $3-6/1$ and $17-22/1$ 1940 }	12 evenings
B	1	$23/2$ 1939	19 ²⁵ —20 ³⁰
»	2	$24/3$ 1939	19 ²⁸ —20 ⁴⁵
»	3	$25/3$ and $26/3$ 1939	19 ²⁵ —20 ³⁵
»	4	$27/3$ 1939	19 ³⁰ —20 ⁴⁰
»	5	$28/3$ 1939	19 ³³ —20 ⁴⁵
»	6	$2-5/4$ 1939	19 ⁴⁰ —20 ⁵⁰
»	7	$14/3$ 1939	20 ⁰⁰ —21 ¹⁰
»	8	$20-21/4$ 1939	20 ⁰⁵ —21 ¹⁰
			20 ¹⁰ —21 ²⁰
			20 ³⁰ —23 ⁵⁰
			22 ⁵⁰ —23 ⁵⁰
			22 ²⁰ —22 ³⁰







Explanation to Plate IV.

Twilight spectra.

Plate	Date	Spectr. No.	Height	Direction	Exposure	Plate	Date	Spectr. No.	Height	Direction	Exposure
A	13/1—1936	1	25°	SSW	16 ⁵⁰ —16 ⁵⁸	G	28/2—1939	10	90°		18 ⁰¹ —18 ¹¹
		2	»	»	17 ⁰⁵ —17 ²⁰			11	60°	W	18 ¹¹ —18 ²¹
		3	5—10?	»	17 ³⁰ —17 ³⁶			12	20°	»	18 ²¹ —18 ³¹
B	26/4—1939	1	90°		21 ⁰⁰ —21 ¹⁵	H	8/3—1939	1	90°		18 ³¹ —18 ⁴³
		2	»	»	21 ¹⁵ —21 ³⁵			2	»	»	18 ⁴³ —18 ⁵⁵
		3	13°	W	21 ³⁷ —21 ⁴⁶			3	»	»	18 ⁵⁵ —19 ¹¹
		4	»	»	21 ⁴⁶ —22 ⁰⁸			4	»	»	
		5	»	»	22 ⁰⁸ —22 ⁵²			5	»	»	
C	28/4—1939	1	90°		20 ⁵⁴ —21 ⁰²	I	24/3—1939	1	90°		18 ¹² —18 ¹³
		2	»	»	21 ⁰² —21 ¹²			2	»	»	18 ¹³ —18 ¹⁵
		3	»	»	21 ¹² —21 ²²			3	»	»	18 ¹⁵ —18 ²¹
		4	»	»	21 ²² —21 ³⁷			4	»	»	18 ²¹ —18 ²⁹
D	28/4—1939	1	10°	W	21 ⁴² —21 ⁵³	K	25/3—1939	1	90°		19 ¹⁴ —19 ¹⁵
		2	»	»	21 ⁵³ —22 ¹²			2	»	»	19 ¹⁵ —19 ¹⁶
		3	»	»	22 ¹² —22 ⁴²			3	»	»	19 ¹⁶ —19 ¹⁸
		4	»	»	22 ⁴² —23 ¹²			4	»	»	19 ¹⁸ —19 ²²
E	5/5—1939	1	12°	SE	20 ⁵³ —20 ⁵⁴	K	25/3—1939	5	»	»	19 ²² —19 ²⁸
		2	»	»	20 ⁵⁶ —21 ²³			6	»	»	19 ²⁸ —19 ³⁴
		3	»	»	21 ⁰² —21 ⁰⁶			7	»	»	19 ³⁴ —19 ⁴⁰
		4	»	»	21 ⁰⁶ —21 ¹¹			8	»	»	19 ⁴⁰ —19 ⁵⁰
		5	»	»	21 ¹¹ —21 ¹⁸			9	10°	W	19 ⁵⁰ —19 ⁵⁴
		6	90°		21 ¹⁸ —21 ²⁵			10	»	»	19 ⁵⁴ —20 ⁰⁰
		7	»	»	21 ²⁵ —21 ⁴⁰			11	»	»	20 ⁰⁰ —20 ¹⁰
		8	»	»	21 ⁴⁰ —22 ⁰⁰			12	»	»	20 ¹⁰ —20 ²⁰
F	5/5—1939	1	13°	W	22 ⁰⁰ —22 ⁰⁴	K	25/3—1939	13	»	»	20 ²⁰ —20 ³⁰
		2	»	»	22 ⁰⁴ —22 ¹⁰			14	»	»	20 ³⁰ —20 ⁴⁰
		3	»	»	22 ¹⁰ —22 ²⁰			15	»	»	20 ⁴⁰ —20 ⁵⁰
		4	»	»	22 ²⁰ —22 ³⁵			16	»	»	20 ⁵⁰ —21 ⁰⁰
		5	»	»	22 ³⁵ —23 ⁰⁰			1	90°		19 ¹⁷ —19 ¹⁹
		6	»	»	23 ⁰⁰ —23 ³⁰			2	»	»	19 ¹⁹ —19 ²²
		7	»	»	23 ³⁰ —24 ⁰⁰			3	»	»	19 ²² —19 ²⁶
		8	»	»	00 ⁰⁰ —00 ³⁰			4	»	»	19 ²⁶ —19 ³²
		9	»	»	00 ³⁰ —01 ⁰⁰			5	»	»	19 ³² —19 ³⁸
G	28/2—1939	1	90°		17 ²⁵ —17 ^{25,5}	K	25/3—1939	6	»	»	19 ³⁸ —19 ⁴⁴
		2	»	»	17 ²⁸ —17 ^{28,8}			7	»	»	19 ⁴⁴ —19 ⁵⁴
		3	»	»	17 ³¹ —17 ³²			8	10°	W	19 ⁵⁴ —19 ⁵⁸
		4	»	»	17 ³⁴ —17 ³⁵			9	»	»	19 ⁵⁸ —20 ⁰⁴
		5	»	»	17 ³⁷ —17 ³⁹			10	»	»	20 ⁰⁴ —20 ¹⁰
		6	»	»	17 ⁴⁰ —17 ⁴³			11	»	»	20 ¹⁰ —20 ¹⁶
		7	»	»	17 ⁴³ —17 ⁴⁷			12	»	»	20 ¹⁶ —20 ²²
		8	»	»	17 ⁴⁷ —17 ⁵³			13	»	»	20 ²² —20 ²⁸
		9	»	»	17 ⁵³ —18 ⁰¹			14	»	»	20 ²⁸ —20 ³⁴

