WEAK BANDS AND ATOMIC LINES IN THE AURORAL SPECTRUM

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1. The most Prominent Bands and Lines of the Auroral Spectrum.

Previous investigations have shown that the auroral luminescence has a spectrum mainly composed of nitrogen bands, but in addition the green $OI(^1S_0—^1D_2)$-line and sometimes the red $OI(^1D_2—^3P_{012})$ triplett appear with great intensity.

The somewhat strong nitrogen bands belong to one of the three groups:

The negative group: $N_2^+ : B(^2\Sigma)—X(^2\Sigma)$.

The second positive group: $N_2 : C(^3\Pi)—B(^3\Pi)$.

The first » » : $N_2 : B(^3\Pi)—A(^3\Sigma)$.

It appears from the interpretation that the two positive groups correspond to successive electronic jumps from C to B (2nd P. G.) and from B to A (1st P. G.).

2. The ε-System and its Presence in the Auroral Spectrum.

Although the bottom state (A) of the 1. P. G. is not the normal one, usually no N_2-bands, corresponding to a transition from (A) to the normal X-state, are observed in an ordinary discharge tube containing gaseous nitrogen.

The group of N_2-bands corresponding to the transition ($A—X$) was discovered by the writer in 1924 in the luminescence from the α-form of solidified nitrogen (1), and was called the ε-system.

The complete classification of the ε-system was given by the writer (1, 2, 3, 4) and it fixed for the first time exactly the position of the A, B, C, levels relative to the ground state.

The fact that the ε-bands appeared with great intensity in the luminescence from α-nitrogen, while it was usually absent in sources of gaseous nitrogen, is due to the fact that the $A(^3\Sigma)$-state is metastable and the transition ($A—X$) a forbidden one.

In addition to the prominent OI-lines and the nitrogen band-groups mentioned, the auroral spectrum contains a number of weak bands and lines (5, 6, 7). The relative intensity of these lines was found to be much greater in the luminescence from diffuse auroral forms (cfr. e. g. Paper 5. Pl. I, Fig. 2) and for high altitudes (7) than is found for distinct aurorae at low altitudes.

In 1932 it was found that a number of these weak auroral bands belonged to the series $\varepsilon(l, n)$ (called the b'-series) (5) and later on it was found that also a number of other ε-bands was present in the auroral spectrum (10, 11).

At that time it had been shown that the temperature of the auroral region was about ÷35° Centigrades, which means *that in that region nitrogen is present in the gaseous state.*

The discovery of the presence of ε-bands in the auroral luminescence had thus for the first time shown *that the nitrogen band-group corresponding to the forbidden transition $A(^3\Sigma)—X(^1\Sigma)$ is emitted from gaseous nitrogen at very low pressure.*

Two years later Kaplan (8) was able to observe some of the ε-bands in the luminescence from gaseous nitrogen produced in laboratory experiments, and somewhat later R. Bernard (9) also observed some of the ε-bands from nitrogen discharge tubes.

It appears from the data given that *before Kaplan reproduced some of the ε-bands in the luminescence from a nitrogen discharge tube, the ε-system had been completely analysed and interpreted by the author. It had been shown to be due to the for-*

bidden transition $A(^3\Sigma)-X(^1\Sigma)$ of the nitrogen molecule, its term-formula had been determined and published (2, 3, 4) and it had been shown that the ε-system could be emitted from the gaseous as well as from the solid state of nitrogen.

3. Atomic Lines in the Auroral Spectrum.

Apart from the weak ε-bands, the auroral spectrum contains a number of other weak lines which were found to be situated close to atomic lines from nitrogen and oxygen (5, 6). Until recently most of these lines were obtained on spectrograms with small dispersion and consequently the possible error in the wave-length measurements would make the interpretation somewhat uncertain.

During the last two years, the writer, together with Tønsberg, obtained some of the weak lines on spectrograms with great dispersion (12, 13). Particularly two of these (4415,1) and (4368,2) appeared quite distinctly. The fairly high accuracy with which the wave-length was found from these spectrograms (the error is only a small fraction of 1 Å) enabled us to show that these two lines were due to oxygen atoms.

A comparison of these spectrograms, showing the fairly strong atomic *O*-lines, with previous spectrograms, indicates that the *O*-lines are relatively stronger near sunspot maxima than at sunspot minima, which would indicate that the concentration of oxygen atoms follows the sunspot cycle.

It now became a matter of importance to find which auroral lines might possibly be due to atoms of oxygen and nitrogen. In a previous paper (13), it was shown that about 20 weak lines might be due to atoms of oxygen and nitrogen in the neutral or ionised state.

The appearance of forbidden bands and lines in the auroral spectrum and in that of the night sky, indicates that there is a certain similarity between the physical conditions of the upper atmosphere and those of the stellar nebulae. According to Bowen's interpretation (14) the most prominent and typical nebular lines correspond to forbidden transitions from one of the metastable low states (ground states) e. g. to the normal state of the neutral or ionised atom. The strong green line and particularly the red triplett belong to this nebular type of lines. In fact we find that the two strongest components of the red triplett (6300,3) and (6364) appear in the nebular spectrum. It has also been suggested in previous publications (5, 13) that the weak auroral line 5003 might be identical with the nebular line 5007 referred to *OIII*. Further, the auroral line 4415, originating from *OII*, is observed in Nebulae.

It would therefore be of interest to see whether other nebular lines might possibly appear in the auroral spectrum, and in this connection it would be particularly important to know whether other forbidden lines resulting from transitions from the metastable ground-states of atomic nitrogen or oxygen were present in the auroral luminescence.

The investigation in this direction which *I* undertook, led to the results which are summarised in the table.

The first column gives the observed auroral lines which may possibly be interpreted as atomic lines of oxygen or nitrogen.

The second column contains those nebular lines which within the limit of error coincide with auroral lines. *We notice that no less than 10 nebular lines may possibly be present in the auroral luminescence.*

The third and fourth columns give the interpretation: first the kind of atom, then the term symbols and finally the corresponding wave-length as measured from laboratory light sources.

For each of the three lines 5003, 4368,2 and 4226, we have given two different interpretations. In the case of 5003 and, 4226 the wave-length measurements are not sufficiently accurate for making the right choice between the two possibilities. The line 4368,2, however, is one of those which we obtained with our large glass spectrograph. It appeared very sharp on the spectrograms and the error of the wave-length determinations is a small fraction of an Ångström Unit. It is now very remarkable that in the *OI*-spectrum we have a prominent line ($4p\,^3P_{0,1,2}$—$3s\,^3S_1^0$) which (although theoretically a triplett) should appear as a sharp line with the wave-length 4368,3, which is only 0,1 Å greater than that of the auroral line.

In the *OII*-spectrum we have the two lines 4369,3 and 4366,9. If they both appeared in the auroral spectrum with about the same intensity they would hardly be separated with the dispersion used. We would observe a line with a wave-length equal to the mean value 4368,1. This value fits equally well with that of the auroral line as the *OI*-line. It is, however, to be remembered that it is not likely that the two lines (which do not form a doublet)

Table of Atomic Lines in Aurora.

Auroral lines	Nebular lines	Interpretation	
		Atomic transition	Wave-length
6363	6364	*OI* $2s^2 2p^4 (^1D_2 - ^3P_1)$	6364,9
6300,30	6302	» —»— $(^1D_2 - ^3P_2)$ G. S.	6300,30
5577,345	-	» —»— $(^1S_0 - ^1D_2)$	5577,34
6454	-	» $2s^2 2p^3 (^4S)(5s^5S_2 - 3p^5P_{123})$	6454,7
4368,2	-	» —»— $(^4S)(4p\,^3P_{0,1,2} - 3s\,^3S_1^0)$	4368,3
3942,8	-	» —»— » $(4p\,^5P_2 - 3s\,^5S_2)$	3947,5
3728,6	3728,9	*OII* $2s^2 2p^3 (^2D_2^0 - ^4S_2^0)$ } G. S.	3726,12
		—»— $(^2D_2^0 - ^4S_3^0)$ } G. S.	3728,91
3872	3869	» $2s^2 2p^2 (^3P)(3d\,^4P_1 - 3p\,^4D_2^0)$	3872,5
4048,5	-	» —»— » $(4f\,^4F_4^0 - 3d\,^4F_4)$	4048,2
4076	4076,2	» —»— » $(3d\,^4F_5 - 3p\,^4D_4^0)$	4075,9
4092	-	» —»— » $(3d\,^4F_4 - 3p\,^4D_4^0)$	4092,9
4119,7	-	» —»— » $(3d\,^4D_4 - 3p\,^4P_3^0)$	4119,2
4368,2	-	» —»— » $(3d\,^2D_2 - 3p\,^2D_2^0)$	4369,3 } 4368,1
		» —»— » $(3p\,^4P_2^0 - 3s\,^4P_3)$	4366,9 } 4368,1
4415,1	4416	» —»— » $(3p\,^2D_2^0 - 3s\,^2P_1)$	4416,97 } 4415,9
		» —»— » $(3p\,^2D_3^0 - 3s\,^2P_2)$	4414,89 } 4415,9
5003	5007	*OIII* $2s^2 2p^2 (^1D_2 - ^3P_2)$ } G. S.	5006,9
4362	4363	» —»— $(^1S_0 - ^1D_2)$ } G. S.	4363,1
3469	-	*NI* $2s^2 2p^3 (^2P_{1,2} - ^4S_2^0)$ G. S.	3470,2
4226	-	» $2s^2 2p^2 (^3P)(4p\,^4P_1 - 3s\,^4P_2)$	4224,7
4484	-	» $2s^2 2p^2 (^3P)\,4d\,^4P_3 - 2s\,2p^4\,^4P_3$	4484,4
6543	6545	*NII* $2s^2 2p^2 (^1D_2 - ^3P_2)$ } G. S.	6546,9
6526	-	» —»— $(^1D_2 - ^3P_1)$ } G. S.	6525,6
5751	5755	» —»— $(^1S_0 - ^1D_2)$ } G. S.	5754,8
5891	-	» $2s\,2p^3$ $(^3D_{1,2} - ^3P_{1,2})$ } ?	5892,5
-	-	» —»— $(^3D_3 - ^3P_{1,2})$ } ?	5887,6
5003	-	» $2s^2 2p$ $(3p\,^3S_1 - 3s\,^3P_0)$	5002,7
4780	-	» —»— $(3d\,^3D_1^0 - 3p\,^3D_1)$	4779,8
4566	-	» —»— $(3d\,^3F_2^0 - 3p\,^1D_2)$	4564,8
4226	-	» —»— $(4s\,^1P_1 - 3p\,^1P_1)$	4227,8

appear with about the same intensity. Further, the two lines differ so much in wave-length that they should produce a marked broadening of the line. Such a broadening is not observed.

I therefore take the auroral line 4368,2 to be identical with the OI-line 4368,3.

It appears from the table that possibly also two other weak *OI*-lines corresponding to transitions from the upper *OI*-levels appear in the auroral spectrum.

It is a matter of great importance that we have been able to show that *in addition to the strong forbidden OI-lines from the ground-states, we also find in the auroral spectrum OI-lines, which correspond to allowed transitions from the upper electronic levels of the OI-atom.*

It is of interest to notice that the auroral luminescence contains a number of lines corresponding to transitions from the metastable ground-states. These transitions are marked G. S. in the Table. As regards the forbidden *NI*-lines those which correspond to the transition between successive levels $(^2P_{1,2} - ^2D_{2,3})$ and $^2D_{2,3} - ^4S_2^0)$ have not yet been observed in the auroral spectrum.

The first one is situated far in the infra red, the second one should have a wave-length 5206,3. This line is situated near the so-called second green auroral line (5238); but the difference of wave-length is too large by far to be accounted for by error.

In a recent letter to "Nature", Kaplan (15) announces that a line with a wave-length 3470 under certain conditions appears in the light from a nitrogen discharge tube and he refers the line to the forbidden transition $NI(^2P_{1,2} - ^4S_2^0)$.

René Bernard recently published a letter to "Nature" (16), where he describes auroral spectrograms obtained at the Tromsø-Observatory. From his spectrograms he derives the following results:

1. He finds that a number of bands belonging to the ε-system (called by him Vegard—Kaplan bands) appeared in the auroral spectrum.

2. He finds that in the spectrum from diffuse auroras a number of lines or bands appears, which are either absent or weak in spectra from ordinary distinct forms.
3. He announces the presence of a line with a wave-length nearly equal to 3470, and he assumes his line to be identical with the line measured by Kaplan and which may possibly be due to the forbidden transition $NI(^2P_{1,2}—^4S_2^0)$.

Bernard does not seem to be aware of the fact that the observational results he derives from his spectrograms are well known and have been described by the writer in papers published many years ago.

As already mentioned, bands of the ε-system have been found by the writer in the auroral spectrum (5, 10, 11), and also spectra from diffuse aurora were found to give a number of weak lines, especially in the blue part, which are absent or relatively weaker in spectra from distinct forms.

The line with a wave-length nearly equal to 3470 was observed and measured by the writer from spectrograms obtained in 1923, and has since been measured on a large number of spectrograms. The mean wave-length derived from our spectrograms is 3469,4 Å. The line has been interpreted by the writer as the head of a band belonging to the 2nd positive group. The band head 2. P. G. (3—4) has a wave-length 3469 which agrees well with the auroral line in question. This interpretation is also supported by the fact that several other bands of the series 2 P. G. (3-n) appear in the auroral spectrum.

There are, however, certain facts which might indicate that *in addition to the band 2. P. G. (3—4)* also some atomic line appear so close to the band, that with the dispersion as yet used, they are not separated. Thus it has been found that the intensity of the line (3469,4) relative to that of the other bands of the 2. P. G. may vary considerably. Compare e. g. the intensity numbers given in paper (7) Table XI with those of Paper (5) Table X. Further, this line sometimes appears to be sharper than we usually find for the bands. This might speak in favour of the interpretation proposed by Bernard.

Although the present observational data do not settle the question as to the origin of the auroral line (3469,4), *the interpretation suggested by Bernard acquires particular interest when seen in connection with the interpretation of weak auroral lines which is given by the writer and summarised in the Table.*

When Bernard's interpretation of the line 3469,4 is added, we see that in the auroral spectrum *lines possibly appear, which correspond to forbidden transition from the metastable ground-states of the following atomic systems:*

Neutral (O) and (N) atoms (OI, NI)

Singly ionised (O) and (N) atoms (OII, NII)

and *O-atoms which have lost two electrons (OIII).*

The results summarized in the table have a most important bearing on the question as to the composition and state of the upper atmosphere.

When we remember that the auroral luminescence is primarily excited by swift cathode rays, the appearance of lines originating from atomic oxygen and nitrogen in the ionised state would show *that atoms of oxygen and nitrogen must be present in the auroral region and with a relative concentration which is of the same order of magnitude as that of molecular nitrogen and oxygen. At any moment a relatively large number of the O- and N-atoms must be in an ionised state.*

The auroral lines originating from atomic nitrogen and oxygen are not restricted to those corresponding to transitions from the metastable ground-states, but also lines from the upper levels appear. With exception of the strong green *OI*-line and the red *OI* triplett, all the lines from atomic nitrogen (*NI, NII*) and oxygen (*OI, OII, OIII*) are most probably excited directly by the impact between the atom and the primary solar electron ray.

In order to explain the prominent intensity of the green *OI*-line and the red *OI*-triplett, and the great variability of the red triplett, the writer (5, 10, 11 a) has assumed that the excitation of the strong *OI*-lines mentioned, requires some secondary processes.

For the excitation of the $^1S_0$-state which results in the emission of the green line, the writer (5) introduced the process:

$$O_2 + N_{\text{act}} = OI(^1S_0) + OI(^3P_2) + N_2$$

where N_{act} represents active nitrogen most of which is formed through the effect of the rays.

To account for the great variation of the red triplett some process is necessary which brings the O-atom directly to the $^1D_2$-state. The writer (5, 11) has suggested that the $^1D_2$-state may be directly excited through collisions of the second kind between ozone (O_3) and nitrogen in an activated state, e. g. nitrogen molecules in the metastable $A(^3\Sigma)$-state.

The interpretation of weak auroral lines has shown that oxygen and nitrogen atoms are present in such large concentrations, that they may possibly play some part also in the excitation processes, which lead to the emission of the strong *OI*-lines. This view is supported by the fact that also *OI*-lines — corresponding to allowed transitions from the upper *OI*-levels — appear in the auroral spectrum.

The fact that the intensity of the green line relative to that of the negative nitrogen bands decreases with increase of altitude (6, 7) shows that *probably only a small fraction of the intensity of the green line and the red triplett is due to direct excitation of an oxygen atom through collision with a rapidly moving electron.*

On the other hand, our interpretation of the weak bands and lines explains the fact that they appear relatively stronger as we pass upwards in the auroral region. The enhancement of the ε-system with increase of altitude is accounted for by the fact that it corresponds to a forbidden electronic transition from the metastable $A(^3\Sigma)$-state of N_2, because the probability of a transition $A(^3\Sigma)\rightarrow X(^1\Sigma)$ will increase as the pressure diminishes towards greater altitudes.

The enhancement of the weak atomic *O*- and *N*-lines with increase of height is what we may expect when we remember that the relative concentration of atomic oxygen and nitrogen must increase towards higher altitudes.

The presence in the auroral region of atomic oxygen and the emission of *OI*-lines corresponding to transitions from the higher electronic *OI*-levels give us new possibilities for the explanation of the relative enhancement of the red *OI*-triplett with the strongest component 6300. Let us assume that the $^1S_0$-state is mainly excited according to the equation given above. Through the emission of the green line $OI(^1S_0—^1D_2)$ the $^1D_2$ will be excited and the further transition to the $^3P_{0,1,2}$ states results in the emission of the red *OI*-triplett. In addition, *both the* $^1S_0$ *and the* $^1D_2$ *states will be reached as the result of transitions from the upper electronic levels, which give emission lines so far in the ultra-violet that they are absorbed in the atmosphere.* Now it is probable that the lines which correspond to transition to the $^1D_2$-state are stronger and more numerous than those which correspond to transitions towards the $^1S_0$-state. An increase in the concentration of atomic oxygen and in the intensity of the *OI*-lines attached to the upper levels thus will produce an enhancement of the red *OI*-triplett relative to the green line. Now the concentration of atomic oxygen must increase upwards and should also increase with solar activity and in this way we would be able to account for an enhancement of the red *OI*-triplett with altitude, with sunspot frequency and with the presence of sunlight.

The diagrams figs. 1 and 2 give for the systems *NI, NII, OI, OII* a representation of those groups of electron levels which are of particular importance in connection with the interpretation of the auroral spectrum.

In the case of *OIII* we have as yet only observed two auroral lines which may possibly be due to this system. The level system of *OIII* is similar to that of *NII*. The *OIII* lines here given thus correspond to the transitions from the ground-states as illustrated in the *NII* diagram.

We notice from the diagrams that only a comparatively small number of possible lines of atomic oxygen and nitrogen have as yet been observed in the auroral spectrum.

This may be due to various causes.

1. The lines are situated in infra-red or ultra-violet outside the range of our observations.
2. A number of lines is masked by stronger lines and bands.
3. Apart from the strong lines corresponding to the ground-states of (*OI*) all atomic lines are very weak and only the strongest which are not masked by others are detected and measured.
4. Spectrograms corresponding to high altitudes or to diffuse auroral forms show a large number of weak lines; but with the small dispersion used they fall so close together that they form more or less continuous bands and only a comparatively small number occasionally appears sufficiently distinct to be measured.

From the *NII* diagram fig. 1 and from the table we notice that the transition $2s2p^3(^3D_{1,2}-^3P_{1,2})$ if it occurred, would result in the emission of a line with the wave-length (5892,5). Within the limit of error this line coincides with the auroral line (5891) and it coincides almost perfectly with the corresponding line observed in the spectrum of the night sky.

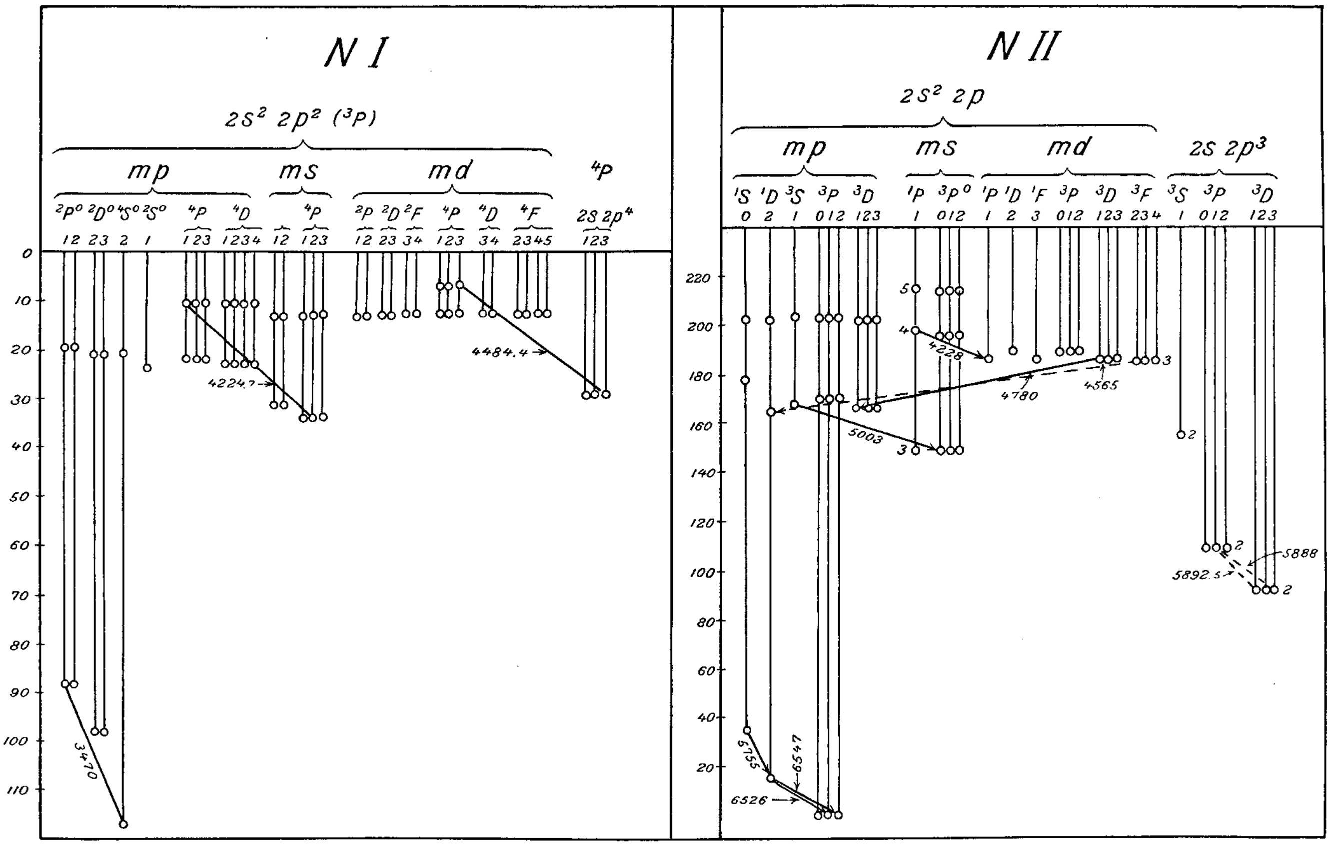

Fig. 1.

From a very distinct spectrogram of the night sky obtained by the writer at Oslo, we found the wave-length 5892,6 (17). This value, which agrees well with the best ones found by other observers, is almost exactly equal to the *NII* line mentioned.

Recently R. Bernard (18) and about simultaneously Cabannes, Dufay and collaborators (19, 20) advocated the view that the line 5892,6 which also appears in the twilight spectrum, should originate from sodium and represent the mean value of the two *D*-lines of sodium. Now the transition $NII\,2s2p^3\,(^3D_3 - {}^3P_{1,2})$ if it occurred would give a line 5887,6 close to the other, and the presence of this line might account for the fact that the night sky line in our spectrograms appeared a little broader than an ordinary single atomic line. In view of the great difficulty we meet in accounting for the presence of relatively large quantities of *Na* in the upper atmosphere, it seems that the interpretation here given deserves earnest consideration. It is, however, to be borne in mind that the lines 5892,5 and 5887,6 do not occur among the observed and tabulated *NII* lines.

On certain auroral spectrograms we have obtained a somewhat broad line with wave-length 5139. It has been suggested in earlier publications (5) that the line might either be a band belonging to the 1. P. G. of nitrogen or an oxygen line. I think that the latter possibility deserves further consideration.

In the oxygen arc spectrum (*OI*-spectrum) tabulated in Kayser's Handbuch der Spectroscopie we find the two prominent lines 5146,2 and 5130,7. The mean value 5138,4 coincides within the limit of error with the observed line. It must be remembered that the spectrograph with which the line was obtained has a too small dispersion to effect a separation of the two *OI*-lines. The two *OI*-lines 5146,2 and 5130,6 correspond to the transitions $2s2p^5\,{}^3P_j^0 - 2s^2 2p^3 (^4S)\,5p\,{}^3P_{0,1,2}$, where $j=2$ and 1 respectively.

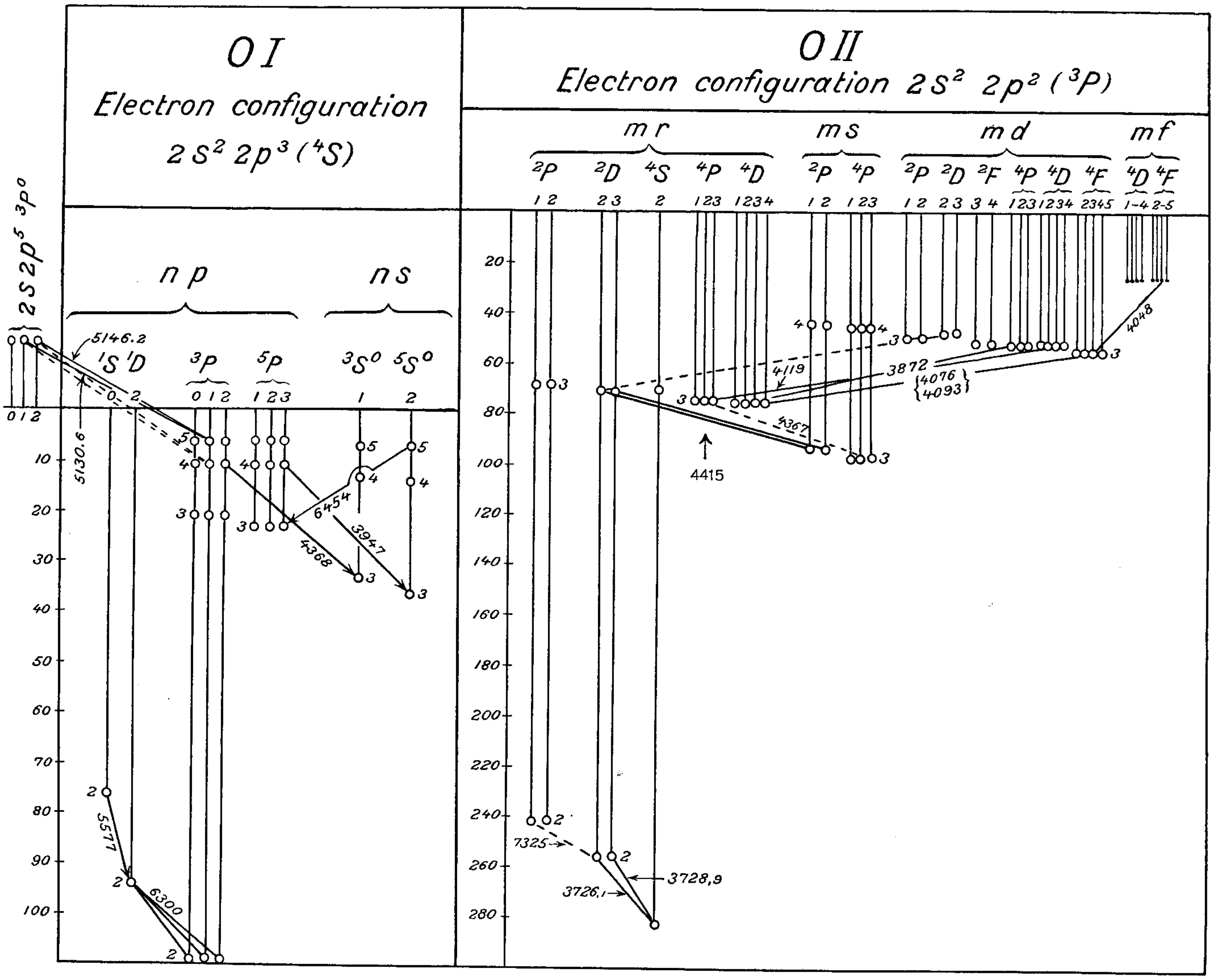

Fig. 2.

Summary.

1) The ε-system corresponding to the forbidden electronic transition $N_2 : A\,(^3\Sigma)$—$X\,(^1\Sigma)$ was discovered by the writer in 1924 in the luminescence from solid nitrogen. The true interpretation and term formula of the ε-system were given in 1932 and at the same time the writer showed that a number of ε-bands appeared in the auroral spectrum showing for the first time that the ε-system is emitted not only from solid nitrogen, but also from the gaseous state. Thus the emission of the ε-system corresponding to the forbidden transition $N_2\,(A—X)$ was found for the gaseous phase and fully interpreted by the writer two years before Kaplan observed some of these bands from gaseous nitrogen.

2) It has been shown that most lines observed in the auroral spectrum, and which do not belong to any of the band groups of nitrogen, may be due to the atomic spectra of oxygen and nitrogen. Two lines 4415,1 and 4368,2 have recently been measured very accurately. The first is identical with the nebular line 4416 and originates from *OII*, the second one is identical with the prominent *OI*-line 4368,3.

3) Auroral lines to a number of 10 may be due to transitions from metastable-ground states of the atomic systems *NI, NII, OI, OII* and *OIII.*

4) No less than 10 auroral lines are found to coincide approximately with lines observed in stellar nebulae.

5) The observational data, which R. Bernard (16) deduced from auroral spectrograms obtained at Tromsø,

are well known from previous observations by the writer and his collaborators.

6) The broad line (5139) may possibly be identified with the two *OI*-lines 5146,2 and 5130,7.

7) The line 5891, probably identical with the night sky line 5892,6, may possibly be due to the *NII* spectrum.

8) The appearance in the auroral spectrums of lines of *NI*, *NII*, *OI*, *OII* and *OIII* shows that atoms of nitrogen and oxygen partly neutral and partly ionised must be present in the auroral region and with concentrations which above a certain attitude are of the same order of magnitude as that of molecular nitrogen and oxygen.

9) The interpretation of the weak auroral lines here given explains the fact that the weak lines increase in number and relative intensity as we pass upwards, for this only means that the percentage of atomic nitrogen and oxygen increases upwards in the auroral region.

10) The presence of atomic oxygen and the emission of *OI*-lines corresponding to higher *OI*-levels may essentially contribute to the observed fluctuations in the relative intensity of the red *OI*-triplett ($^1D_2$—$^3P_{0,1,2}$).

List of Papers.

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2. L. Vegard: Ann. d. Phys. 5. V. 6, 487, 1930.
3. L. Vegard: Z.S. f. Phys. V. 75, 30, 1932.
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