VARIATIONS OF THE INTENSITY DISTRIBUTION WITHIN THE AURORAL SPECTRUM

OBSERVATIONS FROM THE AURORAL OBSERVATORY, TROMSØ

BY L. VEGARD AND E. TØNSBERG

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§ 1. The typical auroral spectrum.

Before dealing with the variations within the auroral spectrum, we shall give a brief summary of the auroral lines and bands and of their interpretation. The results of analysis of the auroral spectrum carried out in this country will be found in a number of papers previously published (1, 3, 4, 12, 13, 18, 19, 20). For the sake of convenience the results have been collected and summarized in Table I.

The first column gives the wave-length values of the 90 lines and bands observed. The intensity numbers given in the second column are found by means of photometric measurements and represent a kind of average or typical intensity distribution within the auroral spectrum.

The interpretation of the bands is indicated in the third column 1. P. G., 2. P. G. and N.G. means the 1st and 2nd positive and the negative group of nitrogen. The numbers added to these symbols indicate the vibrational quant numbers of the upper and lower level, corresponding to the transition resulting in the band in question.

In the case of the bands of the 1st positive group several vibrational transitions ($n' - n''$) may give nearly coinciding bands. *"CB"* indicates bands coinciding with bands of a series called *C*, which one of us observed in the luminescence from solid nitrogen.

$\varepsilon(n', n'')$ are bands of the ε-system discovered by Vegard in the luminescence from solid nitrogen and interpreted by him as being due to the transitions between the electronic levels $A\,(^3\Sigma)$ and $X\,(^1\Sigma)$ of the nitrogen molecule. b' is the series $\varepsilon\,(1, n'')$.

It appears from Table I that the auroral spectrum is essentially a band spectrum mainly composed of nitrogen bands, belonging to the 1st and 2nd positive and the negative group; some weak bands belong to the ε-system (transition $A - X$) and perhaps some faint bands of the C-series.

In addition to these nitrogen bands, the auroral spectrum contains the strong green line 5577 and the red triplet with the strongest component 6300. Interferometer measurements of these lines (19, 20) have proved that they originate from the normal oxygen atom, as first suggested by MCLENNAN.

In order to explain the prominence of these *OI* lines due to the transitions ($^1S_0 - {}^1D_2$) and ($^1D_2 - {}^3P_{012}$) and the probable absence of other oxygen lines or bands, Vegard (13) assumes that the oxygen atom is brought into the $^1S_0$ and the $^1D_2$ states by collision of the second kind between oxygen and nitrogen in some activated state.

The following reactions were considered as very probable:

$$N_{\text{act}} + O_2 = N_2 + OI + OI\,(^1S_0) \;\ldots\ldots\; (1)$$

and:

$$N_2{}^A + O_3 = N_2 + O_2 + OI\,(^1D_2) \;\ldots\ldots\; (2)$$

The first of these processes (1) means that active nitrogen acting on ordinary oxygen molecules result in the formation of a normal nitrogen molecule and dissociation of the oxygen molecule into one normal *O*-atom and one left in the $^1S_0$-state.

In this process there is very nearly balance of energy, so the probability of its occurrence is enhanced by resonance. The second process (1) means that nitrogen molecules in the metastable $A\,(^3\Sigma)$ state by clolision with an ozone-molecule, produce a normal O_2-molecule and an excited oxygen atom.

Assuming that after collision the oxygen atom is left in the $^1D_2$-state, VEGARD explains the fact

Table I. Auroral spectrum.

λ	Intensity	Interpretation
8132		1. P. G. 5—4, 6—5
8035		
7906	47	» 7—6
7867		
7734		» 8—7, (2—0)
7594		» 9—8, (3—1)
7479		» (10—9), 4—2
7368		» (11—10), 5—3
7264		» 6—4
7068		» 8—6
6861		» 10—8
6784		
6768		» 11—9 (4—1)
6753		
6696		» 5—2
6682		
6669		» 12—10
6619		
6605	40	» 6—3
6592		» 13—11
6543		
6526		» 7—4
6512		» 14—12
6469		8—5
6454		
6441		» (15—13)
6398		» 15—13 OI ($^1D_2$—$^3P_0$)
6363		» (9—6) OI ($^1D_2$—$^3P_1$)
6300,3	28	» (10—7) OI ($^1D_2$—$^3P_2$)
6185		» 12—9
6129		» 5—1
6108		» 13—10
6068		» 6—2
6058		» 6—2
6011.1		» 7—3
6001		» 15—12
5990,8	15	» 15—12
5966,4		» 8—4
5891		» 9—5
5867	13	» 17—14
5833		» 10—6
5751		12—8
5577, 3445	100	OI ($^1S_0$—$^1S_2$)
		15—10
5238	6,0	16—11 N_2B, ε (5—18)
5002		N (5002,7)- Nebulium
4858		ε (2—15)
4780		N, O II (4779), CB
4708,7	7,8	N. G. 0—2
4652,2	4,6	» 1—3
4596,1	3,4	» 2—4
4566,0		
4550,8	2,0	» 3—5
4535	1,6	ε (3—15)
4507	1,2	N ε (4—17)
4484	1,6	N. G. 5—7 (CB)
4437	1,6	ε (2—14)
4424	3,0	
4375,6	1,6	ε (5—16)
4345,6	3,0	2 PG 0—4
4319,5	1,6	b′ [ε (1—13)]
4277,6P	24,4	NG 0—1
4267,6R		
4236	5,9	» 1—2
4218	3,0	CB ε (0—12)
4200,0	2,0	NG, 2—3
4176,2	1,4	ε (3—14)
4142,6	1,4	2 PG 3—7
4119,7	1,6	N
4092,0	1,6	ε (5—15)
4076,0		ε (2—13)
4058	3,4	2 PG 0—3
4048,5		
3997,7	3,7	» 1—4
3981	1,0	b′ [ε (1—12)]
3942,8	2,2	2. PG 2—5
3914,4P	47,4	NG 0—0
3903,5R		
3884,5	2,2	» 1—1
3872,0	1,0	ε (3—13)
3805,4P	4.9	2. P G 0—2
3801,0R		
3769	1,0	ε (2—12)
3755.2	4,2	2 PG 1—3
3728,6	1,0	ε (5—14)
3711,1	2,4	2 PG 2—4
3708,0		
3685,3	1,6	b′ [ε (1—11)]
3671,8		2 P. G. (3—5)
3603,0	1,0	ε (0—10) ε (3—12)
3583	1,6	N. G. 1—0
3577,6P	9,8	2 P. G. 0—1
3570,0R		
3563,5	1,6	N. G. 2—1
3536,8P	4,9	2 P. G. 1—2
3531,5R		
3503,2	2,2	2—3
3484	1,0	7—8
3468,7	3,0	3—4
3429,0	2,0	b′ [ε (1—10)]
3371,3	9,0	2 P. G. 0—0
3339,3	1,2	» 1—1
3285,3	1,8	» 3—3
3202,7	2,2	b′ [ε (1—9)]
3192,4		
3168,7		2 P. G. (9—7)
3159,3P	5,8	» 1—0
3135,2R		
3135.7	3.6	» 2—1
3114,0		» 3—2

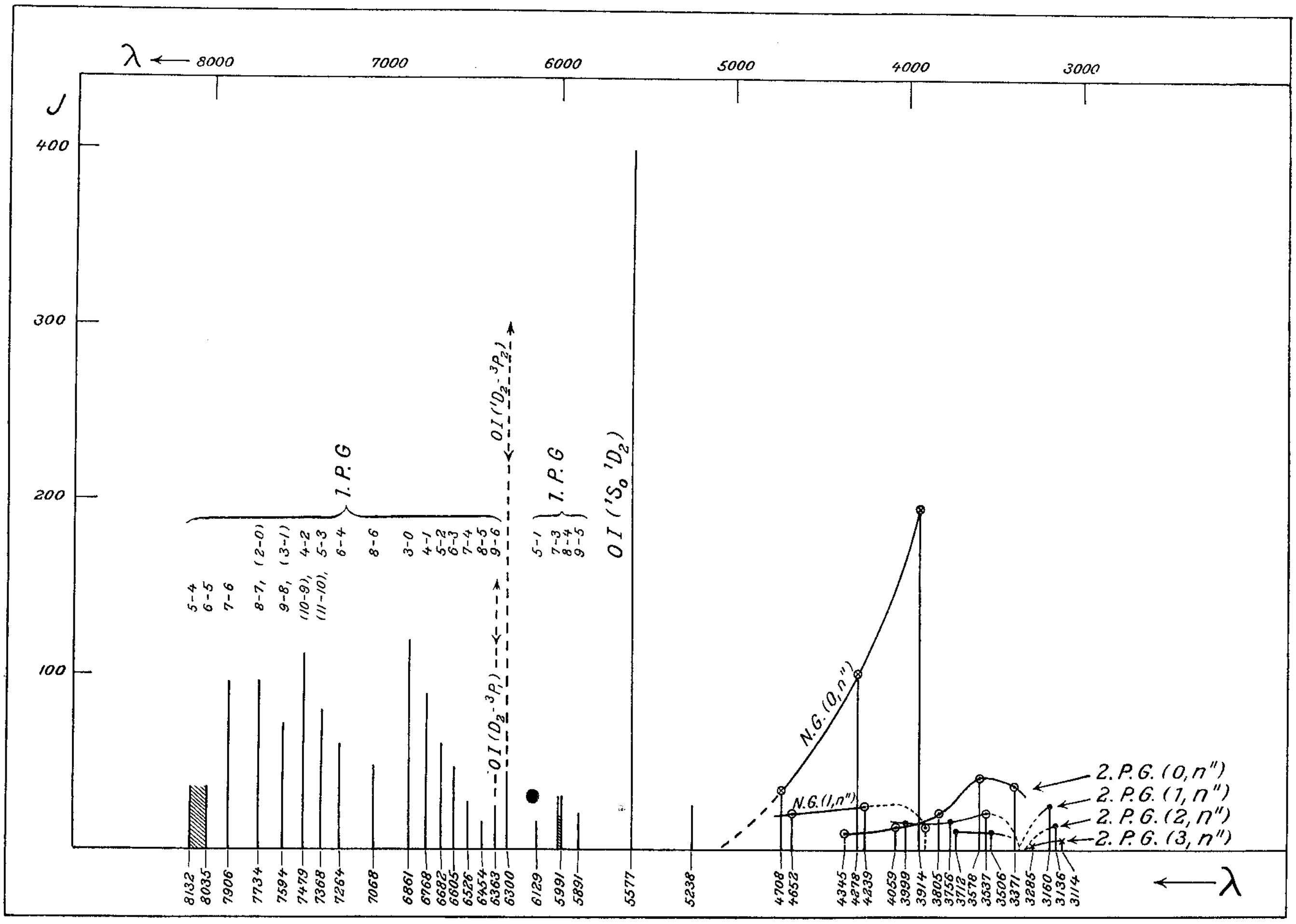


Fig. 1.

that under certain conditions the red triplet is enormously enhanced relative to the green line.

In addition to the nitrogen bands and the oxygen lines mentioned, a few faint bands or lines were observed, the origin of which is not definitely settled. Certain possible interpretations are indicated in Table I.

The principal bands and lines occurring in the auroral spectrum, as well as an indication of the typical intensity distribution, are illustrated in Fig. 1.

In connection with our studies of intensity changes, it is of interest to notice that all these bands and lines originate from only a few energy states of the nitrogen molecule and the oxygen atom. These states and the transitions corresponding to the observed band-systems and lines are illustrated in Fig. 2 for the N_2-molecule (to the left) and the *OI* atom (to the right).

§ 2. Spectral variations to be studied.

Having thus obtained a fairly complete interpretation of the auroral spectrum, we are able to draw up the main problems with which we have to deal by the study of the variations of intensity distribution within the spectrum. The problems naturally fall into the following groups:

1. Variations of intensity distribution of vibrational bands belonging to the same band system.
2. The intensity distribution within a certain rotational branch and the possible variation of the intensity distribution of rotational components. This is a question which is intimately connected with the determination of the temperature of the auroral region by means of auroral bands. This question has been dealt with in previous papers (12, 21) and will be treated in papers to be published separately.

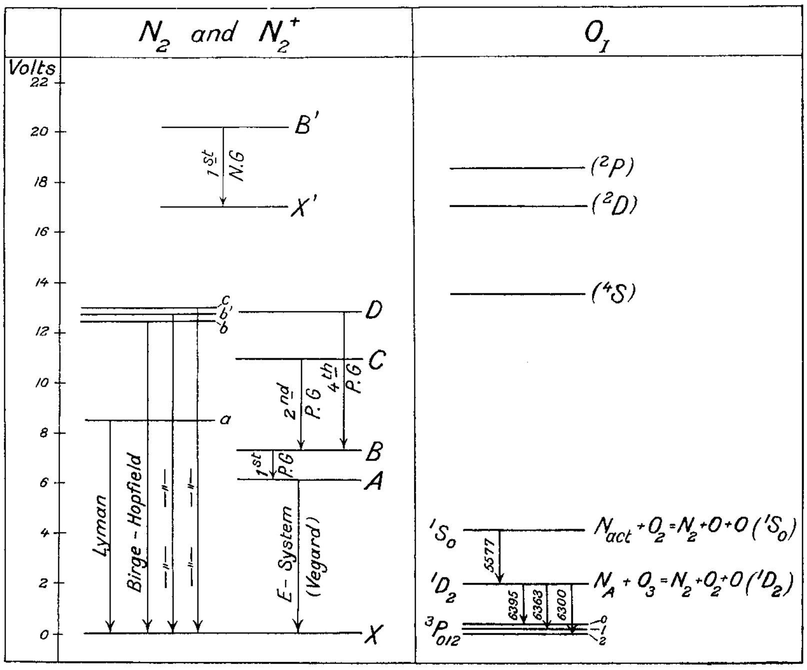


Fig. 2.

3. Variation in the relative intensity of the nitrogen band groups. This is equivalent to the determination of the relative occurrence of the electronic transitions (A—X), (B—A), (C—B) and (B'—X'). (Cfr. Fig. 2). The last one belongs to the positive nitrogen ion and the others to the neutral N_2-molecule.
4. Variations of the intensity of red triplet *OI* ($^1D_2$—$^3P_{012}$) as compared with that of the green line *OI* ($^1S_0$—$^1D_2$).
5. Variation of the intensity of the green line 5577 relative to that of any of the nitrogen bands.

The possible variations of intensity distribution may either be due to changes in composition and state of the atmospheric matter which form the source of light emission, or to changes in the excitation process, or to simultaneous changes in both these conditions.

But from the outset these conditions are unknown to us, and it lies outside our power to influence them. On the contrary, the problem before us will be: from the possible variations of intensity distribution to find out something regarding the excitation processes and the changes taking place with regard to the composition and state of the upper atmosphere.

The conditions mentioned which determine the intensity distribution, may be expected to vary with altitude, with auroral type, with the position of the sun and with the solar activity.

Thus we may expect to find certain diurnal variations of the intensity distribution, and it will be of particular interest to compare typical night spectra with spectra obtained from an atmosphere exposed to sunlight. We may further expect that spectra obtained from aurorae accompanied with very strong magnetic disturbances, may show intensity distributions different from that of spectra from aurorae which are observed by weak perturbations.

It will also be a matter of importance to find out whether certain spectral features may show changes which follow the 11-years period of solar activity.

§ 3. Short account of spectral changes previously discovered and described.

I. *Altitude effects.*

a) Comparing spectra corresponding to the lower border with spectra obtained from places near the upper limit of auroral streamers, it was found by one of us in 1923 (2, 3, 4, 5, 6), that the intensity of the green line relative to that of the negative nitrogen bands, diminished considerably with increase of altitude.

This important fact showed that nitrogen was a predominant component of the atmosphere to its extreme limit, and led to the first more definite determination of the formation, enormous extension and structure of the Heaviside-Kenelly layer (1, 4, 10, 11, 12).

b) The intensity of certain lines (or bands) 4566, 4444 and a band 4353 probably belonging to the 2nd positive group of nitrogen and the ε-system, increased upwards as compared with that of the negative nitrogen bands (12).

c) During an auroral display occurring 16. Oct. 1936 one of us observed at Oslo a red aurora of type *A*: which was red towards the upper limit, while the lower part had the ordinary greenish colour.

A spectroscopic examination showed that this was due to an enormous enhancement with altitude of the red oxygen triplet *OI* ($^1D_2$—$^3P_{013}$) relative to the green line *OI* (^1S—$^1D_2$) (17).

Already in 1926 one of us had found that one type of red aurora (type *A*) owed its redness to the enhancement of the red line 6300 relative to the strong green auroral line (7).

d) In certain fairly rare cases, we observe aurorae (usually in the form of drapery-shaped arcs) which are intensively red at the lower border, while the upper part has the ordinary greenish colour.

These red aurorae of «type *B*» give evidence of a very pronounced altitude effect, consisting in the relative enhancement of certain red lines or bands as we pass downwards towards the lower limit of the streamers. Already in 1917 (13, 22, 23) one of us suggested that the red colour was due to enhancement of certain red bands of nitrogen (the 1st positive group). As such an enhancement was known to occur by increase of pressure and diminution of the velocity of the cathode rays, the opinion was held that the bands with red lower limits should reach down to unusually low altitudes.

The height of red aurorae of type *B* (with red bottom edge) was measured by HARANG and BAUER in 1932 and they actually found that the bottom edge reached down to the exceptionally low height of about 70 km.

During the last winter season, we have obtained spectrograms with red lower border, the results of which will be dealt with in the present paper and which show that the red aurorae of type *B* owe their redness to the enhancement of red bands of the first positive group of nitrogen.

II. *Type effects.*

When we use small spectrographs of high light power, we may obtain spectrograms with exposures of say 15 minutes to one hour, and it is possible to obtain spectrograms of a definite and fairly well defined auroral type.

The spectrograms obtained at Tromsø during the years 1922—26 already indicated that the spectra of the various auroral types might differ considerably (12).

Some spectrograms taken at the new observatory during the first years of its activity also gave evidence of great variations of the spectrum with type of aurorae (13). Certain diffuse forms showed a fairly large number of weak bands or lines in the blue part which are not found with spectra from the more distinct auroral forms (e. g. arcs and draperies). It was also found that the intensity of the green line (5577) compared with that of the negative bands, was smaller for diffuse, than for the more distinct auroral forms.

III. *Changes in relative intensity of the red and green oxygen line.*

The physical conditions which determine the relative intensity of the green line and the red triplet, and the possible causes of variations, have been treated in previous papers (7, 12, 13, 14, 16, 29); but we shall also give here a somewhat more complete and systematic treatment of these questions.

When an oxygen atom has performed a transition from the metastable state $^1S_0$ to the state $^1D_2$ under emission of a photon, belonging to the green line, a further jump of the atom to the normal $^3P_{013}$ state, results in a quantum belonging to one of the components of the red triplet.

Let us first assume that the process of excitation is of such a nature that the $^1D_2$-state is only reached by jumps from the higher $^1S_0$-state.

If the transitions (${}^1D_2$—${}^3P_{013}$) were «allowed» ones, they would follow the first one (${}^1S_0$—${}^1D_2$) instantaneously, and the number of quanta belonging to the green line would be equal to the total number of quanta of the red triplet emitted during the same interval of time.

Let the intensity of the green line and the strongest component of the red triplet (6300) be I_a and I_b respectively, then:

$$I_a = n_1 h\nu_a \;\ldots\ldots\ldots\ldots\ldots \quad (3)$$

$$I_b = n_2'' h\nu_b \;\ldots\ldots\ldots\ldots\ldots \quad (4)$$

n_1 and n_2'' are the number of quanta emitted in unit time from the source for the two lines, ν_a and ν_b the corresponding frequencies.

Let the number of quanta of the two other red components be n'_2 and n_2^0: Then, under the conditions here considered, we should have:

$$n_1 = n_2'' + n_2' + n_2^0$$

or putting:

$$\frac{n_2'}{n_2''} = \alpha \quad \text{and} \quad \frac{n_2^0}{n_2''} = \beta$$

$$n_1 = n_2''\,(1 + \alpha + \beta) \;\ldots\ldots\ldots\ldots \quad (5)$$

From equations (3), (4) and (5) we find:

$$\frac{I_b}{I_a} = \frac{\lambda_a}{\lambda_b\,(1 + \alpha + \beta)} \;\ldots\ldots\ldots\ldots \quad (6a)$$

As α and β give expression to the relative intensities of the components of the same triplet, they may be considered as constants. Spectrographic observations of the auroral spectrum (13, 18, 20) have indicated that α should be less tkan 0,6 and β not greater than 0,3. These values of α and β inserted in equation (6) give:

$$\left(\frac{I_b}{I_a}\right)_{\max} = 0{,}5 \;\ldots\ldots\ldots\ldots\ldots \quad (6b)$$

Thus if the ${}^1D_2$-state only resulted from the transition (${}^1S_0$ — ${}^1D_2$) and if all atoms brought into the ${}^1D_2$-state performed the transition (${}^1D_2$—${}^3P_{012}$) under emission of the red triplet, then the strongest red component (6300) should never have more than about half the intensity of the green auroral line.

As already mentioned, the intensity relation I_b/I_a is very variable. Usually it is much smaller than the «theoretical value» 0,5; it may be 0,1 or even smaller. Quantitative measurements from a spectrogram obtained with a large glass spectrograph, giving sufficient dispersion for complete separation of the components of the red triplet gave a value for I_b/I_a of about 0,04.

The small intensity of the red triplet is accounted for by the fact, that the ${}^1D_2$-state is metastable, and that the energy of excitation is lost in collisions of some sort before the transitions occur.

In order that the collisions shall have an essential effect to reduce the relative intensity of the red triplet, the necessary and sufficient condition is that the average time between successive collisions of an oxygen atom, should be so small that it is of the same order of magnitude as the average lifetime of the ${}^1D_2$-state of an atom not exposed to collisions. (Cfr. papers Nos. 17 and 26.)

Consequently, the relative intensity of the red triplet should diminish with increase of pressure.

IV. *Enhancement of the red line with altitude.*

If we follow an auroral ray streamer from the top to its lower limit, the pressure increases considerably as we pass downwards. We should therefore expect the intensity of the red triplet relative to that of the green line to increase upwards in the auroral region. In fact such an effect exists and was first described by one of us in a letter to «Nature» (17). Spectrograms showing the same effect were obtained at Oslo 7./8. Jan. 1937, and were dealt with in a previous paper. (29).

V. *Enhancement of the red triplet in red aurorae of type A.*

As already mentioned, the red aurora of type *A* owes its red colour to the enhancement of the red triplet relative to the green line and relative to the nitrogen bands. In the paper where this discovery was first announced (7), it was stated that the red colour was not restricted to a certain part of the ray, but the deep red colour extended from the bottom to the top of the streamers, which might be of large extent.

We know that the isolated auroral rays — even when they extend to altitudes of 600—800 km. — usually have the greenish-bluish colour, although the density of matter at the upper end must be extremely small. On the other hand, it is a typical feature of the red aurorae of type *A*, that the streamers have the same deep red colour from top to bottom edge.

Now it is beyond doubt that the density or pressure near the *bottom edge* of the long *red* auroral streamers must be greater than the pressure at the extreme upper limit of the longest rays of the *ordinary colour.*

As stated by one of us in previous papers (17, 26), we cannot explain the enhancement of the red line which produces the red aurorae of type *A*, as an effect of pressure due to the disturbing influence of collisions on the metastable $^1D_2$-state.

In order to explain the enhancement of the red line in the case of red aurorae of type *A*, we have to consider two possibilities:

1. Oxygen is exposed to some excitation process which brings an oxygen atom directly to the $^1D_2$-state without the $^1S_0$-state being reached in this process. This possibility has been treated in previous papers and it was suggested that collisions between excited nitrogen and ozone might produce such an effect e. g. in the way give by equation (2).
2. The oxygen atom may be exposed to influences which have the effect of making the $^1D_2$-state less metastable or increasing the probability of the transition ($^1D_2 - {}^3P_{012}$). Such influences might either be due to electric or magnetic fields or to some sort of radiation.

VI. *The enhancement of the red triplet in an atmosphere exposed to sunlight.*

As already stated in a note to «Nature» (16), we found recently that the red *OI* triplet is considerably enhanced when the auroral luminescence is emitted from an atmosphere exposed to sunlight.

The explanation of this effect which first of all might suggest itself, would be to assume that the sun's radiation which falls on oxygen atoms in the $^1D_2$-state induces an increased probability for the transition ($^1D_2 - {}^3P_{012}$). This possibility was mentioned in a paper read by one of us at the Edinbrough Congress of the International Geophysical Union (26); but for various reasons, it was found to be less propable when the effect of sunlight was seen in connection with the enhancements producing the red aurorae of type *A*.

It can also be shown theoretically that the direct influence of sunlight on the probability of the transition ($^1D_2 - {}^3P_{013}$) is by far too small to give any noticeable enhancement of the red line.

We base our theoretical considerations on Einstein's theory of the radiation from a black body. Let the number of oxygen atoms which at a certain moment are in the $^1D_2$-state be *N*, then we have:

$$\left(\frac{dn}{dt}\right)_s = - N A^n_m \quad \ldots\ldots\ldots\ldots \quad (7a)$$

where ($A^n{}_m$) is the factor introduced by Einstein, and which represents the probability of spontaneous transition from an upper state (*n*) to a lower state (*m*).

The number of transitions in unit time which is induced by the sun's radiation, is, according to Einstein:

$$\left(\frac{dn}{dt}\right)_i = N B^n_m \varrho_\nu \quad \ldots\ldots\ldots\ldots \quad (7b)$$

Where (ϱ_ν) is the density of light corresponding to the frequency produced by the transition ($n - m$). In our case the frequency is that of the red line 6300, corresponding to the transition *OI* ($^1D_2 - {}^3P_2$).

Let I_s and I_i be the intensities corresponding to the spontaneous and induced transitions respectively, then:

$$I_i \Big/ I_s = \frac{B^n_m \varrho_\nu}{A^n_m} \quad \ldots\ldots\ldots\ldots\ldots \quad (8)$$

According to Einsteins theory:

$$A^n_m = f B^n_m \quad \ldots\ldots\ldots\ldots\ldots \quad (9a)$$

Further, we have:

$$\varrho_\nu = \frac{f}{e^{\frac{h\nu}{hT_s}} - 1} \left(\frac{r}{2R}\right)^2 \quad \ldots\ldots\ldots\ldots \quad (9b)$$

where $f = \frac{8\pi h\nu^3}{c^3}$, T_s is the surface temperature of the sun, *r* the radius of the sun and *R* the mean distance between sun and earth, $\frac{r}{2R} = \frac{\omega}{4\pi}$, where ($\omega$) is the angular surface of the sun.

Using equations (9a) and (9b), the equation (8) takes the form:

$$\frac{I_i}{I_s} = \frac{1}{e^{\frac{k\nu}{kT_s}} - 1} \left(\frac{r}{2R}\right)^2 \quad \ldots\ldots\ldots\ldots \quad (10)$$

Putting: $\nu = \frac{c}{6 \cdot 310^{-3}} = 4{,}66\ 10^{14}$, $h = 6{,}6\ 10^{-27}$

$k = 1{,}35\ 10^{-16}$, $T_s = 6500°$

$R = 107\ r$ we get:

$$\frac{I_i}{I_s} = 6{,}5\ 10^{-7}$$

The formula (10) does not contain the average lifetime of the upper electronic state. The result is therefore applicable to any line or band appearing in the auroral spectrum. Hence we conclude *that the effect of the sunlight, which falls on the upper atmospheric layers, to increase the probability of the transition between electronic states, is by far too small to produce any noticeable enhancement of the line resulting from the transition or to alter, to any noticeable degree, the intensity distribution within the auroral spectrum.*

An electron colliding with an O-atom in the $^1D_2$-state should according to the theory of KLEIN and ROSSELAND (27), have the effect that the energy of excitation of the atom might be transferred to the electron in the form of increased translatory kinetic energy. Consequently, collisions with electrons like collisions with other atoms and molecules, should have the effect that the metastable state is likely to be disturbed before the forbidden transition and the light emission take place, and thus produce a relative reduction of the intensity of the red line. An effect of electron encounters to increase the probability of transitions from a metastable state to a lower electronic state, is not known to exist.

As regards the possible influence of electric and magnetic fields, we know that strong fields may have the effect of promoting the occurrence of forbidden transitions, but the field intensities and the changes within the auroral region, are hardly sufficiently large to have any marked effect on the lifetime of the metastable $^1D_2$-state.

The magnetic field intensity even in the auroral region is of the order of magnitude of 1 gaus, and the possible electric field intensity hardly exceeds the order of 1 volt-cm.

Summing up the results of our considerations, we may say that the enhancement of the red oxygen triplet, which is found in the case of red aurorae of type A and from an atmosphere exposed to sunlight, must be due to some process of excitation which leaves the oxygen atom in the excited $^1D_2$-state, while this particular process does not transfer to the O-atom sufficient energy to bring it to the $^1S_0$-state.

In a previous paper dealing with the auroral spectrum and its interpretation (13), it was shown that in order to account for the dominating intensity of the green and red oxygen lines in a spectrum dominated by nitrogen bands, and where there is no other oxygen bands or lines to be observed, it was necessary to suppose that the oxygen atom was not brought into the $^2S_0$ or $^1D_2$-states by direct excitation of the primary electric rays, but the two states must result from an indirect excitation process due to the effect of some type of activated nitrogen.

By collisions of the second kind, the energy of activation of nitrogen is transferred to the oxygen atoms.

In the papers referred to it was shown that the energy of active nitrogen available for excitation (according to OKUBO and HAMADA (28) is 9,55 volts) is just sufficient for dissociating the O_2 molecule and for bringing one of its atoms to the $^1S_0$-state in accordance with equation (1).

Similarly activated nitrogen molecules e. g. in the metastable A (or $^3\Sigma$)-state acting on ozone, might result in a dissociation of O_3 into normal oxygen molecules and an O-atom in the $^1D_2$-state (Equation 2).

As the $^1S_0$ and $^1D_2$-states are not reached through direct excitation by the electric rays which primarily cause the luminescence, the great change in the intensity of the red triplet relative to the green line cannot be due to possible variations in the composition of the rays. Further, we saw that the enhancement of the red line cannot be due to an influence of radiation or fields of force to reduce the lifetime of the metastable state.

Therefore the large variations in the intensity relation between the green and red lines, must be due to some change in the composition and state of the atmospheric matter in the auroral region.

It is not excluded that the composition of the atmosphere in the auroral region may change on account of matter which comes from space; but even when we put aside this possibility, we have to consider a number of ways in which the composition and state of the upper atmosphere may vary.

Owing to the action of ultra-violet radiation and electric rays, molecules of nitrogen and oxygen will be dissociated and a certain percentage of these components will at any time exist in the form of free atoms.

If neutral oxygen atoms may be brought into the $^1S_0$ or $^1D_2$-state through collision of the second sort with activated nitrogen, a change of concentration of atomic oxygen might produce changes in the intensity of the green and red lines relative to that of the nitrogen bands and relative to each other.

The analysis of the auroral spectrum indicates, however, that only a fairly small fraction of the predominant gases N_2 and O_2 exist in the atomic state. If the emission of the green and red lines was due to the excitation of the oxygen atoms, we should expect also other oxygen lines to appear with about the same intensity as the green and red ones. As these other lines are absent or extremely weak, we are justified in the conclusion, that the fraction of oxygen existing in the atomic state is small. This holds good at any rate for the region from 80—125 km. above the ground, from which the greater part of the observed luminescence is emitted. We are therefore justified in assuming that the green OI-line and the red OI-triplet is due to collisions of the second kind between some sort of oxygen *molecules* and nitrogen in an active or excited state.

Now it is a remarkable fact that the green line is the strongest in the whole spectrum, and the variations of its intensity relative to that of the nitrogen bands are fairly small. This would suggest that the $^1S_0$-state results from collisions with ordinary oxygen-molecules O_2, which make out the predominant part of the oxygen present. The excitation process, most likely to take place, is the one already mentioned and given in equation (1).

The enhancement of the red line in a sunlit atmosphere and in the red aurorae of type A should be due to the excitation of a form of oxygen which may be produced by the effect of sunlight and the electric rays producing the aurorae and magnetic disturbances. With our knowledge of the chemical properties of oxygen, the only form of molecular oxygen which may come into consideration, is ozone (O_3).

It is well known that ozone is formed from O_2 by the action of ultra-violet light. We also know ozone to be formed by electric discharge, which means that processes leading to ionisation also promote the formation of ozone. Consequently ozone should be produced by the electric radiations which cause aurorae and magnetic storms.

Thus the $^1D_2$-state is partly produced indirectly as the result of the transition ($^1S_0 — {^1D_2}$) or directly through collisions of the second kind between ozone (O_3) molecules and nitrogen molecules (or atoms) in an excited state. *The enhancement of the red line thus means an increase of ozone concentration within the auroral region.*

In this way we understand the enhancement observed from a sunlit atmosphere, and the fact that red aurorae of type A is most frequent in years of maximum solar activity. Years of high sunspot number give increased intensity of the electric radiation resulting in high auroral and magnetic activity, increased ozone concentration, increased relative intensity of the red OI-triplet and increased frequency of red aurorae of type A.

As regards the type of activated nitrogen which acts on ozone to produce O-atoms in the $^1D_2$-state several possibilities might come into consideration. In accordance with statements given in previous papers (13, 15, 26), we think it is very likely that nitrogen in the metastable A ($^3\Sigma$)-state may be the form which is mainly responsible for the dissociation of ozone which leads to an O-atom in the $^1D_2$-state.

From the analysis of the auroral luminescence (Table I), we know that the 1st positive group appears with considerable strength in the auroral spectrum. After the emission of this group, the nitrogen molecules are left in the metastable A ($^3\Sigma$)-state. Now the energy of activation might be lost either trough collisions or by a transition to the normal state under emission of bands belonging to the ε-system discovered and interpreted by *Vegard.*

Bands of the ε-system have been observed in the auroral spectrum (13), but they are faint as compared with the bands of the first positive group. This means that by far the greater part of N_2-molecules in the A-state must lose their energy through collisions with other molecules e. g. O_3-molecules.

The enhancement of the red line should therefore depend not only on the ozone concentration, but also on the concentration of N_2-molecules in the A-state. This explains the fact that we often found a large intensity of the OI-triplet to be accompanied by a relatively large intensity of the 1st positive group of nitrogen.

§ 4. The observations to be dealt with in the present paper.

After having given this outlook upon the problems and briefly mentioned some of the most important results previously obtained relating to the intensity variations within the auroral spectrum, a short description of our observational material will be given.

For the study of spectral variations it is essential that spectrograms are obtained with exposures of less than one hour, and for this reason we have to use spectrographs of high light power, and a dispersion large enough to give a fairly good separation of the lines and bands. Two small spectrographs which are very suitable for our purpose were built in 1922 and were described by one of us in a previous paper. (Cfr. paper No. 12, Fig. 2 and 4.)

Although these spectrographs are very similar with regard to optical and mechanical parts, they cannot be regarded as identical with respect to energy distribution within the spectrum, and therefore spectrograms taken with the two spectrographs are not comparable even when the photographic plates might be regarded as identical in properties.

If the relation between photographic density and light-energy was determined in each case, we would obtain a true intensity distribution which should be a property of the luminescence only and be independent of the spectrograph and plate used. Such a reduction of the true energy distribution involves considerable errors, and can only be applied in the case of very large intensity variations.

In order to detect and measure the smaller variations, it is necessary to compare spectra which have been taken with the same spectrograph, and they should also be taken on the same plate. For an approximate evaluation of a somewhat pronounced intensity change, we may also compare spectrograms taken on different plates when they are taken with the same spectrograph on the same sort of plate and with the same width of slit. The two spectrographs used will be denoted by (*a*) and (*α*).

The observational material to be treated in this paper falls into three groups:

Group I.

Spectrograms taken with spectrograph (*a*) on ortho-chromatic plates (Ilford X-press) during the Winter season, 1932—33.

Group II.

Spectrograms obtained during February and March 1934 with spectrograph (*a*) on Ilford hypersensitive panchromatic plates, hypersensitized with ammonia.

Group III.

This group includes spectrograms taken during the Winter season, 1935—36, with spectrograph (*α*) on Ilford hypersensitive pan-chromatic plates hypersensitized with ammonia.

As it is only spectrograms taken on the same plate which are strictly comparable, we have given each plate within each group a current number. The spectrograms appearing on the same plate are indicated by the plate number and letters a, b, c, etc. In order to indicate the auroral type which corresponds to each spectrogram, we have as far as possible used the symbols given in Størmers Atlas of Auroral Form published by the International Geodetic and Geophysical Union (Oslo 1930).

For the sake of convenience, we give a summary of the symbols used:

A = Arcs.
B = Bands.
C = Corona.
D = Draperies.
F = Flaming aurora.
G = Feeble glow near horizon.
R = Rays.
S = Luminous surfaces.
HA = Homogeneous quiet arcs.
HB = Homogeneous bands.
PA = Pulsating arcs.
PS = Pulsating surfaces.
RA = Arcs with ray structure.
RB = Bands with ray structure.
DS = Diffuse luminous surfaces.
DA = Diffuse Arcs.
GS = Gray surfaces or spots.

On each plate we have photographed a series of continuous spectra from an incandescent lamp with known spectral intensity distribution. The time of exposure of the series of spectra stands in the relation 1 : 2 : 4 : 8. This spectral series gives us a density scale for any wave-length wanted, and from the distribution of density within the spectrum, we are able to deduce the true spetral intensity distribution of the luminescence, which enters the slit of the spectrograph. For the study of intensity variations this reduction to true intensities are usually not necessary. The wave-length values within the continuous spectrum are fixed by means of a known line spectrum photographed at the head of the density scale.

§ 5. Remarks regarding the determination of intensities of lines and bands from the spectrograms.

For the determination of relative intensities within the spectrum from the photographic density, we used a registering microphotometer of the Moll type from Kipp & Zohnen. From the photometer registram we obtain the reduced deflection (μ) of the galvanometer which is an expression for the photographic density.

As the widths of the slits and the intensity of the lamp of the photometer may not be exactly the same for all spectrograms, we have to reduce the deflections to the same photometer sensitivity. The sensitivity is obtained from points on the diagram corresponding to zero absorption and complete shielding of the thermophile of the instrument.

The deflection is measured from the «normal» line which corresponds to the ground fogging of the plate. The procedure to be used for the determination of intensities from the photometer registrams have been described by one of us in previous papers, we may refer to paper No. 12 Chapter III. For the sake of convenience, we shall give a short résumé of the method adopted and the formulae to be used, in this paper.

Let (i) be the intensity of light falling on unit area of the plate, and let the time of exposure be t, then according to Schwartz-schield:

$$i t^p = \varphi_\lambda(\mu) \quad \ldots\ldots\ldots\ldots (11a)$$

Both (p) and $\varphi(\mu)$ depend on the wave-length. For our present purpose, we may regard (p) as a constant for a definite sort of plate and put:

$$\varphi_\lambda(\mu) = \frac{\varphi(\mu)}{k_\lambda} \quad \ldots\ldots\ldots\ldots (12)$$

where $\varphi(\mu)$ is independent of wave-length, and k_λ is a coefficient which depends on the sensitivity of the photographic plate for the wave-length in question. The equation (11a) may then be written:

$$k_\lambda i t^p = \varphi(\mu) \quad \ldots\ldots\ldots\ldots (11b)$$

In order to determine $\varphi(\mu)$, we may either take a series of exposures with constant time of exposure (t), and known variations of (i) (intensity scale), or we may take a series of pictures from a constant source and vary the time (t) (time scale). The latter procedure is usually the more convenient and has been used by us. The function $\varphi(\mu)$ is now found graphically by drawing a curve with (μ) as abscisse and (t) as ordinates. By means of this curve we can for any wave-length find the relative intensity corresponding to any value of the deflection (μ).

Let the luminescence, which enters the slit of the spectrograph contain homogeneous light of wave-length λ and intensity I_λ. The intensity may e. g. be measured by the energy passing the unit area of the slit within the effective cone of the collimator. Then the intensity per unit area of this light falling on the plate, can be written:

$$i_\lambda = I_\lambda f(\lambda) \quad \ldots\ldots\ldots\ldots (13)$$

Where $f(\lambda)$ is a function characteristic of the spectrograph, and will be the same as long as the spectrograph is kept under the same conditions.

From equation (11b) and (13) we get:

$$k_\lambda f(\lambda) I_\lambda t^p = Q_\lambda I_\lambda t^p = \varphi(\mu) \quad \ldots\ldots (11c)$$

where $Q_\lambda = k_\lambda f(\lambda)$ is a function of λ.

Suppose now, we want to compare the relative intensities of two lines (a) and (b) for two spectra I and II taken on the same plate with the spectrograph under the same conditions:

For spectrum I we have:

$$Q_a I_a' t^p = \varphi(\mu'_a)$$

$$Q_b I'_b t^p = \varphi(\mu'_b)$$

and:

$$\frac{I'_a}{I'_b} = \frac{Q_b}{Q_a}\,\frac{\varphi(\mu'_a)}{\varphi(\mu'_b)} \quad \ldots\ldots\ldots\ldots (14a)$$

For the spectrum II:

$$\frac{I''_a}{I''_b} = \frac{Q_b}{Q_a}\,\frac{\varphi(\mu''_a)}{\varphi(\mu''_b)} \quad \ldots\ldots\ldots\ldots (14b)$$

or:

$$\frac{I'_a}{I'_b} : \frac{I''_a}{I''_b} = \frac{\varphi(\mu'_a)}{\varphi(\mu'_b)} : \frac{\varphi(\mu''_a)}{\varphi(\mu''_b)} = D \quad \ldots\ldots (15)$$

$\varphi(\mu'_a)$ etc., are the apparent intensities directly found from the $\varphi(\mu) =$ curve, giving the relation between intensity and density (μ). $D = 1$ means that the relative intensity of two lines is the same in the two spectra which is compared. If D is different from 1, we may either arrange the proportion so that we get a value $D_1 > 1$, or one $D_2 < 1$, and we have $D_1 = \frac{1}{D_2}$.

The amount of change in the relative intensity may be measured by the quantity:

$$\Delta = D_1 - 1 = \frac{1 - D_2}{D_2} \quad \ldots\ldots\ldots (16)$$

100 Δ may then be regarded as expressing the relative change in percentage.

Thus if we have comparable spectra, we can obtain a quantitative determination of the *change* of intensity distribution without determining the true relative intensities of lines (or bands) within each spectrum. In order to find the true intensity distribution within a spectrum, we shall, according to equation (14), have to determine the quantity (Q) as a function of (λ) for the spectrograph and photographic plate used.

This is done by a spectrum from a light source of known energy distribution. As a rule, we use a light source which gives a continuous spectrum. Let the total intensity be L then:

$$L = \int_0^\infty E_\lambda d_\lambda \quad \dots\dots\dots\dots\dots \quad (17)$$

We assume (E_λ) to be known as a function of (λ). The light intensity falling on unit area of the plate is given by the expression:

$$i = df(\lambda) E_\lambda \frac{d\lambda}{ds} \quad \dots\dots\dots\dots\dots \quad (18)$$

(d) is the width of the slit, and (s) the distance from the considered element of the spectrum to a certain fixed line. The quantity $\left(\frac{d\lambda}{ds}\right)$ is the inverse of the dispersion and is usually expressed in Ångstrøm per millimeter.

This value (i) inserted in equation (11b) gives:

$$d \cdot k_\lambda f(\lambda) E_\lambda \frac{d\lambda}{ds} t^p = \varphi(\mu) \qquad \text{or:}$$

$$Q_\lambda = C \frac{\varphi(\mu)}{E_\lambda \frac{d\lambda}{ds}} \quad \dots\dots\dots\dots\dots \quad (19)$$

$\varphi(\mu)$ is found from the density curve (E_λ) and $\left(\frac{d\lambda}{ds}\right)$ are known, and (C) being independent of the wave-length, equation (18) gives us relative values of (Q) as a function of (λ).

Having thus determined the (Q) = function, the true relative intensities of the spectral lines are given by the equation:

$$I = \frac{\varphi(\mu)}{Q} \quad \dots\dots\dots\dots\dots \quad (20)$$

Following the procedure here described, we find the spectral intensy distribution of the light which enters the slit of the spectrograph. When we are dealing with the auroral luminescence, the intensity distribution which interests us is the one which exists in the auroral region. Owing to atmospheric extinction, which depends on the wave-length, this true distribution is different from that which we observe near the ground, and which is also a function of the zenith distance (z) of the collimator.

The intensity in the auroral region (I_0) is related to the intensity near the ground by the formula:

$$I_0 = \frac{I}{p^{\sec z}} \quad \dots\dots\dots\dots\dots \quad (21)$$

The quantity (p) which is a function of the wave-length is taken from tables e. g., those of Abbot given in Pertner and Exner: Meteorologische Optik. p. 754.

§ 6. Spectra of Group I.

Spectrograph (a), Ilford X-press plates.

These spectra were taken for the purpose of studying variations in the intensity distribution within the blue and violet part as compared with the intensity of the green line. With the spectrograph and plates used, the density of the green line came out about equal to that of the two strongest bands of the negative group of nitrogen (4278 and 3914).

An exposure which gives us the green line with a suitable density for photometric measurements, usually only gave the stronger negative bands while the positive bands were usually not visible. This group of spectra can therefore only be used for the study of the intensity of the green line relative to that of the negative nitrogen bands, or possible changes in the relative intensity of the bands belonging to the negative group.

Registrams of most of the spectra treated, are given in Figs. 3 *A* and 3 *B*. The results of the intensity measurements are given in Table II.

For each spectrum we have given the current number of the spectrum which corresponds to that of Fig. 3, the date and time interval of the exposure, the approximate height above the horizon of the collimator axis, the direction of the collimator in the horizontal plane and the auroral type. Finally, the head of the table also contains a number which expresses the relative density of the spectrum. The numbers express relative values of $\varphi(\mu)$ for the green auroral line, and they are of importance by the comparison of the spectra.

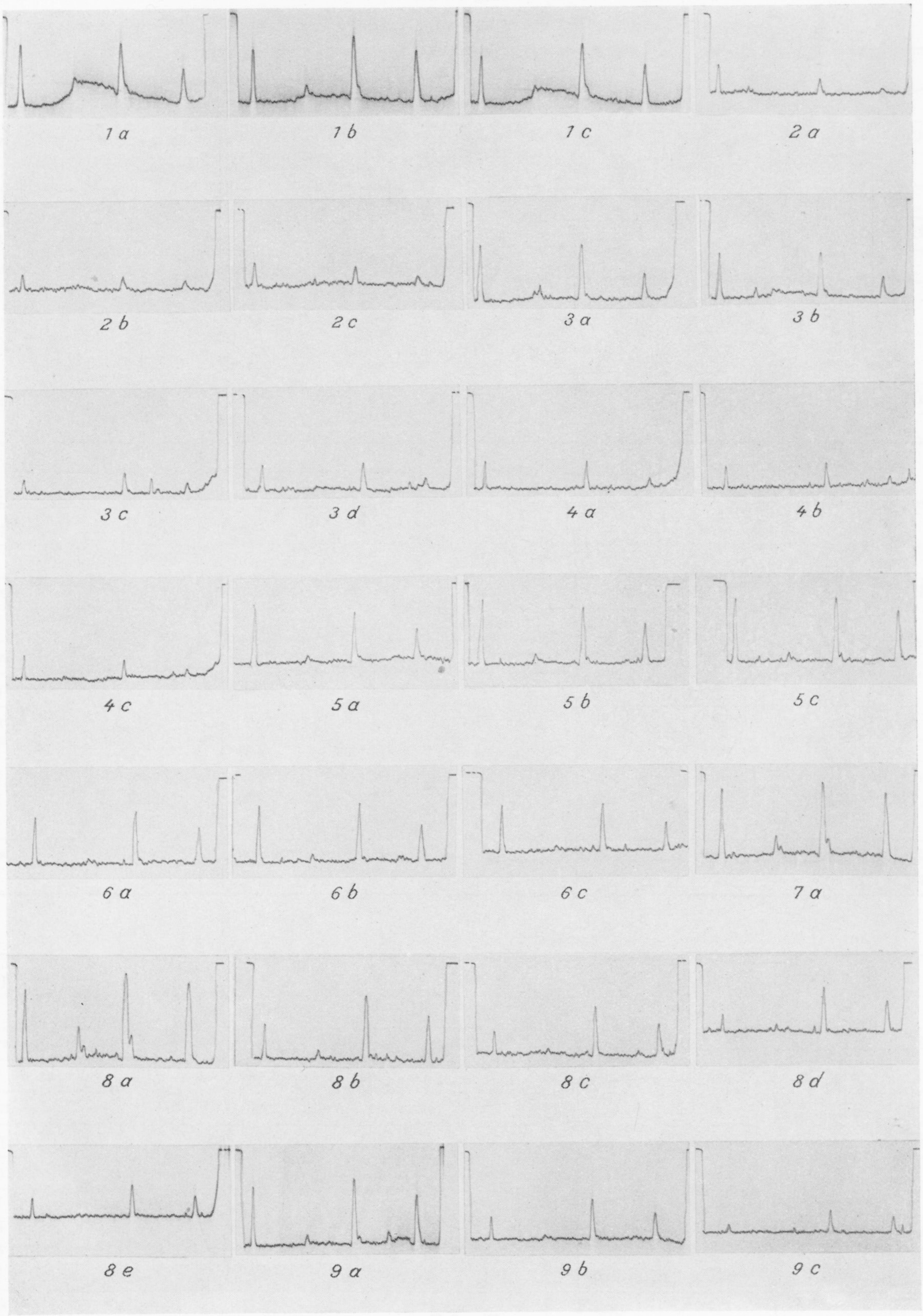


Fig. 3 A.
Group I. Spectrograph (a) Ilford X-press plates.

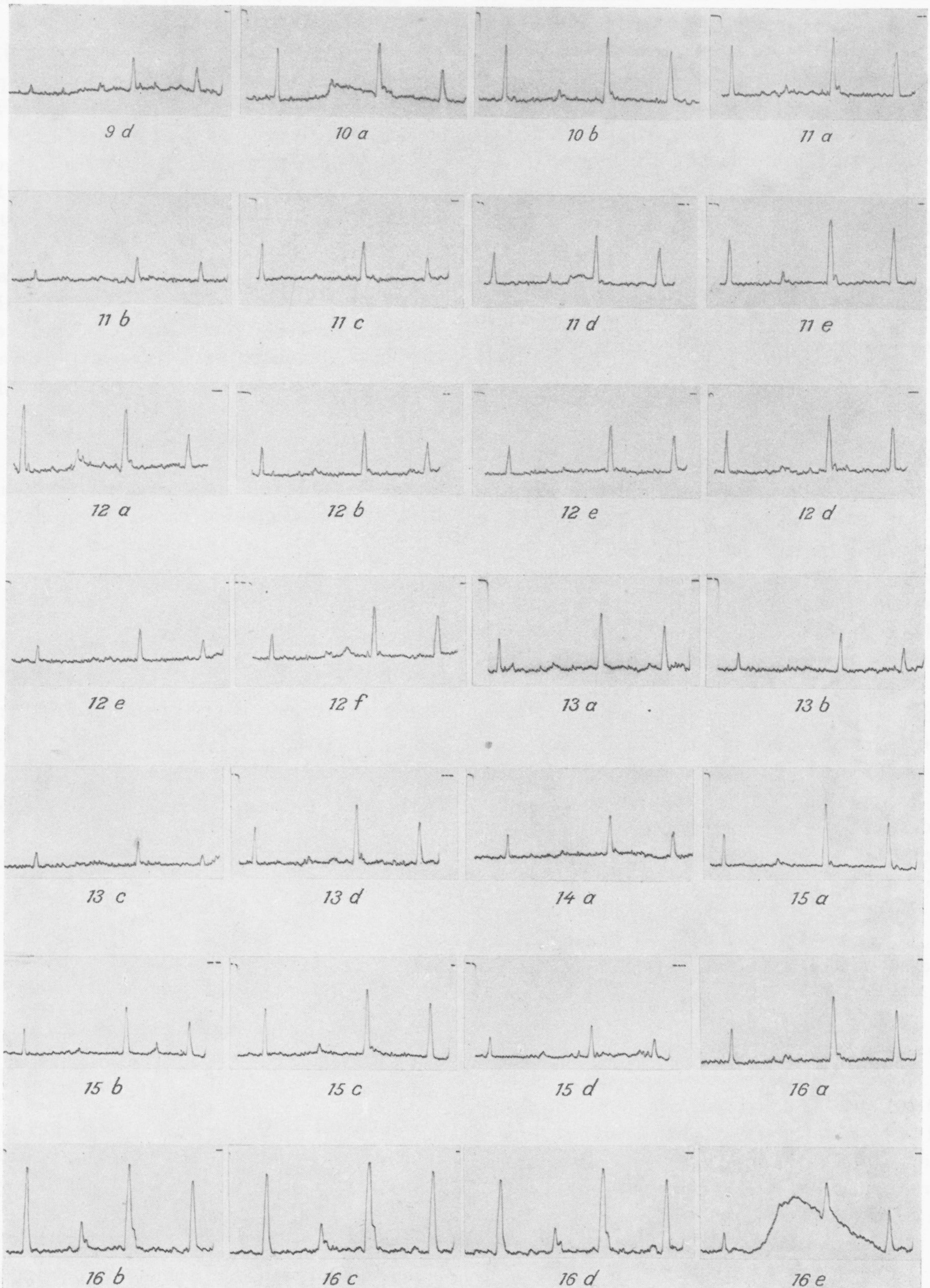


Fig. 3 B.
Group I. Spectrograph (a) Ilford X-press plates.

Table II.

Fig. 3. Spectrograph (a)

No. of spectr.	1 a	1 b	1 c	2 a	2 b	2 c	3 a	3 b
Date	$^{15}/_{12}$ — 32	$^{15}/_{12}$	$^{15}/_{12}$	$^{22}/_{12}$	$^{22}/_{12}$	$^{22}/_{12}$	$^{7}/_{1}$ — 33	$^{7}/_{1}$
Exposure	22^{15}—22^{30}	22^{38}—22^{45}	22^{48}—22^{58}	22^{27}—20^{34}	20^{35}—20^{54}	21^{02}—21^{45}	18^{52}—19^{02}	19^{00}—19^{13}
Height	12°	29°	18°	10°—13°	18°—28°	9°—10°	12°—15°	16°
Direction	N	N	W.S.W.				N	W
Aur. Type	D	D	A	D (L)	D + R	DS	A	B + DS
Strength of Sp.	46	41	37	26	17	21	39	33
5577	100	100	100	100	100	100	100	100
4708		22					32	30
4278	209	187	222	145	139	263	228	206
3914	279	200	268	146	149	364	215	196
Remarks	Moonlight		Moonlight	Lower Limit		Foggy	Moonlight Partly diffuse	Moonlight

No. of spectr,	6 a	6 b	6 c	7 a	8 a	8 b	8 c	8 d
Date	$^{19}/_{2}$ — 33	$^{19}/_{2}$	$^{19}/_{2}$	$^{20}/_{2}$	$^{22}/_{2}$	$^{21}/_{2}$	$^{21}/_{2}$	$^{21}/_{2}$
Exposure	20^{45}—11^{25}	21^{26}—21^{46}	23^{39}—0^{05}	2^{24}—2^{44}	0^{01}—1^{20}	1^{20}—2^{35}	2^{35}—3^{05}	3^{05}—3^{40}
Height	21°	13°—16°	17°	18 °	24°	22°	23°	23°
Direction			S	SW	S			S
Aur. Type	DA	DS	A	B	DS	DS	DS	PS
Strength of Sp.	37	45	41	57	52	27	20	20
5577	100	100	100	100	100	100	100	100
4708		24		44	59	37		
4278	203	218	207	230	282	348	333	443
3914	203	234	196	282	280	337	338	435
Remarks	Foggy	Clouds	Weak		Pulsating Foggy	Weak Foggy	Foggy	Rapidly pulsating

No. of spectr.	8 e	9 a	9 b	9 c	9 d	10 a	10 b	11 a
Date	$^{21}/_{2}$ — 33	$^{21}/_{2}$	$^{22}/_{2}$	$^{22}/_{2}$	$^{22}/_{2}$	$^{23}/_{2}$	$^{23}/_{2}$	$^{23}/_{2}$
Exposure	3^{54}—3^{57}	19^{44}—20^{03}	0^{33}—0^{58}	1^{07}—1^{13}	1^{28}—2^{23}	18^{19}—18^{24}	18^{31}—18^{42}	21^{55}—22^{22}
Height	30°	16°—18°	28°	60°	40°	20°	47°—66°	18°—25°
Direction						W		E
Aur. Type	D	DS + Spots	RA	RA	PS	R + D	A	B + DS
Strength of Sp.	23	42	20	11	11	37	43	43
5577	100	100	100	100	100	100	100	100
4708		39				28	29	29
4278	264	260	247	207	579	217	201	165
3914	271	287	237	200	579	196	135	121
Remarks	Coloured				Foggy			Gray

Table II (continued).

No. of spectr.	11 b	11 c	11 d	11 e	12 a	12 b	12 c	12 d
Date	$^{23}/_{2}$ — 33	$^{23}/_{2}$	$^{23}/_{2}$	$^{23}/_{2}$	$^{24}/_{2}$	$^{24}/_{2}$	$^{24}/_{2}$	$^{24}/_{2}$
Exposure	22^{23}—22^{43}	22^{47}—23^{03}	23^{37}—23^{48}	23^{49}—23^{58}	18^{52}—19^{05}	19^{05}—19^{12}	19^{13}—19^{20}	19^{21}—19^{32}
Height	60°—75°	16°	30°	66°	10°	52°	51°	42°
Direction		S			W		S	S
Aur. Type	DS	DA	B	D	A	A	A	A
Strength of Sp.	13	31	28	38	61	26	27	36
5577	100	100	100	100	100	100	100	100
4708			60	36	46	40		
4278	230	231	216	279	215	171	193	206
3914	222	255	254	220	241	151	189	182
Remarks	Foggy & Gray		Striated	Coloured	Sunset		Reddish lower border	Reddish lower border

No. of spectr.	12 e	12 f	13 a	13 b	13 c	13 d	14 a	15 a
Date	$^{24}/_{2}$ — 33	$^{24}/_{2}$	$^{24}/_{2}$	$^{24}/_{2}$	$^{24}/_{2}$	$^{24}/_{2}$	$^{24}/_{2}$	$^{17}/_{3}$
Exposure	19^{32}—19^{40}	19^{50}—20	21^{35}—21^{42}	21^{42}—21^{50}	21^{52}—22^{03}	22^{20}—22^{35}	23^{50}—0^{20}	21^{40}—21^{55}
Height	31°	48°	72°	32°	14°	10°	14°	20°
Direction					SW	N	NW	N
Aur. Type	A	A	D	A	A	GS	DS	D + DS
Strength of Sp.	18	25	26	16	14	29	22	26
5577	100	100	100	100	100	100	100	100
4708		41						53
4278	255	277	207	333	364	921	354	374
3914	234	255	187	268	356	917	470	399
Remarks	Reddish border	Reddish border		Greenish-white			Foggy	Foggy

No. of spectr.	15 b	15 c	15 d	16 a	16 b	16 c	16 d	16 e
Date	$^{17}/_{3}$ — 33	$^{17}/_{3}$	$^{18}/_{3}$	$^{18}/_{3}$	$^{19}/_{3}$	$^{19}/_{3}$	$^{19}/_{3}$	$^{19}/_{3}$
Exposure	21^{56}—22^{37}	22^{46}—0^{33}	0^{33}—1^{30}	23^{55}—0^{25}	0^{26}—1^{00}	1^{04}—1^{45}	1^{46}—2^{42}	3^{55}—4^{05}
Height	22°	19°	15°	25°	14°	27°	22°	25°
Direction					S	S		SW
Aur. Type	DS	DS	DS + A	F + PS	A	DS + A	A	GS
Strength of Sp.	22	35	18	24	72	61	52	16
5577	100	100	100	100	100	100	100	100
4708		45	74		28	27	32	
4278	289	297	289	352	269	319	249	566
3914	333	357	363	338	252	245	255	517
Remarks	Foggy							Yellow-grey Foggy. Sunset

For each spectrum the table gives for the green line and the three strongest negative bands, the values for $\varphi(u)$ corrected for extinction. The band 4708 is often too weak to be observed or measured on the spectrogram. In order to facilitate the comparison, the value of $\varphi(u)$ is for all spectra put equal to 100 for the green line.

It is particularly important to compare the intensity distribution of spectra obtained on the same plate and which is indicated by the same number.

Comparison of the intensity of the green line with that of the negativ bands.

The correction for extinction has a considerable influence on the relative intensity, and this influence increases with the difference of wave-length. In our case this influence in greatest when we compare the green line with the negative band 3914. In this case the zenith distance has a considerable influence, and as for good reasons the azimuth is not accurately known, we shall base our comparison between the negative bands and the green line, on the intensity of the band 4278.

The spectra of Plate I indicate that the negative bands for the same intensity of the green line is somewhat stronger for arcs, than for the draperies. Spectra on Plate 2 show that the negative bands are nearly twice as strong for diffuse-foggy aurorae as for draperies.

The spectra on Plate 5 also show the enhancement of the negative bands from gray surfaces and rays.

The spectra on Plate 6 are of interest because they show that diffuse and apparently foggy surfaces may give the same intensity distribution as an ordinary well defined arc. In this case the foggy form only means that the primary electric rays which may from the arc type spread out to form a more diffuse surface.

The spectra of Plate 8 of foggy and pulsating forms, all show a considerable enhancement of the negative bands or what is the same, a weakening of the green line. The effect is particularly large in the case of 8d, corresponding to rapidly pulsating aurorae. This effect is also very pronounced for spectrogram 9d from pulsating, foggy surfaces.

The spectrograms 12c and 12d corresponding to aurorae with a red lower limit, show that red aurorae of type B have about the same intensity of the negative bands relative to the green line as ordinary arcs and draperies.

The spectrograms 12e and 12f, however, indicate some relative weakening of the green line for red aurorae of type B.

Very marked enhancement of the negative bands for diffuse, foggy aurorae is shown by the spectrograms 13d, 14a and 15a.

Spectrogram 16e is particularly interesting because it corresponds to an aurora exposed to sunlight.

The spectrograms show a large enhancement of the negative bands, as compared with ordinary arcs or draperies, but as the spectrum corresponds to a gray and foggy form, we should also for this reason expect a considerable enhancement of the negative bands. We cannot therefore from this spectrogram draw any conclusions as to whether an aurora from a sunlit atmosphere will give a spectrum with enhanced negative bands (or a weakening of the green line).

Although spectrograms taken on different plates are not strictly comparable, all spectrograms of this group have been taken with the same spectrograph in the same condition and on plates of the same sort treated in the same way. The spectrograms of each group therefore may be regarded as so nearly comparable as to justify a statistical treatment of the material in order to see how far the various types on an average differ with regard to intensity distribution.

The results of our statistical summary are given in Table III.

Table III.
$k_1 = {}^1/_4, \; k_2 = 2.0$

Type	n	$\frac{I_{4278}}{I_{5577}} \frac{1}{k_1}$	$\frac{I_{3914}}{I_{4278}} \frac{1}{k_2}$
D	7	1.00	1.00
B	4	1.05	1.00
RA	2	1.16	0.94
A	12	1.22 }	0.94
A^x	5	1.24 }	
DS	13	1.54	1.06
PS	3	2.36	0.96
GS	2	3.84	0.94

A^x are arcs with a red bottom edge.

The first column gives the auroral type, the second one the number (n) of spectra of each type for which the mean intensity relation has been deduced. The third column gives the ratio (I_{4278}/I_{5577}) of the intensity of the negative band 4278 to that of the green line 5577. In the case of the draperies, this ratio is put equal to 1.00 k_1 where k_1 is the true mean intensity ratio I_{4278}/I_{5577}. From the intensity distribution given in Table I and Fig. 1, we find that k_1 is approximately equal to 0.244 or $^1/_4$.

Similarly the last columns gives the ratio $\frac{I_{3914}}{I_{4278}}$, which for draperies is put equal to 1.00 k_2. From Table I we find that k_2 is approximately equal to 2.0.

It appears from the Table III that *within the limit of error the ratio* $\frac{I_{3914}}{I_{4278}}$ *is the same for all auroral types.*

This would indicate that the intensity distribution of vibrational bands within the negative group of nitrogen is the same for the auroral forms of the auroral luminescence in general.

The intensity of the negative group relative to that of the green line — on the oter hand — shows very considerable differences for various types. On an average the green line is relatively strongest in the case of draperies, bands and drapery-shaped arcs. In the case of ordinary arcs its relative intensity is reduced by about 25 %. In the case of pulsating aurorae and gray-surfaces its relative intensity is reduced to $^1/_3$—$^1/_4$ of that of draperies and bands.

§ 7. Spectra of Group II.

Spectrograph (a) Ilford hypersensitive panchromatic plates.

Reproductions of the spectrograms of this group are given on Plate 1 and the corresponding microphotometer curves in Fig. 4.

It will be seen from the reproductions that the density of the negative bands is small as compared with that of the green line. These spectrograms are therefore not so well suited for the study of the intensity of the negative bands compared with that of the green line. The spectra of these groups was taken mainly for the object of studying possible variations in the red part.

The relative values of $\varphi(\mu)$ of this group are given in Table IV for the green line (*a*), the red line (*b*), the red bands of the first positive group (*c*, *d* and *e*) and the three strongest bands of the negative group (*f*, *g*, *h*). The necessary data for each spectrum are given at the head of the table in the same way as described for Table II, and further in the description to Plate I at the end of the paper.

Table IV.

Plate I, Fig. 4. Spectrograph (a).

Pl. No.	1 d	1 e	1 f	2 a	2 b	3 a	3 b	3 c
Date	$^9/_2$—34	$^9/_2$	$^9/_2$	$^{10}/_2$	$^{12}/_2$	$^{20}/_2$	$^{20}/_2$	$^{22}/_2$
Exposure	18^{15}—20^{30}	20^{30}—23^{40}	23^{40}—1^{00}	17^{30}—1^{00}	17^{30}—0^{30}	19^{10}—21^{00}	21^{00}—23^{30}	19^{00}—21^{00}
Height	25°	13°	15°	55°	50°	12°	12°	48°
Direction	NW	N	N & W	SW	SE	N	N	E
Auroral Type	GS	A	B + A	NL & NS	NL & NS	A + NS	NS	NS
Strength of sp.	47	93	85	135	111	21	3.5	4.0
e 6590	15	11	10	22	31			
b 6300	41	18	18	40	44	48	250	89
d 5950	15	11	9	18	29			
c 5890		13	9	20	29	36	134	79
a 5577	100	100	100	100	100	100	100	100
f 4708	17	12	12	13	10			
g 4278	60	51	47	43	34			
h 3914	60	57	56	33	26			
Shadow limits and remarks	162—563	Weak						

Table IV (continued).

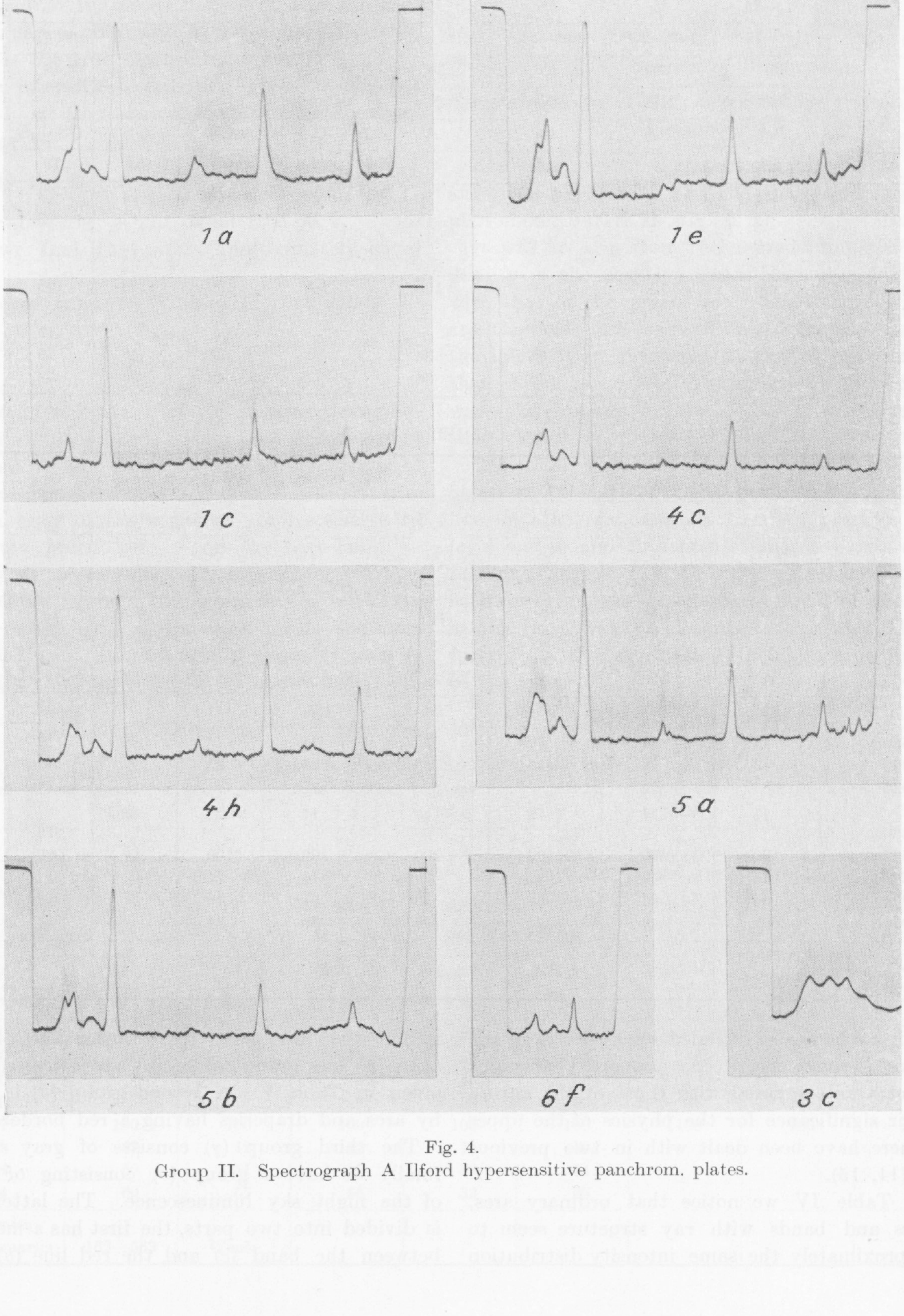
Pl. No.	4 a	4 b	4 c	4 d	4 e	4 f	4 g	4 h	4 i
Date	$^5/_3$—34	$^5/_3$	$^5/_3$	$^5/_3$	$^5/_3$	$^5/_3$	$^5/_3$—$^6/_3$	$^6/_3$	$^6/_3$
Exposure	19^{00}—19^{30}	19^{30}—20^{00}	20^{00}—21^{05}	21^{05}—21^{35}	21^{35}—21^{57}	22^{30}—23^{10}	23^{30}—0^{35}	0^{35}—1^{10}	1^{10}—4^{10}
Height	30°	30°	15°	20°	40°—60°	42°	22°	40°	20°
Direction	NE	NW	N	N	varying				
Aur. Type	RA	RA	A	A	A + D + R	GS	GS	GS + B	GS
Strength of Sp.	103	58	86	47	49	38	56	79	128
e 6590	11	10	9	10	13	18	14	13	21
b 6300	13	13	11	11	12	19	17	12	22
d 5950	9	9	9						
							} 13	11	18
c 5890		9							
a 5577	100	100	100	100	100	100	100	100	100
a′ 5240									7
f 4708	12							11	17
g 4278	41	34	36	36	40	53	53	46	68
h 3914	31	30	39	36	35	49	55	39	76
Shadow limits and remarks	117—174	122—179	Diffuse	Diffuse	Partly red border			Red border	Diffuse

Pl. No.	5 a	5 b	5 c	5 d	5 e	5 f	6 d	6 e	6 f
Date	$^6/_3$ 34	$^6/_3$	$^8/_3$	$^8/_3$	$^9/_3$	$^{10}/_3$	$^{14}/_3$	$^{15}/_3$	$^{15}/_3$
Exposure	19^{30}—19^{50}	21^{00}—23^{00}	20^{15}—22^{15}	22^{15}—24^{00}	20^{30}—1^{00}	21^{00}—24^{00}	21^{00}—0^{15}	0^{15}—4^{10}	20^{30}—0^{30}
Height	16°	22°	10°	50°	25°	10°—30°	45°	45°	45°
Direction		N	N	S	N	N	S	S	S
Aur. Type	A	DS	DA	NS + NL	Foggy A	A + DS	NS	NS—NL	NS
Strength of Sp.	82	67	45	34	106	111	8	79	15
e 6590	13	14	10	17	17	12	55	15	29
b 6300	13	16	14	23	20	23	92	24	61
d 5950								14	
	} 11	11	15	18	17	12	69		38
c 5890								15	
a 5577	100	100	100	100	100	100	100	100	100
f 4708	15	11			14	11		12	
g 4278	58	41	51	39	51	40		44	
h 3914	57	41		40	56	34		41	
Remarks	Red lower border				+ NS				

In this table is also included some spectra of the night sky luminescence. The properties of night sky spectra as compared with those of the aurora and their significance for the physics of the upper atmosphere have been dealt with in two previous papers (14, 15).

From Table IV we notice that ordinary arcs, draperies and bands with ray structure seem to give approximately the same intensity distribution within the red part; these forms are therefore taken as one group (α) in the statistical summary given in Table V. A second group (β) is formed by arcs and draperies having a red border.

The third group (γ) consists of gray surfaces, finally we have a group (δ) consisting of spectra of the night sky luminescence. The latter group is divided into two parts, the first has a maximum between the band (e) and the red line (b), so (e)



1a 1e 1c 4c 4h 5a 5b 6f 3c

Fig. 4.
Group II. Spectrograph A Ilford hypersensitive panchrom. plates.

and (b) cannot be distinguished separately. The second division consists of spectra with a pronounced red line (b).

Table V.
Statistical summary of Group II.

Auroral form	α $A + D + R + B$	β $A + D$ Red border	γ $G.S.$	δ Night sky ($N.S.$)	
	$\varphi(\mu)$	$\varphi(\mu)$	$\varphi(\mu)$	$\varphi(\mu)$	
e 6590	10.4	13	16.1 k_1	170	42
b 6300	15.1	12.5	22.3 k_2		77
d 5950	10.6				
			14.2		
c 5890	10.3			107	54
a 5577	100	100	100	100	100
f 4278	40.6		53. k_5		
n	8	2	7	2	2

At the bottom line of the table is given the number of spectra (n) in each group.

Aurora with red tower limit.

As mentioned in the introduction, arcs and bands with red bottom edge owe their red colour to the enhancement of red bands of the 1st positive group of nitrogen. In the group of spectra here considered, we have two spectrograms (4 e, 5 a) which clearly shows this effect. For arcs and draperies of the ordinary colour, the value of $\varphi(\mu)$ is as a rule considerably larger for the red line 6300 than for the band 6590. In the case of the spectrograms of aurorae with reddish border, the value of $\varphi(\mu)$ is seen to be equally large or even larger for the band 6590 than for the red oxygen line.

In the present case the red colour was not very pronounced, and it cannot be avoided that a great deal of light from aurorae of ordinary colour enters the spectrograph. The enhancement of the 1st positive group in the red portions, is therefore much greater than the effect derived from our spectrograms, which only to a small extent originates from the red parts.

Applying equation (15) to the line (b) and the band (e), then for the comparison of spectra from auroras with red border (column β) with ordinary arcs and draperies (column α), we get:

$$\left(\frac{I_e}{I_b}\right)_\beta : \left(\frac{I_e}{I_b}\right)_\alpha = 1.51$$

Acording to equation (16) this result means that the enhancement of the band 6590 is about 50 % as compared with the red oxygen line. The red band 6590 is also enhanced as compared with the green line and the negative nitrogen bands.

Gray surfaces and spots.

The enhancement of the negative bands which was so pronounced for the spectrograms of Group I is less marked in this case. Applying equation (15):

$$D_1 = \left(\frac{I_f}{I_a}\right)_\gamma : \left(\frac{I_f}{I_a}\right)_\alpha = 1.31$$

The mean enhancement of the negative bands relative to the green line is in this case merely 30 %.

Comparing the green line with the red band 6590, we get:

$$D_1 = \left(\frac{I_e}{I_a}\right)_\gamma : \left(\frac{I_e}{I_a}\right)_\alpha = 1.54$$

The red bands of the 1st positive group show an enhancement of about 55 %, and in the gray surfaces the bands of the 1st positive group are also enhanced as compared with the negative bands.

For the red oxygen line, we get:

$$D_1 = \left(\frac{I_b}{I_a}\right)_\gamma : \left(\frac{I_b}{I_a}\right)_\alpha = 1.48$$

In the gray surfaces as compared with arcs and draperies, the red oxygen line is enhanced nearly 50 % in relation to the green line.

With regard to the intensity distribution within the spectrum from night sky luminenscence as compared with that of the auroral spectrum, we may refer to previous papers (14, 15) dealing with this subject. The most important results may be summarized as follows:

a) Bands belonging to the first positive group are enormously enhanced as compared with the green line.

b) The negative bands or perhaps also those of the second positive group are either absent or extremely weak.

c) The intensity distribution of vibrational bands within the first positive group is very different in the night sky and in the auroral luminescence.

d) The night sky luminescence shows an intensity distribution of nitrogen bands which is essentially similar to that of the nitrogen after glow emitted from active nitrogen, and this result is in accordance with the explanation of the night sky luminescence given by Vegard in 1924.

e) Both in the night sky luminescence and in the aurorae the green oxygen line is mainly excited by collisions of the second kind between active nitrogen and oxygen molecules (O_2) and the enhancement of the red line, at any rate partly, is to be referred to an excitation which brings the oxygen atom directly to the $^1D_2$-state, e. g. the action of N_2-molecules in the A-state on ozone molecules (O_3).

§ 8. Spectra of Group III.

Spectrograph (*a*) *Ilford hypersensitive pancromatic plates.*

The spectra of this group were mainly taken in order to investigate the intensity distribution in spectra from an atmosphere exposed to sunlight compared with spectra taken under night conditions.

In connection with height measurements of auroral rays in a sunlit atmosphere Størmer (8, 9) took a spectrogram on an ortho-chromatic plate of rays exposed to sunlight. Although this spectrogram was not taken under such conditions as to enable quantitative measurements to be made, it suggested that the green line was unusually weak, as compared with the negative bands.

It was, however, pointed out by Vegard (10, 11) that a fairly large effect in this direction would result from the altitude effect, because the spectrum of the sunlit rays corresponded to an altitude probably more than 100 km. larger than that of spectra from ordinary aurorae.

The intensity distribution of the auroral spectrum in a sunlit atmosphere was therefore still an open question until quite recently, when we succeeded in obtaining spectra from arcs and bands in a sunlit atmosphere where the altitude effect at any rate is very small.

A preliminary account of some of our first results was given in a note to «Nature» (16). It was found that the negative bands were somewhat enhanced, and probably somewhat more than was to be accounted for by the altitude effect, on account of the fact found by Harang that the arcs are situated somewhat higher in a sunlit than in a dark atmosphere.

Table VI.

Plate II. Fig. 4. Spectrograph (*a*).

Pl. No.	14 a	7 a	7 b	7 c	7 d	7 e	8 a	8 b	8 c
Date	$^{21}/_{10}$ — 35	$^{27}/_{10}$ — 35	$^{27}/_{10}$	$^{27}/_{10}$	$^{27}/_{10}$	$^{27}/_{10}$	$^{14}/_{1}$ — 36	$^{15}/_{1}$	$^{16}/_{1}$
Exposure	18^{25}—18^{40}	17^{02}—17^{20}	17^{11}—17^{20}	17^{23}—17^{32}	17^{38}—17^{47}	18^{33}—18^{45}	20^{30}—1^{30}	17^{30}—23^{00}	17^{45}—23 0^{15}—2^{45}
Height	11°	15°—25°	23°	85°	35°	20°	20°	20°	50°
Direction	N	W	E & W	zenith	S E & S W	N	SW	SW	S
Aur. Type	R A	A + R	RB	RA	RA	RA & H + A	NS + NL	NS + NL	NS + NL
Strength of Sp.	200	23	56	62	59	64	67	14	16
6590	10	36	7				10	22	50
6300	9	45	10	(12)	(13)		19	63	91
6137	6								
5950	8								
5890	7	17	3				7		52
5577		100	100	100	100	100	100	100	100
5240	4								
4708	7		4				weak	weak	weak
4278	54	54	36	38	36	46			
3914	84	118	65	53	43	84			
Shadow limit and remarks	Red border	98—108 km.	Partly in sunlight						

Table VI (continued).

Pl. No.	8 d	8 e	8 f	8 g	9 a	9 b	9 c	9 d	9 e
Date	$^{17}/_{1}$ — 36	$^{20}/_{1}$	$^{20}/_{1}$	$^{20}/_{1}$	$^{17}/_{2}$	$^{17}/_{2}$	$^{17}/_{2}$	$^{17}/_{2}$	$^{17}/_{2}$
Exposure	17^{15}—24^{00}	18^{20}—18^{45}	18^{45}—19^{45}	21^{10}—21^{20}	17^{16}—17^{20}	17^{21}—17^{25}	17^{26}—17^{30}	17^{31}—17^{36}	17^{37}—17^{43}
Height	90°	12°	20°	90°	38°	21°	50°	42°	21°
Direction	Zenith	N	N	Zenith	N	E	S	S	W
Aur. type	NS	HA	HA	HB	RA	RA	RA	RA	RA
Strength of Sp.	15	40	150	40	58	22	43	25	22
6590	18				15	28	8	(17)	29
6300	103	16	13		15	30	8	(17)	33
5950									29
5890	33				6	14			
5577	100	100	100	100	100	100	100	100	100
4708	weak	26							
4278		47	29	33	27	54	45	50	(54)
3914		106	51	40	72	165	88	95	(155)
Shadow limit					29—32 km	103—112 km	56—62km	60—67 km	23—40 km

Pl. No.	9 f	9 g	9 h	9 i	10 a	10 b	10 c	10 d	10 e
Date	$^{17}/_{2}$ — 36	$^{17}/_{2}$	$^{17}/_{2}$	$^{17}/_{2}$	$^{18}/_{2}$	$^{18}/_{2}$	$^{19}/_{2}$	$^{19}/_{2}$	$^{19}/_{2}$
Exposure	17^{47}—17^{51}	18^{01}—18^{06}	18^{07}—18^{11}	20^{08}—20^{22}	19^{14}—19^{40}	19^{40}—20^{00}	17^{38}—17^{45}	17^{45}—17^{56}	17^{56}—18^{07}
Height	25°	22°	27°	33°	24°	18°	30°	28°	28°
Direction	SW	S	S	WE	N	W	E	W	NW
Aur. type	RA	RA	RA	HB + RB	HA	HB	RA	RA + D	D
Strength of Sp.	23	43	120	42	65	51	17	51	69
6590		(12)	8		10			5	3
6300	(24)	(12)	6	16	12	15	60	36	16
5950									
5890			7						
5577	100	100	100	100	100	100	100	100	100
4708									
4287	57	64	45	67	36	57	61	55	49
3914	111	92	63	104	53	90	140	98	80
Shadow limit and remarks	55—61 km	109—120 km Partly sunlit	123—132 km Not sunlit				99— 112 km	43—56 km	69—85 km

Table VI (continued).

Pl. No.	10 f	10 g	10 h	10 i	11 a	11 b	11 c	11 d	11 e
Date	$^{19}/_{2}$ — 36	$^{19}/_{2}$	$^{19}/_{2}$	$^{19}/_{2}$	$^{21}/_{2}$	$^{21}/_{2}$	$^{21}/_{2}$	$^{21}/_{2}$	$^{21}/_{2}$
Exposure	18^{07}—18^{19}	18^{19}—18^{28}	18^{28}—18^{40}	18^{40}—18^{50}	18^{01}—18^{13}	18^{24}—18^{34}	18^{34}—18^{40}	18^{40}—18^{52}	19^{14}—19^{20}
Height	15°	18°	35°	16°	33°	27°	25°	18°	25°
Direction	W	W	NE	W	W	WSW	E	W	NW
Aur. type	R + D	RB	HB	RB	R + RB	HA	RB	RB	RB reddish
Strength of Sp.	53	45	60	34	16	47	60	103	61
6590	3	5	6		24		9	6	14
6300	22	20	8	22	61	12	9	12	13
5950									10
5890									
5577	100	100	100	100	100	100	100	100	100
4708								11	23
4278	67	64	41	62	73	59	53	47	95
3914	117	101	64	89	164	82	78	81	144
Shadow limit and remarks	41—55 km	66—80 km	180—208 km Not sunlit	91—110 km	58—75 km	86—109 km	215—230 km Not sunlit	86—110 km	

Pl. No.	11 f	11 g	12 c	12 e	12 f	13 a	13 b	13 c
Date	$^{21}/_{2}$ — 36	$^{21}/_{2}$	$^{23}/_{2}$	$^{23}/_{2}$	$^{23}/_{2}$	$^{26}/_{2}$	$^{26}/_{2}$	$^{26}/_{2}$
Exposure	19^{47}—19^{56}	19^{57}—20^{04}	18^{35}—18^{47}	20^{00}—20^{09}	20^{10}—20^{17}	18^{31}—18^{45}	18^{45}—18^{57}	18^{57}—19^{12}
Height	24°	24°	14°	33°	33°	20°	13°	13°
Direction	NW	NW	WNW	NW	NW	W	W	W
Aur. type	RA reddish	RA reddish	RA	HA	HB	HB + RB	RB	RB
Strength of Sp.	111	129	15	46	55	45	76	31
6590	10	8				18	10	14
6300	9	7	60			29	19	41
5950	8	7						
5890						15	12	15
5577	100	100	100	100	100	100	100	100
4708	10	9						
4278	53	46		56	68	78	83	87
3914	77	73		89	106	125	124	162
Shadow limit and remarks	Not sunlit	Not sunlit	59—75 km			54—73 km	45—58 km	58—79 km

The most striking feature regarding the intensity distribution of the auroral spectrum was, however, *that the red line 6300 and usually also the bands of the 1st group of nitrogen, were considerably enhanced in a sunlit atmosphere.*

Since our preliminary communication of the new effect was published, we have obtained a considerable number of additional spectrograms from sunlit aurorae, which are now included in our Group III.

The spectrograms of this group are reproduced on Plate II and the corresponding microphotometer curves are represented in Fig. 5 A and 5 B. The results of our intensity measurements are given in Table VI. For each spectrogram is given the necessary data regarding type and exposure, and for the lines and bands measured, the values of $\varphi(\mu)$ relative to that of the green line which is put equal to 100. The relative strength of the exposure is given in the last line at the head of Table VI. The numbers give relative values of the quantity $\Sigma\, it^{p}$.

It is a matter of importance that spectra from a sunlit atmosphere and spectra during the night, have been taken on the same plate, so that they are strictly comparable.

The effect relating to the enhancement of the red lines and bands is very clearly seen from Plate 7, from Oct. 27. 1935, by comparing the spectrum (*a*) from aurora in a sunlit atmosphere with the normal night spectra (*c*, *d*, *e* and *f*) on the same plate. In this case both the red line 6300 and the bands of ths 1st positive group are enhanced.

In other cases the enhancement is mainly restricted to the red line 6300 (or rather OI triplet). Such cases are illustrated by the spectra (*c*, *d*, *e*, *f*, *g*) on Plate 10 from a sunlit atmosphere early in the evening of 19th Feb. 1936. The spectra *a*, *b*, *h* of the same plate correspond to night conditions.

The enhancement of the OI-line is very pronounced on spectrogram, *c* and *d* on Plate 12. Here the red line has nearly the same photographic density as the strong green line, the spectra (*e*) and (*f*) on the same plate corresponding to eight conditions show the green line over-exposed while hardly any trace of the red lines or bands is to be seen.

The spectra (*a*, *b*, *c*) Plate 13 give instanees of cases in which the 1st positive group as well as the red OI line are enhanced.

In addition to the spectrograms taken to study the enhancement of the red auroral spectrum from a sunlit atmosphere, Group III also contains some night-sky spectrograms and some spectrograms from auroral arcs and bands having a red lower edge.

During the evening of 17th Feb. 1936 we took a number of spectrograms from a sunlit atmosphere (*a*, *b*. *c*, *d*, *e*, *f*) Plate 9, which arouse great interest. Some of the these which were obtained from certain parts of the sky e. g. (*a*, *b*, *e*, *f*) show a very marked enhancement of the red lines and bands, while two others (*c*) and (*d*) taken towards the south, also from a sunlit atmosphere, give practically no enhancement although they correspond to a sunlit atmosphere. This result seems to show *that the enhancement must be associated with a certain form of matter in the upper atmosphere, the concentration of which may change from one part of the sky to another.*

Table VII.

Form	α Sunlit atmosphere	β Night conditions	γ Red border Night conditions
Line	I	I	I
e 6590	12.3 k_1	$<$ 6 k_1	10.5 k_1
b 6300	29.3 k_2	9.5 k_2	9.5 k_2
a 5577	100	100	100
f 4278	59.2 k_5	47.8 k_5	
Number of spectra	18	12	4

Table VII gives the mean distribution for three principal types of spectra contained in Group III. The first column gives the wavelengths of lines and bands. The second (*a*) gives the mean relative intensity (*I*) for the auroral spectra from a sunlit atmosphere, the third (β) the corresponding values for ordinary aurorae under normal night conditions and the fourth, corresponds to aurorae with a red lower border.

For each type the mean intensity of the auroral line has been put equal to 100 and the numbers given for the other lines are the corresponding relative mean values of $\varphi(\mu)$, and the relative intensity is then equal to $\varphi(\mu)\,k$. As all spectra were taken with the same spectrograph and on the same kind of plate, the spectra are approximately comparable and the value of *k* for a given

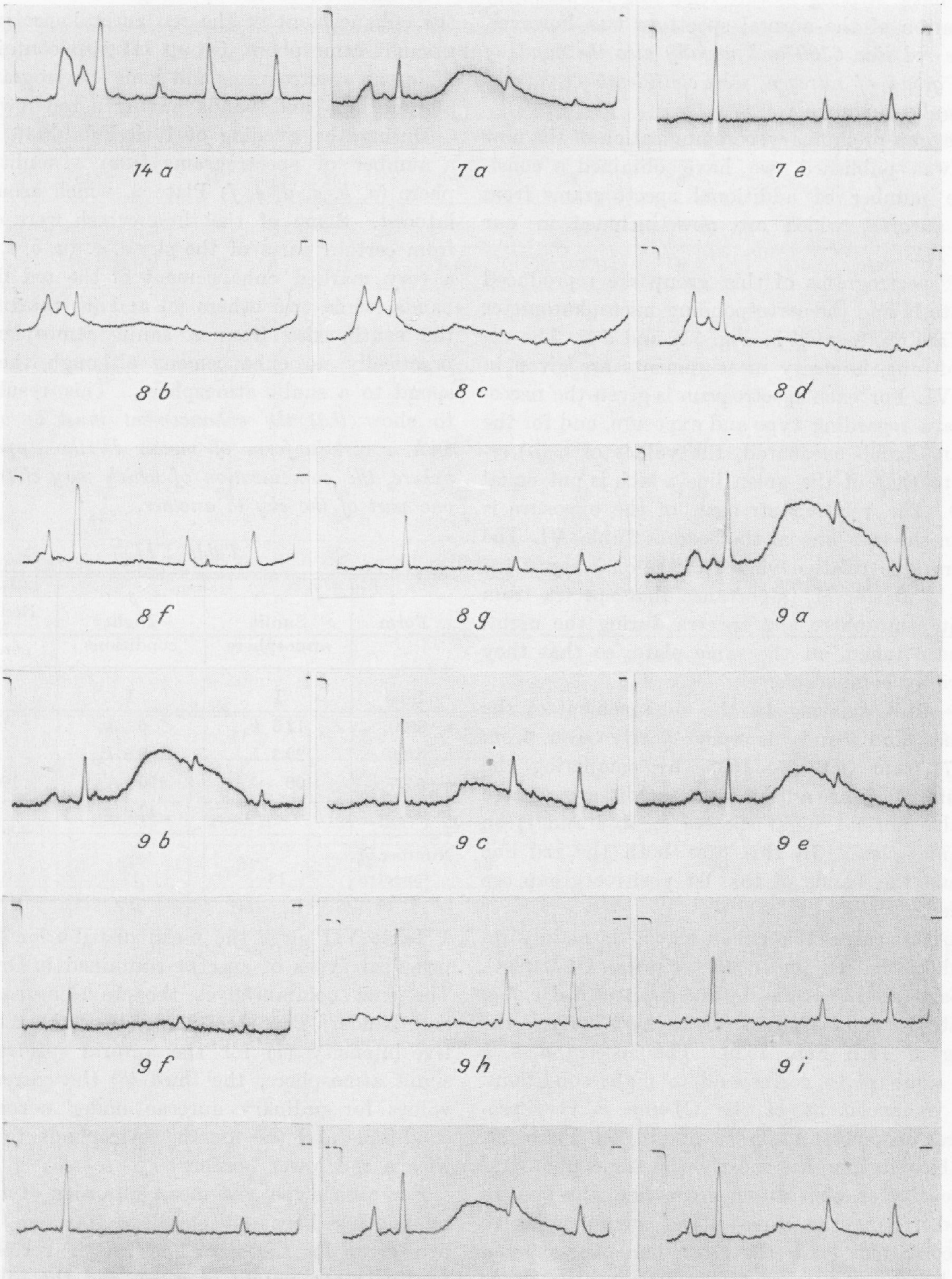


Fig. 5 A.

Group III. Spectrograph *α*. Ilford hypersensitive panchrom. plates.

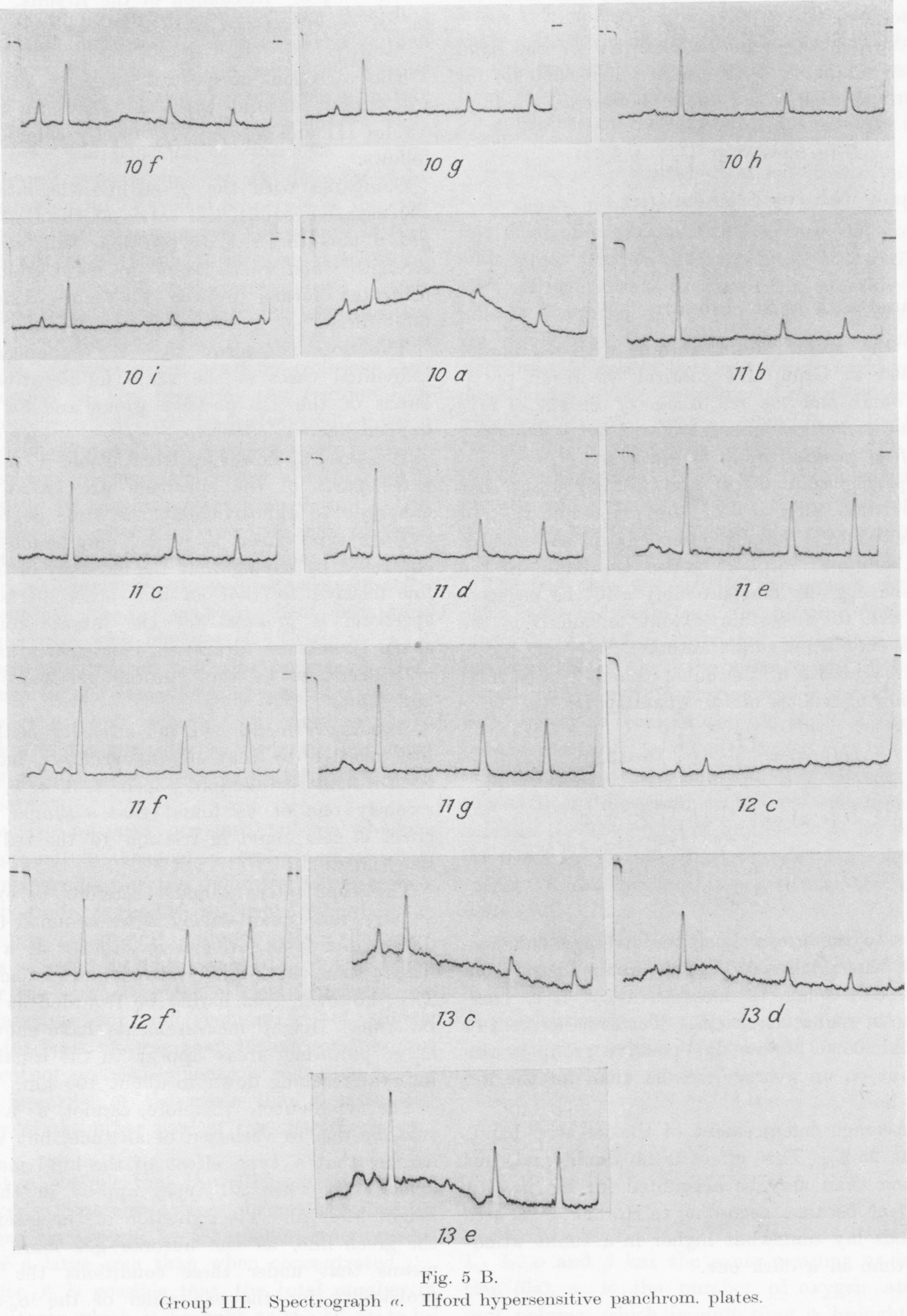


Fig. 5 B.
Group III. Spectrograph α. Ilford hypersensitive panchrom. plates.

line or band will be approximately the same for all types.

Considering the relative intensity of the band 6590 (e) compared with the red line 6300 (b) for the aurorae with a red lower border (γ) we find:

$$D\ (\gamma, \alpha) = \left(\frac{I_e}{I_b}\right)_\gamma : \left(\frac{I_e}{I_b}\right)_\alpha = 2.64$$

(compared with sunlit aurora)

$$D\ (\gamma, \beta) = \left(\frac{I_e}{I_b}\right)_\gamma : \left(\frac{I^e}{I_b}\right)_\beta \geqq 1.75$$

(compared with night aurora).

Also the spectra from aurorae with red border contained in Group III confirm the result previously found, *that the red colour of aurorae of type B is due to the enhancement of red bands belonging to the first positive group of nitrogen.*

Comparing column (α) and (β) we notice that for the same intensity of the green line the red OI line 6300 is largely enhanced in the spectra from a sunlit atmosphere. Also the bands of the 1st positive group and probably also the negative bands are to a certain extent enhanced in the luminescence from sunlit aurorae.

The magnitude of the enhancement is seen from the following values of the quantity D:

$$D\,(b, a) = \left(\frac{I_b}{I_a}\right)_\alpha : \left(\frac{I_b}{I_a}\right)_\beta = 3.10$$

$$D\ (e, a) = \left(\frac{I_e}{I_a}\right)_\alpha : \left(\frac{I_e}{I_a}\right)_\beta \overset{=}{>} 2.05$$

$$D\,(f, a) = \left(\frac{I^f}{I_a}\right)_\alpha : \left(\frac{I_f}{I_a}\right)_\beta = 1.24$$

Relative to the green line, the average enhancement of the red line 6300 in the luminescence from a sunlit atmosphere is more than 200 % as compared with night conditions. The enhancement of the band 6590 of the 1st positive group is also large, but on an average smaller than for the red oxygen line.

The average enhancement of the negative bands is about 25 %. This effect is no doubt real, but not larger than may be accounted for by the altitude effect because, according to Harang, even arcs and bands lay somewhat higher in a sunlit atmosphere than in a dark one.

§ 9. Discussion of the Results.

a. *Type effects and relative Intensity of Nitrogen Bands.*

The variations of spectral intensity distribution for various auroral types as they are given in Tables III and V, may be briefly summed up as follows:

Compared with the green line, the intensity of the negative bands, the bands of the first positive group and the red oxygen line will increase in strength when we go from the more intense, concentrated forms towards the more diffuse and faint forms.

This does not mean that the enhancement in individual cases is the same for negative bands, bands of the 1st positive group and for the red oxygen line.

It appears, however, from Table V that these three parts of the spectrum are *on an average* enhanced to approximately the same degree. This average type effect, therefore, may be most simply expressed by saying that the intensity of the green line relative to that of the other parts of the spectrum is greatest for the intense form with sharp boundaries (draperies, bands, arcs and rays) and decreases as the aurorae get more diffuse and faint.

As already mentioned, the intensity of the green line relative to that of the negative bands decreases with altitude (cfr. papers 2, 3, 4, 5, 6), and recently one of us found that a similar altitude effect is also found in relation to the red oxygen line (17, 29).

The type effect would, therefore, be explained at any rate qualitatively if we assumed that the diffuse and faint forms were situated at a greater height than the ordinary strong and distinct forms. This, however, can hardly be regarded as a general rule. Height measurements have shown that e. g. pulsating areas appear in the usual height interval reaching down to about 100 km.

The type effect, therefore, cannot, as a general rule, be due to variation of altitude, but we must assume that a type effect of the kind mentioned exists even when all types appear in the same height interval. The reduction of the intensity of the green line, as the aurorae get more diffuse, means that under these conditions the relative probability for the excitation of the ${}^1S_0$-state is diminished.

The view we take as regards the way in which this is effected will depend on our view regarding the excitation process which brings the oxygen atom to the $^1S_0$-state. If the excitation process given in equation (1) is the one which is mainly responsible for the emission of the green line, then we may draw the following conclusions:

The auroral type is first of all determined by the distribution and physical properties of the electric rays coming in from space, and change of type can hardly have anything to do with possible variations in the density of the atmosphere.

We know that the probability for the transition between the metastable state ($^1S_0 — {}^1D_2$) to occur before the $^1S_0$-state is disturbed by collisions, will be a function of the pressure; the fraction ε_s of excited atoms which give transition and emission of the green line will be zero for large pressure, but when the pressure falls below a certain limit, the quantity of ε_s-will increase from 0 to 1. This means that an increase of pressure may diminish the relative intensity of the green line. This variation of ε_s with pressure, can neither account for the type effect nor for the altitude effect, because ε_s cannot decrease with increase of altitude.

The concentration of molecular oxygen must on an average be the same for all types. If, then, the $^1S_0$-state is excited according to equation 1, the diminution of the intensity of the green line must therefore be due to *a change in the concentration of active nitrogen.*

The active nitrogen per unit volume which is always present in the higher strata, and which is mainly responsible for the night sky luminescence, is usually quite negligible as compared with the amount present in unit volume within that part which is situated inside the auroral form and which is under the bombardement of electric rays.

The amount per unit volume is, of course, smaller for faint aurorae than for intense ones, but that does not necessarily mean a reduction in the *relative* intensity of the green line, because the intensity of the other part of the spectrum is also reduced.

But it is possible that the efficiency of the electric rays to produce active nitrogen may — for the same ray bundle — be smaller, when spread out over a large area than when concentrated.

Further, it is possible that the total number of oxygen atoms which is brought to the $^1S_0$-state by a certain amount of active nitrogen, is smaller when this amount is spread into a large volume than when concentrated into a much smaller one. In this way, the type effect may be accounted for if we assume that the green line is mainly excited by a process as that expressed in equation (1).

b. *The enhancement of the red oxygen triplet.*

As shown in previous papers (7, 12, 17, 29) the red line 6300 may appear with an intensity considerably larger than that of the green line (5577). In view of the result expressed in equation (6), it follows that the $^1D_2$-state is not only excited as the result of the transition ($^1S_0$—$^1D_2$), *but the $^1D_2$-state must be excited by some process which acts independently of the emission of the green line, and which leaves the oxygen atom in the $^1D_2$-state without the $^1S_0$-state being reached.*

The enhancement of the red line in sunlit aurorae and red aurorae of type A must therefore be due to an excitation process like that expressed in equation (2).

The fact that the large enhancement of the line 6300 both in sunlit and red aurorae during long intervals of time is restricted to certain parts of the sky, shows that the effect ought to be associated with a certain change which has taken place with regard to composition or state of the atmospheric matter.

According to equation (2) this change should consist in an increased ozone concentration. *This accounts for the effect of sunlight and the fact that the frequency of the red aurora and the relative intensity of the red line increases with the solar activity.*

As already mentioned, and as more fully treated in a previous paper (29), the intensity of the red line increases very considerably with altitude. As shown in that paper (29) the intensity of the red line can in general be expressed by the formula:

$$\frac{I_b}{I_a} = \varkappa \varepsilon_d \left(1 + \frac{\Delta_d}{\varepsilon_s n_s}\right) \tag{22}$$

where:

$$\varkappa = \frac{\lambda_a}{\lambda_b (1 + \alpha + \beta)}$$

$$\Delta_d = n_d — \varepsilon_s u_s$$

λ_a, λ_b, α and β has the same meaning as in equation (6a), n_s is the number of oxygen atoms in unit volume, which in unit time is brought to the

$^1S_0$-state and ε_s the fraction which performs the transition ($^1S_0$—$^1D_2$). Similarly n_d is the number of oxygen atoms which in unit volume in unit time is brought to the $^1D_2$-state, and hence Δ_d is the number brought to this state directly without passing through the $^1S_0$-state.

The enhancement of the red line in sunlit and red aurorae is mainly due to an increase in the quantity Δ_d. The altitude effect may either result from variations in the quantity ε_d or a variation in $\frac{\Delta_d}{\varepsilon_s n_s}$.

The quantity ε_d will be such a function of the pressure, that it is zero for all pressures above a certain limit. When the pressure is reduced below this limit, ε_d will increase from 0 to 1. ε_d will obtain a finite value when the average lifetime of the electronic state is of the same order of magnitude as the average time between two collisions of an oxygen atom. $^1D_2$ being a metastable state, this will first occur for the very low pressures existing in the auroral region. It is therefore very likely that the increase of ε_d from 0 to 1 will take place from say 80 km. and upwards, and thus, according to the equation (22), produce an increase of the red line with increasing altitude.

The variation of ε_d, however, cannot explain the whole altitude effect which in certain cases is very large indeed. We have to assume that also the quantity $\frac{\Delta_d}{\varepsilon_s n_s}$ under certain conditions may increase considerably with altitude. The further explanation of the way in which the latter quantity may be increased with altitude will depend on the view we take with regard to the excitation processes which bring the oxygen atom directly to the $^1S_0$ and the $^1D_2$-state.

As far as the altitude effect results from this quantity, it means that the transitions $^1S_0$—$^1D_2$ resulting in the emission of the green line, decrease more rapidly with altitude than the frequency with the $^1D_2$-state is produced by an independent excitation process. The altitude effect of the negative bands also shows that the emission of the green line is relatively weaker as we pass upwards.

As already stated, the $^1S_0$-state must be excited indirectly by collisions of the second kind between oxygen and nitrogen in an activated state. In order to explain the absence of other oxygen bands or lines, the only possibility seems to be that the activated nitrogen acts on molecular oxygen.

If there are free oxygen atoms, the $^1S_0$-state might also be excited through collisions between these atoms and nitrogen molecules in an activated state e. g. in the A-state. The process may be expressed as follows:

$$N_2^A + O = N_2 + O\,(^1S_0) \qquad (1')$$

On account of the violent motions in the upper atmosphere, and as oxygen is more easily ionised than nitrogen, the diminution of the intensity of the green line with altitude cannot be due to a relatively smaller percentage of oxygen as we pass upwards. The weakening must be due to a diminution of the percentage of activated nitrogen or its efficiency in exciting the $^1S_0$-state by collisions of the second kind.

The A-state being the lowest known state of the nitrogen molecule and as the energy of this state (6,2 volts) is more than sufficient to bring the oxygen atom to the $^1S_0$-level, we can hardly assume that collisions between oxygen atoms and any state of excited nitrogen molecules may bring the atom only to the $^1D_2$-level and not to the $^1S_0$-level. Thus an excitation of *atomic* oxygen cannot account for the enormous enhancement of the red line with increasing altitude.

The excitation process expressed in equation (2), however, will account for the enhancement of the red line (6300) with altitude, provided the concentration of ozone *relative to that of the other components in the atmosphere during an auroral display increases upwards.* It must be borne in mind that the ozone is produced by radiations coming in from space, and an increase in the ozone percentage upwards may be possible even though the percentage of oxygen and nitrogen keeps constant.

If the main causes of excitation of the $^1S_0$ and $^1D_2$-states are those expressed in equation (1) and (2), a relative enhancement of the red line with increase of altitude would occur if the concentration of nitrogen molecules in the A-state relative to that of active nitrogen increased with altitude.

This will also account for the fact that not only the red oxygen line, but also bands of the 1st positive group are enhanced in a sunlit atmosphere and with increase of altitude. From Fig. 2 we see that after the emission of the 1st positive group, the nitrogen molecule is left in the metastable A-state.

The ε-system discovered by Vegard in the luminescence from solid nitrogen (also called Vegard-Kaplan bands), was shown by Vegard to result from the transition $A\,(^3\Sigma)-X\,(^1\Sigma)$. Vegard also found some bands of the ε-system in the auroral spectrum and it will be a matter of importance to see whether these bands are enhanced with altitude, as we should expect if the relative concentration of nitrogen in the A-state during an aurora increased upwards in the auroral region.

Some of the most important results may be summarized as follows:

1. The intensity of the green line 5577 relative to that of the negative bands is greatest for the intensive, condensed and well-defined auroral types like draperies, bands, arcs and ray-bundles, and is largely reduced for faint and diffuse forms like pulsating surfaces, foggy surfaces and similar types.
2. The red oxygen line as well as red bands of the first positive group as compared with the green line are weakest for intensive and definite forms and are considerably enhanced for faint and diffuse forms.
3. Aurorae with a red lower border show a considerable enhancement of bands belonging to the 1st positive group of nitrogen relative to the red oxygen line.

   In accordance with previous results, this shows that the red aurorae of type B owe their red colour to the enhancement of red bands belonging to the 1st positive group of nitrogen.
4. Aurorae appearing in an atmosphere exposed to sunlight give spectra where the red oxygen line is considerably enhanced relative to other bands and lines of the spectrum. This result was discussed in relation to the fact discovered by Vegard in 1926 that the red aurorae of type A owe their redness to the enhancement of the red line 6300.
5. In sunlit aurora not only the red oxygen line, but also red bands of the 1st positive group of nitrogen usually appear considerably enhanced.
6. Reference was also made to the altitude effects discovered by Vegard. In 1926 he showed that the intensity of the negative bands and certain weak lines or bands in the blue part relative to that of the green line is considerably increased as we pass upwards in the auroral region. Last year Vegard found that relative to the green line the red oxygen line and bands of the 1st positive group of nitrogen were largely enhanced with increasing altitude.
7. Reference was also made to the fact previously found by Vegard that for red aurorae of type A, and aurorae exposed to sunlight, the intensity of the red oxygen line 6300 might be considerably larger than that of the green line. In a previous paper, one of us showed that if the $^1D_2$-state was only excited indirectly through the transition $(^1S_0-{}^1D_2)$ the intensity of the red line I_b relative to that of the green one could not be greater than $\frac{I_b}{I_a}=0.5$.

   The fact that I_b/I_a is found much greater than 1 shows that the $^1D_2$-state is also, and to a large extent, excited directly by some excitation process acting independently of that which brings the oxygen atom to the $^1S_0$-state.
8. With reference to the theoretical result found by one of us that the sunlight can have no noticeable direct influence on the intensity distribution of the auroral spectrum, it was concluded that the enhancement of the red line 6300 and the bands of the 1st positive group and of the negative group must be referred to certain changes in the composition and state of the atmospheric matter, and that these changes may be influenced by the sun's radiation.
9. The physical interpretation of the observed intensity variations was discussed and as a result we may say that the effects observed may be accounted for on the basis of the processes for the excitation of the $^1S_0$-state and the $^1D_2$-state proposed by Vegard in 1932.

   The $^1S_0$-state should be mainly excited by collisions of the second kind between oxygen molecules and nitrogen in an activated state e. g., as expressed in equation (1). The $^1D_2$-state is directly excited through collisions between ozone molecules and an activated state of nitrogen e. g. as is expressed in equation (2).
10. By referring the excitation of the $^1D_2$-state to ozone, we explain the enhancement of the red line in a sunlit atmosphere and the fact that the frequency of red aurora of type A, and the average relative intensity of the red oxygen line, increase with solar activity and show a pronounced maximum in years of maximum sun-spot frequency.

Explanation to the Plates.

Plate I.

Spectra obtained with a small glass spectrograph (a) February—March 1934, at Tromsö. Ilford Hypersensitive Panchromatic Plates hypersentized with ammonia. On all plates the first spectrum is a helium comparison spectrum. The five next spectra are from the Argenta lamp and are used as density scales.

Plate No.	Spectrum	Date	Exposure	Type of aurora	Height	Direction
1	a	9—2	17^{30}—17^{52}	B		
	b	»	17^{52}—18^{02}	B		
	c	»	18^{02}—18^{12}	R + D		W
	d	»	18^{15}—20^{30}	Grey spots	25°	NW
	e	»	20^{30}—23^{40}	A	13°	N
	f	»	23^{40}—1	B + A	15°	N and W
2	a	10—2	17^{30}—1	NL + NS	55°	SW
	b	12—2	17^{30}—0^{30}	NL + NS	50°	SE
3	a	20—2	19^{10}—21	A + NS	12°	N
	b	»	21 —23^{30}	NS	12°	N
	c	22—2	19 —21	NS	48°	E
	d	»	21 —1^{20}	NS	48°	E
4	a	5—3	19 —19^{30}	A + R	30°	NE
	b	»	19^{30}—20	»	30°	NW
	c	»	20 —21^{05}	A	15°	N
	d	»	21^{05}—21^{35}	A	20°	N
	e	»	21^{38}—21^{57}	D	40°—60°	
	f	»	22^{30}—23^{10}	Grey spots	42°	
	g	»	23^{30}—0^{35}	Grey fog	22°	
	h	6—3	0^{35}—1^{10}	Grey S + Redish B	40°	
	i	»	1^{10}—4^{10}	Grey spots	20°	
5	a	»	19^{30}—19^{50}	A, lower border red	16°	
	b	»	21 —23	Foggy	22°	N
	c	8—3	20^{15}—22^{15}	Foggy A	10°	N
	d	»	22^{15}—24	NL + NS	50°	S
	e	9—3	20^{30}—1	Foggy A	25°	N
	f	10—3	21 —24	A + DS	10°—30°	N
6	a	13—3	20^{45}—21^{10}	A		N
	b	»	21^{10}—22	A + spots		E and W
	c	»	22 —23^{30}	»		N
	d	14—3	21 —0^{15}	NS	45°	S
	e	15—3	0^{15}—4^{10}	NS + NL	45°	S
	f	»	20^{50}—0^{30}	NS	45°	S

Plate II.

Spectra obtained with another small glass spectrograph (*a*) at Tromsö in the years 1935 and 1936. Ilford Hypersensitive Panchromatic Plates hypersensitized with ammonia.

Plate No.	Spectrum	Date	Exposure	Type of auroara	Height	Direction
7	a	27—10—1935	17^{02}—17^{10}	R*	15°—25°	W
	b	—»—	17^{11}—17^{20}	RB	23°	E + W
	c	—»—	17^{23}—17^{32}	RA	85°	Zenith
	d	—»—	17^{38}—17^{47}	RA	35°	SE + SW
	e	—»—	18^{33}—18^{45}	RA + HA	20°	N
	f	—»—	18^{46}—18^{58}	RB	27°	S
8	a	14—1—1936	20^{30}— 1^{30}	NS + NL	20°	SW
	b	15—1—1936	17^{30}—23	»	20°	SW
	c	16—1—1936	17^{45}— 2^{45}	»	50°	S
	d	17—1—1936	17^{15}—24	»	90°	Zenith
	e	20—1—1936	18^{20}—18^{45}	HA	12°	N
	f	—»—	18^{45}—19^{45}	»	20°	N
	g	—»—	21^{10}—21^{20}	HB	90°	Zenith
9	a	17—2—1936	17^{16}—17^{20}	RA*	38°	W
	b	—»—	17^{21}—17^{25}	» *	21°	E
	c	—»—	17^{26}—17^{30}	» *	50°	S
	d	—»—	17^{31}—17^{36}	» *	42°	S
	e	—»—	17^{37}—17^{43}	» *	21°	W
	f	—»—	17^{47}—17^{51}	» *	25°	SW
	g	—»—	18^{01}—18^{06}	» *	22°	S
	h	—»—	18^{07}—18^{11}	»	27°	S
	i	—»—	20^{08}—20^{22}	HB + RB	33°	NE
10	a	18—2—1936	19^{14}—19^{40}	HA	24°	N
	b	—»—	19^{40}—20	HB	18°	W
	c	19—2—1936	17^{38}—17^{45}	RA*	30°	E
	d	—»—	17^{45}—17^{56}	RA + D*	28°	W
	e	—»—	17^{56}—18^{07}	D*	28°	NW
	f	—»—	18^{07}—18^{19}	R + D*	15°	W
	g	—»—	18^{19}—18^{28}	RB*	18°	W
	h	—»—	18^{28}—18^{40}	HB	35°	NE
	i	—»—	18^{40}—18^{50}	RB*	16°	W
11	a	21—2—1936	18^{01}—18^{13}	R + RB*	33°	W
	b	—»—	18^{24}—18^{34}	HA*	27°	WSW
	c	—»—	18^{34}—18^{40}	RB	25°	E
	d	—»—	18^{40}—18^{52}	RB*	18°	W
	e	—»—	19^{14}—19^{20}	RB	25°	NW
	f	—»—	19^{47}—19^{56}	RA	24°	NW
	g	—»—	19^{57}—20^{04}	RA	24°	NW
	h	—»—	22 —23	HA	23°	SW
12	a	22—2—1936	17^{55}—17^{58}	Twilight after sunset	13°	W
	b	—»—	17^{58}—18^{04}		13°	NW
	c	23—2—1936	18^{35}—18^{47}	RA*	14°	WNW
	d	—»—	18^{47}—19	DS*	11°	WNW
	e	—»—	20 —20^{09}	HA	33°	NW
	f	—»—	21^{10}—20^{17}	HB	33°	NW
	g	—»—	20^{20}—20^{24}	HA	18°	NW
13	a	26—2—1936	18^{31}—18^{45}	HB + RB*	20°	W
	b	—»—	18^{45}—18^{57}	RB*	13°	W
	c	—»—	18^{57}—19^{12}	RB*	13°	W
	d	—»—	19^{56}—20^{15}	HA	18°	SE
	e	—»—	20^{38}—20^{45}	RA + D	15°	N
14	a	21—10—1935	18^{23}—18^{40}	AR with red border	11°	N

* indicates aurorae in an atmosphere exposed to sunlight.

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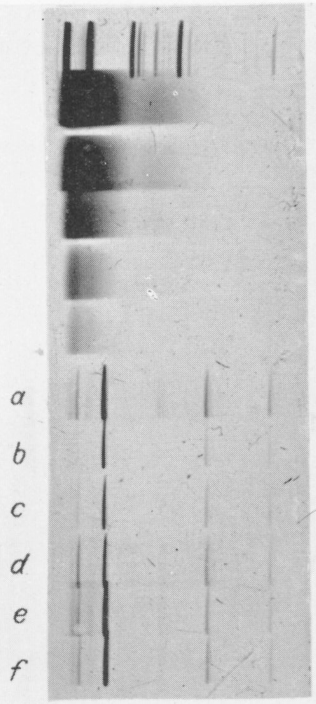
Pl. I.



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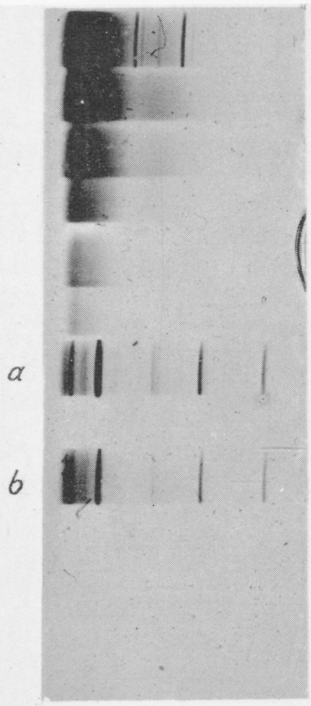

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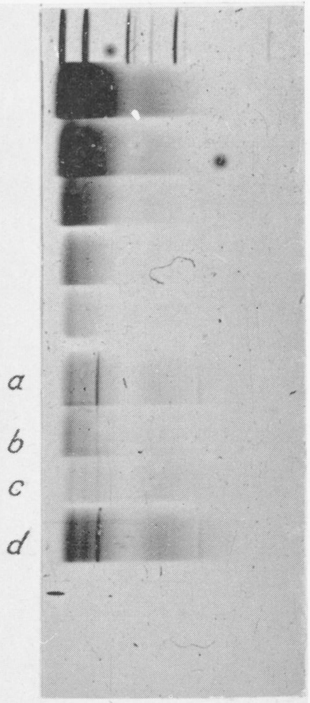

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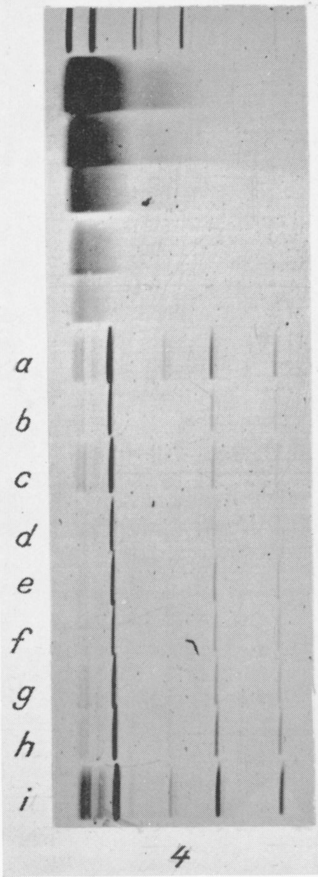

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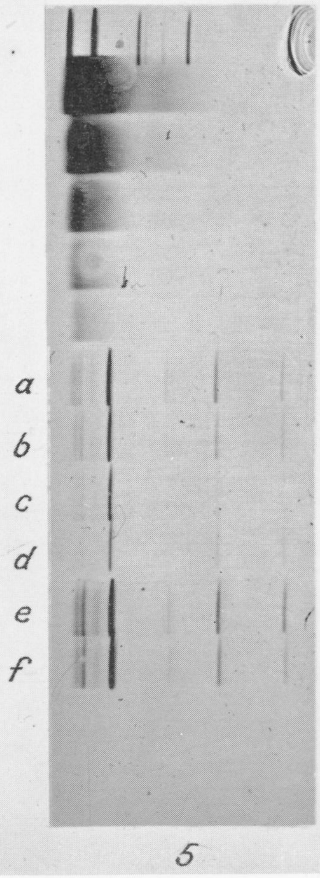

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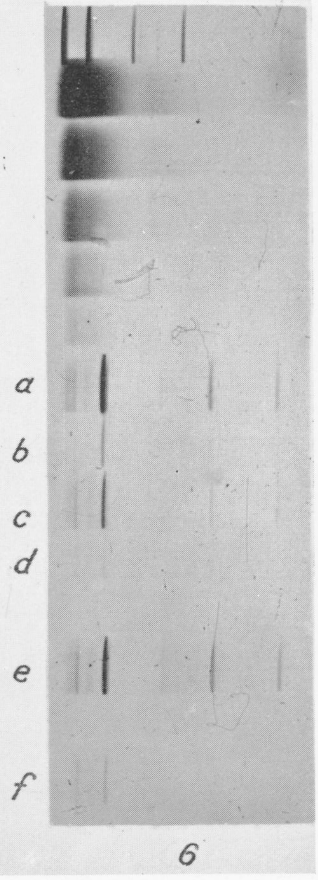

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Pl. II.

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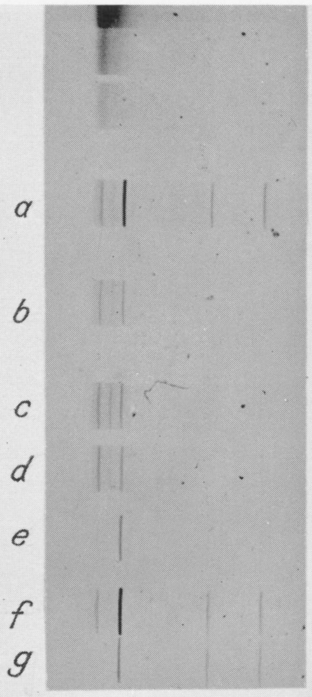

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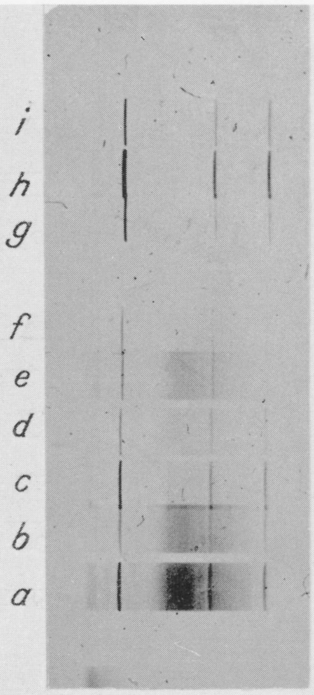

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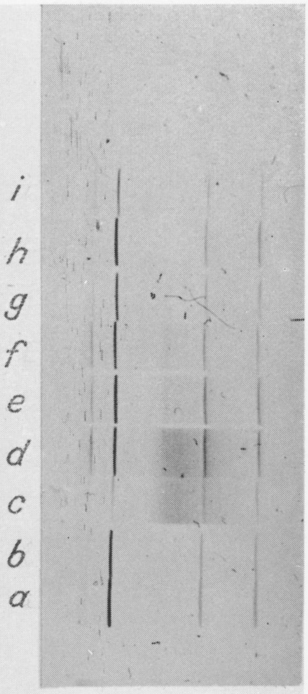

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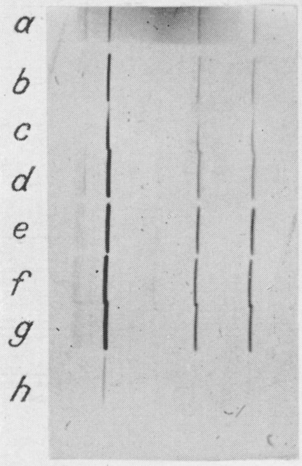

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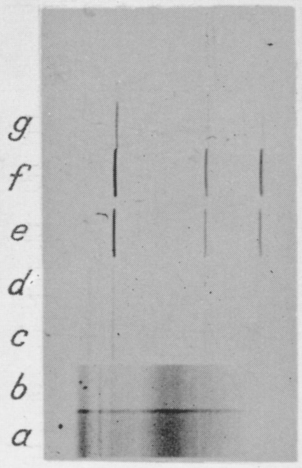

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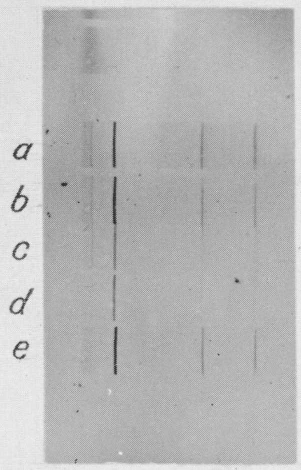

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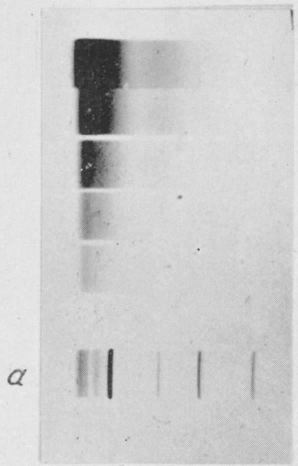

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