

## **A new method of organizing line intensity ratio fluctuations of aurora - and nightglow emissions based on methods with the new intensity formula**

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### **Abstract**

*In this paper a new kind of linearization effect between the atmospheric aurora and nightglow emissions is presented. The same kind of a linearization effect has previous been found in nightglow emissions from different spectrophotometer measurements and in the spectro-chemic field from studies of optical light sources and is based on the new intensity formula. Linear graphs have been obtained for atomic spectral lines and vibration band spectrum when the spectral line ratio fluctuations were plotted versus the photon energies of these emissions. This new effect has been studied with a spectrophotometer in aurora emissions, where linear graphs have been obtained in different aurora occasions. By doing such studies of aurora light it is possible to see the importance of the inelastic scattering cross sections between electrons – atoms and electrons – molecules. In this way it has shown to be possible to determine the mean energy of the interacting thermal electrons which are active in the different aurora phases. Ideas about the structure of new formulas for vibration – and rotation band spectra are also discussed. These formulas are based on the structure of the new intensity formula for atomic emissions.*

**Keywords:** *Auroral spectroscopy, Intensity formula*

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### **I. Introduction**

**Aurora** spectroscopy has been developed in the course of more than a century, since the early pioneer work of Ref 1. Only in the recent decades, however, the physical processes that relate electron bombardment to spectroscopic emissions have been understood sufficiently well to allow detailed computations on this problem. The monograph in Ref 2 provides most of the fundamental concept required to model the spectroscopic aurora, and the book of Ref 3 updates some formulas as many numerical parameters. A fairly good and detailed review of questions concerning optical emission of aurora is given in the book of Ref 4.

In a paper in Ref 5 the effect of various electron energy spectra on the photon emission rates of three aurora radiations, the 6300 Å and 5577 Å lines of atomic oxygen and the 4278 Å band of ionized molecular nitrogen, was studied. There was also explored a quantitative relationship between aurora electron fluxes and these spectroscopic emissions. The model studied there includes two major sources of atomic and molecular excitations energetic electron impact and dissociative recombination. Another thing, which is important to note, is the fact that the model also included thermal electron excitation of the O(<sup>1</sup>D) state.

In another paper in Ref 6 the auroral optical emission rates, thermal ion and electron densities, and low energy electron fluxes were measured in an IBC I by rocket borne payload, simultaneously with the overpass of the Atmosphere Explorer C satellite. In that paper the production rate by electron impact of the various optical emissions is found by evaluating the energy integral of the product of flux and excitation cross section. It is apparent from that investigation that different energy regions of the electron flux contribute to the emissions, especially the thermal energy region, where the excitation cross sections are situated. Several mechanisms to excite the OI 5577 Å-line were proposed. Their calculations indicate that energy transfer from the excited N<sub>2</sub> (A<sup>3</sup>Σ) state provides the principal source below 200 km, and dissociative recombination is the major source above 200 km for that emission. On the other hand, the excitation mechanism of the OI 6300 Å -line was found to be unexplained according to their theory.

These facts are a common feature in the literature, there have been problems to explain the excitation mechanism for the aurora red and green oxygen lines OI 6300 Å and OI 5577 Å in the aurora spectrum. This is rather ironical because these emissions are the most prominent emissions in the whole aurora spectrum. However, there has been a tendency in the literature to be more and more aware of the importance of the low energy electrons to explain auroral emissions. There have also been a lot of observations in the literature indicating the presence of a big population of real low energy electrons taking part in the aurora processes.

**Seasonal** variations of the **nightglow** OH emissions have been reported Ref 7 and Ref 8. Seasonal variations of the rotational temperatures determined from OH bands have been reported in Ref 9 and Ref 10. Ref 11 studied longterm intensity correlations among the OI 6300 Å line, the NaD lines, the OI 5577 Å line, and the 5300 Å continuum. They noted that the correlation study is useful in explaining possible physical relationships between these emissions. Ref 12 have described the seasonal intensity correlations between the OI 5577 Å line and the NaD lines, and between the OI 5577 Å line and the OH (7-2) band. They came to the conclusion that atomic oxygen plays an important part in the time variations of these emissions. Ref 13 have described intensity correlations between the O<sub>2</sub> (0 – 1) and OH (8 – 3) bands, and between the OH (8 – 3) and the OI 5577 Å line, from data of thirty-nine nights. Ref 14 did make studies of seasonal variations of correlations among the NaD lines, the OI 5577 Å line, the O<sub>2</sub> (0 – 1) band and the OH (6 – 2) and OH (8 – 3) bands. They also concluded that the emission mechanism of OH bands was the ozon mechanism.

The purpose of the **present study** is to use a new analysis method on aurora and nightglow emissions, where the fluctuations of line intensity ratios have been studied. For the aurora emissions a new method of analysis has been studied with a spectrophotometer situated at the Lycksele Ionospheric Observatory in Sweden Ref 15 (Thelin 1986)

For the nightglow emissions the spectral data have been taken from different photometer investigations of nightglow emissions at different times and places. Ref 16 Thelin (1986)

From the beginning this kind of analysis has been originated from a certain discovery made by the author and Dr. Sten Yngström during the 1980s, while working with auroral spectroscopy at the Swedish Institute of Space Physics in Kiruna. The data of interest were achieved by using a new computerized, extremely versatile photon counting spectrometer system (IDES), at the Institute of Metals Research in Stockholm, which was suited for the study of intensities of spectral lines.

According to a new theory in Ref 17 Yngström and Thelin (1983) and Ref 18 Yngström (1994), which was created during the 1980s, the intensity I is given

$$I = C \lambda^2 (\exp(-J/kT)) / (\exp(h\nu/kT) - 1) \quad (1)$$

J is here the ionization energy, and C is a factor given by transition probabilities, number densities and sample properties.  $\lambda$  and  $\nu$  are here the wavelength and frequency of the atomic spectral line. This means that the new intensity formula consists of 4 parts : the C-factor,  $\lambda^2$ -part, the J-dependence  $\exp(-J/kT)$  and the Planck factor  $1/(\exp(h\nu/kT) - 1)$ .

Myself and my colleague Dr. Sten Yngström have earlier presented a big number of papers in the past about this formula. We have developed three methods of analyses : the fluctuation method, the absolute intensity method and the detection limit method, which all support the new intensity formula in equation 1.

In this paper a new method of analysis has been used in a study of aurora emission with a spectrophotometer situated at the Lycksele Ionosphere Observatory in Sweden. This study, which principally studies spectral line ratio fluctuations, has earlier been used in the study of seasonal variations in the nightglow emissions Ref 16 (Thelin 1986) and serves as a ground for this aurora and nightglow investigation. From the beginning this kind of analysis has been used for studying a new intensity formula in optical emission spectroscopy by using various kinds of light sources in combination with a versatile image dissector echelle spectrometer system (IDES).

The theory here is presented in Refs 17 and 23 Yngström and Thelin (1983) and in a newer version of the theory by Ref 18 Yngström (1994). From the beginning there have been presented in two spectrochemical papers by Refs 17 and 19 Thelin (1983 and 1985). A more extended version of this method of analysis concerning intensity ratio fluctuations is given by Refs 20 and 21 Thelin (1986 and 1987). A still new analysis method by Thelin and Yngström based on studies of absolute intensities from standard tables and showing the same intensity formula, is presented in Refs 26 and 22.

A summary paper of the whole project including many papers is also presented in Ref 24 (Thelin 2013) in IOSR about the consequences with this new intensity formula in different kinds of spectroscopies.

### **Table I**

#### Experimental parameters used

Spectrophotometer : SP1

Gratings : Bausch and Lomb, 1200 rates / mm, 10 x 12 cm

Spectral range used : 4200 – 6400 Å

Resolution (1:st order) : 1Å

Entrance slit : 0.5 mm

Time / registration : 4 min (measuring time)

Time / registration (total) : 5 min

## II. Experimental

In this investigation a spectrophotometer SP 1 was used, with photoelectric registration and photomultiplier tube. With this spectrophotometer it is possible to choose especially interesting spectral ranges. The smaller spectral area one chooses, the better the resolution is. A synchronous motor driven gearbox and adjustable guiding arms permit the grating to move periodically in such a manner that the whole range from 3500 Å - 8000 Å, or part of it as small as 5 Å, can be recorded. The maximum resolution in the first order is 1 Å and in the second order 0.5 Å. Three scanning speeds can be selected : 15 seconds, 1 minute, and 4 minutes. The spectrum was recorded with a pen recorder, and the total measuring time for the whole wavelength region was 4 min. The back drifting of the grating lasted for 1 min. By repeatedly recording the same spectral range ( 4200 – 6400 Å ) at the same view angle and position, it has shown to be possible to use these spectral data in RD-graphs. The experiment-al parameters and spectral emissions for aurora can be seen in Tables I and II. The emissions for nightglow emissions are shown in Table III. A spectrogram of the observed spectral region including the emissions of the auroral studies, can be seen in Fig 1.

## III. Results and discussion

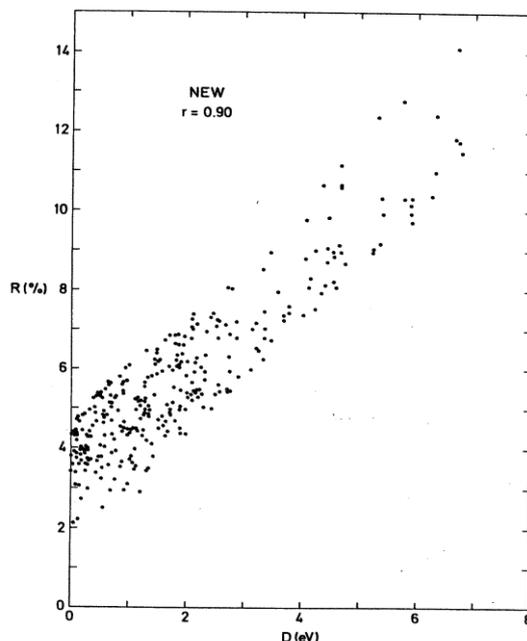
The first method which was developed, was supporting the new intensity formula with an exponential (J+hv) term, is the fluctuation method. This method concerns the study of spectral line intensity ratio fluctuations in Refs 20,21 and 22 where many different optical light sources were used. By forming the ratio between the intensities of two simultaneously measured lines from the same sample and by using logarithmic differentiation of equation 1, we obtain the following linear expression

$$d(I_{mn}^a / I_{kl}^b) / (I_{mn}^a / I_{kl}^b) = d(C_{mn}^a / C_{kl}^b) / (C_{mn}^a / C_{kl}^b) + (1/kT)(dT/T) D(E) \quad (2)$$

where  $D(E) = |J^a - J^b + h\nu_{mn}^a - h\nu_{kl}^b|$  and  $d(I_{mn}^a / I_{kl}^b) / (I_{mn}^a / I_{kl}^b)$  is named R value.

In these studies of the atomic line intensity ratios were measured repeatedly and simultaneously with a spectrometer.  $I_{mn}^a$  and  $I_{m'n}^b$  are here the spectral line intensities of the elements a and b.  $J^a$  and  $J^b$  are the ionization energies of the elements a and b, and  $h\nu_{mn}^a$  and  $h\nu_{m'n}^b$  are the photon energies of the atomic transitions  $m \rightarrow n$  and  $m' \rightarrow n'$  of the elements a and b.

Mathematically this formula is a straight line, which can be seen in Fig 2. from a hollow cathode experiment. In this figure fluctuation data R versus  $D(E) = |J^a - J^b + h\nu_{mn}^a - h\nu_{kl}^b|$  (difference of ionization energy plus photon energy) were used from fifteen steel samples in a hollow cathode lamp. Seventeen elements were studied in this graph giving a correlation coefficient of 0.90 .



**FIG 2** Plot of fluctuation data R versus  $D(E) = |J^a - J^b + h\nu_{mn}^a - h\nu_{kl}^b|$ . (difference of ionization energy plus photon energy) from fifteen steel samples used in a hollow cathode lamp. Seventeen elements were studied in this graph. (Reproduction from Ref 22 )

This paper includes an analysis method (RD-graph) similar to one in the spectrochemical paper by Thelin, where spectral line intensity ratio fluctuations were studied with various kinds of laboratory plasmas such as inductively coupled plasmas (ICP) and different kinds of hollow cathode lamps. In these papers fluctuations of line intensity ratios have been studied and measured repeatedly with a versatile photon counting spectrometer system (IDES).

The same method of analysis was also used when analyzing spectral line ratio fluctuations in the nightglow emissions in a paper by Ref 16 Thelin (1986). The data of these plots were taken from several nightglow investigations at different times and places. This nightglow investigation serves as a basic method of analyzing and combining atomic and molecular spectra.

According to the new method of analysis, Refs 20, 21 and 22 Thelin (1986, 87 and 90) a linear expression was achieved when  $d ({}^a I_{mn} / {}^b I_{m'n'}) / ({}^a I_{mn} / {}^b I_{m'n'})$  was plotted versus

$$D(E) = 1 - {}^a J - {}^b J + {}^a h \nu_{mn} - {}^b h \nu_{m'n'} \quad (2)$$

where line intensity ratios were measured repeatedly and simultaneously with a spectrometer.  ${}^a I_{mn}$  and  ${}^b I_{m'n'}$  are here the spectral line intensities of the elements a and b.  ${}^a J$  and  ${}^b J$  are the ionization energies of the elements a and b,  ${}^a h \nu_{mn}$  and  ${}^b h \nu_{m'n'}$  are the photon energies of the atomic transitions  $m \rightarrow n$  and  $m' \rightarrow n'$  of the elements a and b.

A concept of this is that when spectral lines which differ very much in excitation potentials (big  $D(E)$  – values), are used, the intensity ratios become very temperature dependent, because the exponential factor will be very dominating. This will cause much bigger intensity ratio fluctuations.

The author has found that the same method of studying spectral line ratio fluctuations in the spectrochemical field, is also applicable to atmospheric night glow emissions Ref 16 and auroral emissions Ref 15 which has been demonstrated in detail in the nightglow paper. This means that it is possible to measure spectral intensities (lines and bands) in a long series of repeated simultaneous measurements from the same view angle with a spectrophotometer and to organize the fluctuations of these measurements in the same way as in the spectrochemical papers. The same method of analysis has also been used in this paper, where both auroral and nightglow emissions have been studied. By using intensity ratios, the effect of different view angles or other geometrical parameters are mostly eliminated.

The author has shown that it is possible to obtain a linear relationship by plotting

$$d ({}^c I_{v1,v2} / {}^d I_{v3,v4}) / ({}^c I_{v1,v2} / {}^d I_{v3,v4}) \quad (3)$$

versus

$$D(E) = | ({}^c G'(v_1) - {}^c G''(v_2) - {}^d G'(v_3) + {}^d G''(v_4) ) | \quad (4)$$

which constitutes the total photon exponent at the study of the vibrational transitions. In this way similar plots to those of the spectrochemical papers are achieved for the molecules c and d. By making a standard vibrational analysis of the band systems studied by means of spectra from the standard book of Chamberlain, the vibrational constants were achieved.

$G(v)$  is here the term value of the vibrational state  $v$  and can be written in the following form according to Ref 25 Herzberg (1950).

$$G(v) = \omega_e (v + 1/2) - \omega_e x_e (v + 1/2)^2 + \omega_e y_e (v + 1/2)^3 + \dots \quad (5)$$

$v$  is here the vibrational quantum number, and  $\omega_e$ ,  $\omega_e x_e$  and  $\omega_e y_e$  are vibrational constants referring to the equilibrium of the diatomic molecule.

The author has also found empirically that it is possible to achieve a similar linear relationship by using intensity ratios between vibrational band spectra and atomic spectra. Therefore, it has shown to be possible to obtain a linear relationship by plotting

$$d ({}^a I_{mn} / {}^c I_{v1,v2}) / ({}^a I_{mn} / {}^c I_{v1,v2}) \quad (6)$$

versus

$$D(E) = | ({}^a E_m - {}^a E_n) - C ({}^c G'(v_1) - {}^c G''(v_2)) | \quad (7)$$

or more developed

$$D(E) = | ({}^a E_m - {}^a E_n - C ({}^c G'(v_1) - {}^c G''(v_2)) ) | = | ({}^a E_m - {}^a E_n) - C ({}^c \omega_e (v_1 + 1/2) - {}^c \omega_e x_e (v_1 + 1/2)^2 + {}^c \omega_e y_e (v_1 + 1/2)^3 - {}^c \omega_e (v_2 + 1/2) + {}^c \omega_e x_e (v_2 + 1/2)^2 - {}^c \omega_e y_e (v_2 + 1/2)^3) |$$

where the expression (5) was used. To obtain a linear relationship,  $C$  has been empirically found to be 4.1. The theory of this constant has not yet been quite settled, but it might be the temperature ratio between the internal and the vibrational temperature. This data is in agreement with the results published in Ref 26 and Ref 20 where absolute intensities from standard tables, were studied. In that paper it has been shown that each element studied had individual internal temperature in the same arc measurements. Similar effects seem to appear in the atmospheric emissions.

The same kind of linear relationship is also possible to obtain when studying auroral emissions. This have been done from data outprints from spectrophotometer run at the geophysical observatory at Lycksele and can be seen in an RD-graph in Fig 3 from auroral measurements of a whole night (19.00 – 03.00 LT, 21/7 –

1986 ). According to this graph (triangular points), the points here are much more spread than in an RD-graph of the nightglow emissions in Fig 12.

A logical explanation of this phenomenon could be the influence of the inelastic scattering cross section of incident thermal electrons. According to a paper in Ref 27 this cross section of the process



is equal to the product of transition probability(  $A_{nm}$  ) and an energy function  $f(E)$  according to equation 9.

$$\sigma = A_{nm} f(E) \quad (9)$$

A similar approach has earlier been given by Ref 28 , who has proposed the existence of a de-excitation cross section in the intensity formula. Therefore, it should be seen in RD-graphs of aurora. The energy function  $f(E)$  goes through a maximum at electron energies of about 5 eV, when electrons collide with oxygen atoms. At higher electron energies there is an exponential decrease of  $\sigma$ . According to that paper, spin-forbidden transitions follow an  $E^{-3}$  dependence on the high energy part of that curve, electric dipole-and electric quadropole transitions follow an  $E^{-1} \ln E$  and  $E^{-1}$  dependence respectively. These facts really show the great importance of the spin-flip in auroral emissions.

In an RD-graph where line intensity ratio fluctuations are studied, the author has interpreted the additional fluctuation contribution as coming from the non exponential part(  $C$  – factor ratio fluctuations ) of equations 1 and 2. This can be seen clearly when studying the aurora metastable atomic transitions 5577 Å, 6300 Å, and 6364 Å of oxygen and 5200 Å of nitrogen and can be seen in the RD – graph of Fig 3. The  $\sigma$  – dependence of these atomic emissions is proportional to  $E^{-1}$  ,  $E^{-3}$  ,  $E^{-3}$  ,  $E^{-3}$  respectively. Corresponding  $\sigma$  – values of the diatomic molecule follow an  $E^{-1} \ln E$  dependence according to an experimental paper by Ref 29, where absolute cross section of the electron – impact excitation of  $O_2^+$  first negative bands was measured. In that paper it is clearly seen that the maximum of the  $\sigma$  is situated at much higher energies ( about 100 eV) compared to the cross section of the atoms. By combining different emissions as in the nightglow paper, there will be different additional contributions to the aurora RD – graphs. In this RD – graph aurora emissions have been studied at repeated registrations with a spectrophotometer during a whole night (8 hours) in Fig 3.

For the spin forbidden transitions with  $\Delta S \neq 0$ , the  $\sigma$  –dependence is  $E^{-3}$  , which means that the  $\sigma$ - fluctuation will be  $|d\sigma/\sigma| = 3 |dE/E|$ . For the spin allowed transitions with  $\Delta S = 0$ , this  $\sigma$  –dependence is  $E^{-1}$  , which means that

$$|d\sigma/\sigma| = |dE/E| \quad (10)$$

For example by combining two such alternatives with the cross sections  $\sigma_1$  and  $\sigma_2$  in an RD-graph, there will be contributions from

$$d(\sigma_1/\sigma_2) / (\sigma_1/\sigma_2) = |d\sigma_1/\sigma_1| + |d\sigma_2/\sigma_2| \quad (11)$$

This means that for example  $d(\sigma_{5577}/\sigma_{6300}) / (\sigma_{5577}/\sigma_{6300}) = 4 |dE/E|$  and

$d(\sigma_{6300}/\sigma_{6364}) / (\sigma_{6300}/\sigma_{6364}) = 6 |dE/E|$  respectively

This means that the  $\sigma$ -ratio fluctuations

$$|d\sigma/\sigma| = n |dE/E|, \quad n = \text{integer number} \quad (12)$$

are integer multiples of  $|dE/E|$ . Corresponding  $\sigma$ -fluctuation from the diatomic molecule is

$$|d\sigma/\sigma| = |(1 - 1/\ln E)| |dE/E| \quad (13)$$

where the term is  $|(1 - 1/\ln E)| \approx 1$  at higher mean electron energies. This means for example that the above mentioned fluctuations of  $\sigma_{5577}/\sigma_{6300}$  and  $\sigma_{6300}/\sigma_{6364}$  are proportional 4 and 6 respectively.

Therefore, it is possible to find a straight line, where sigma-ratio fluctuations are subtracted from the observed triangular points of Fig 3. This has been done for the atomic transitions in Fig 3, where the circular black points are  $\sigma$  -corrected for the atomic transitions. Corresponding  $\sigma$  - correction has also been done for the diatomic molecules, which can be seen in Fig 4 (quadratic points). This means that in Fig 4  $\sigma$  - correction has been done for both atomic – and molecular transitions and this line is moved parallel to the line in Fig 3 for atomic transitions. What is really interesting is that we obtain linear graphs (RD-graphs) similar to those of the nightglow emissions. To really see the separation between the triangular points in Fig 3 and the linear graph, a kind of  $\sigma$  –plot can be arranged for the atomic transitions. This can be seen in Fig 5 where the deviation of the triangular points from the “baseline” in Fig 3, has been plotted versus the integer multiple of  $|dE/E|$ . What is really seen from Fig 5 is that this graph is really a straight line supporting the idea of  $\sigma$  – dependence in the aurora emissions. By using different spectral line ratio combinations, the possible integers (1,3,4 and 6) are possible to obtain when combining the atomic transitions. When making corresponding  $\sigma$  -plot for the molecular emissions, there are only two possible integer multiple combinations(1and 2) possibly depending on whether there is one or two molecular emissions in this intensity ratio. Due to equation 13 these “integer” multiples are  $|(1 - 1/\ln E)|$  and  $2|(1 - 1/\ln E)|$  depending on the mean value of the energy  $E$  of the interacting electrons. Such a  $\sigma$ - plot for the molecular transitions is seen in Fig 6. By comparing the slopes in Figs 5 and 6, it is possible to determine  $E$  by using equations 12 and 13. A result of this

study is  $E = 19$  eV as a mean energy value of the interacting thermal electrons measured during a whole night ( 8 hours).

The same kind of RD – graph has also been obtained during a very strong aurora event of 2 hours. This can be seen in Fig 7, where as in Fig 3 the triangular points are situated above the linear “baseline” (filled points), which is  $\sigma$  - corrected for the atomic transitions. What is clearly seen when comparing Fig 7 and 3 is that the mean temperature in Fig 7 is raised for atoms and molecules, because the slope is less than in Fig 3. This is because of the fact that the slope of an RD – graph is  $(1/kT)(dT/T)$ , which means that the slope of the baseline decreases with increasing mean temperature. By making similar  $\sigma$  - plot as Figs 5 and 6 for this strong aurora event, very interesting results concerning the difference between atoms and molecules can be achieved. This can be seen in Figs 8 and 9, where it is easily seen that the slope of Fig 8 for the atoms was increased compared to Fig 5, while the slope of Fig 9 for the molecules was almost unchanged compared to Fig 6. By comparing the slopes in figs 8 and 9 it seems to be possible to determine the mean energy of the interacting electrons by using equations 2 and 4, which gave  $E = 10$  eV. This means that the peak of the Maxwell distribution of the electrons will be situated around 10 eV during this strong aurora event. This means that the strong aurora event of two hours will be a “cooling” (from 19 – 10 eV) of the interacting electron plasma has been going on parallel to the increase of the mean temperature of atoms and molecules. This means that during this strong aurora event it is to a great extent the atomic transitions which have contributed to the fluctuations of the intensity ratios of the emissions. The molecules are excited mostly by electron impact of higher electron energies  $\geq 50$  eV ( Ref 29 Borst (1970). This result also fits well with the excitation cross sections of oxygen, which are situated between ( 3 – 12 eV ) with the mean value = 7 eV, which has been reported in a paper in Ref 6.

After this strong aurora activity ( of 2 hours ), a more calm recovery phase between ( 24.00 – 03.00 LT 22/2, 1973 ) has been studied, too. An RD – graph from this calm period can be seen in Fig10, where the “baseline” for atoms and molecules ( filled lines) are marked. It can be observed that the slope of these lines has increased compared to Fig 7 because of the temperature decrease of the atoms and molecules during this calm recovery phase. The  $\sigma$  -plot of the atoms of this recovery phase can be seen in Fig 11. Obviously there is a great difference between this  $\sigma$  -plot and the one in Fig 8, which indicates an important aurora light mechanism, the  $\sigma$  – dependence. The slope of the line in Fig 11 is obviously more like the line in Fig 5, which indicates that the energy mean value of the Maxwell distribution of the electrons goes back to around 20 eV.

Another obvious observation when comparing Figs 10 and 3 is that the intercept with the R – axis is much lower for Fig 10 (around 12%) than for Fig 3 (around 39%). The explanation of this is that the fluctuations in number density ratios of atoms, molecules, and electrons are much less in Fig 10 than in Fig 3, which is natural to suggest. According to the spectrochemical papers, the number densities are included in the non exponential part of equations 1 and 2, and these intensity ratio fluctuations will be seen as the intercept between the line and the R – axis in an RD – graph.

The results of this investigation are obvious and unequivocal but they are obtained from rather “old fashioned” equipment with rather few spectral emissions used. If for example photon counting equipment and more emissions should be used, more accurate plots would probably be obtained.

By using the differences of the upper states in equations 1 and 2 instead of the differences of the photon energies, no linear relationship could be obtained. Similar results have also been obtained in the nightglow and spectrochemical papers.

The difference between the RD – graphs of the nightglow and aurora emissions is mainly the dependence of the  $\sigma$  -term of the aurora emissions. One can simplify it by saying that the RD – graphs of the nightglow emissions have a similar appearance to the baseline of Fig 4. and Fig 12. There are, of course differences in the number density ratio fluctuations, too, but they are not so great compared to the  $\sigma$  - ratio fluctuations.

As was mentioned above, there are many examples in the literature announcing the importance of the real low energy electrons in explaining aurora emissions. One of these papers is a paper in Ref 5. According to that paper the cross sections for excitation of  $O(^1D)$  and  $O(^1S)$  peak below 20 eV where their model and their observations agree. Since both the electron flux and the excitation cross sections decrease with increasing energy, the product of the two quantities decreases rapidly. According to that paper, this is why the electrons with energies above 20 eV make only a small contribution to excitation of the metastable oxygen levels.

There are also many papers in the literature explaining energy loss of electrons at inelastic collisions with neutrals in accordance with the electron cooling process in Fig 8. Electrons lose energy through various inelastic collisions resulting in the excitation of rotational and vibrational states of molecules, electronic states of atoms and molecules, and fine structure levels of oxygen atoms. The rates at which electrons lose energy in exciting rotational bands of molecular oxygen and nitrogen, are given in a paper by Ref 30 and the expressions for electron loss due to vibrational excitation have been used by Ref 31 and Ref 32. According to these papers, the electron energy loss mechanism from electron impact is an important cooling process in the ionosphere. This

is what is really observed in Figs 7 and 8 during the strong auroral event in this paper; a cooling effect of the electron plasma and an increase in the temperature of the atoms and molecules.

There have also been studied in Ref 33 of the number of quanta of the OI 6300 Å, OI 5577 Å, and N<sub>2</sub><sup>+</sup> 3914 Å emissions, produced per incident electron (energy). These results agree well with the results of this paper, because the number of quanta emitted from the metastable oxygen emissions are much higher (orders of magnitude) than for the N<sub>2</sub><sup>+</sup> 3914 Å emission of real suprathermal electrons (≤ 50 eV). The molecular emissions are more sensitive to impact electrons of a little higher energies (≥ 50 eV).

#### IV. Conclusion

This paper demonstrates that the RD – graphs seem to be effective of revealing fundamental aurora de – excitation mechanisms.

The RD – graphs also make it possible to see the difference between nightglow and auroral processes clearly. A contributor to the aurora light seems to be the electron-atom inelastic scattering cross section  $\sigma$  of the suprathermal electrons in the energy range  $\leq 50$  eV. According to the energy function of equation 9, this investigation also shows that the spin flip is very important for the explanation of the aurora emissions. For the electron – molecule scattering cross sections the corresponding electron energies are situated in the energy range  $\geq 50$  eV). The mean electron energy of the Maxwell distribution has been calculated to be around 20 eV during a whole night of aurora activities.

What has been observed during a strong aurora event is a cooling process for the electron plasma (from  $\approx 20$  to  $\approx 10$  eV), while the temperature of the atoms and molecules will increase according to the RD – graph. These observations have also been made earlier with other methods by many people studying inelastic collisions with neutrals. However, this electron energy loss process due to excitation of rotational and vibrational states of molecules and electronic states of atoms, is an important cooling process in the ionosphere.

The investigation reported in this paper shows that the method by Thelin and Yngström of analyzing relative line intensity ratio fluctuations in optical emission spectroscopy of laboratory plasmas, is also suitable for the nightglow emissions of the upper atmosphere. This can be seen in Figs 12 - 14 where the relative fluctuations of the intensity ratios between the different nightglow emissions have been plotted versus the differences between the photon energies of the emissions used. The data of these plots and other examples were taken from several previous investigations at different times and places. The linearity of these plots can also serve as a check of the vibrational analyses of the band spectra, which are organized along a straight line. From these plots it is possible to find out which combinations of spectra are temperature dependent and which are not, which is important in order to understand the spectral variations in the upper atmosphere.

The present results indicate that the main reason of seasonal spectral variations is temperature variations.

This paper has shown linearity in the RD-graphs where the differences between the vibrational states as in equation 2 are used both in aurora and nightglow emissions. On the other hand, when the differences between the upper states in equation 2 are used, no linear relationship could be obtained. This is in accordance with the new theory and all our different measurements using the new intensity formula for atomic spectra. The same thing is happening in vibrational spectra according to these measurements and means that we ought to have the photon energy in the exponent in stead of the upper state (Boltzmann). This fact is supported by the literature, often showing “Planck factor” structures at the studies of spectra of diatomic molecules.

To construct new formulas for the vibrational and rotational spectra it is convenient to study the structure of the new intensity formula for atomic transitions, because they all produce light. The new intensity formula in equation 1 consists of 4 different parts, as shown in chapter 1. The J-term there is the most probable energy term from the termscheme and the “Planck factor” is the most probable photon distribution. With these distributions as a model for the light formulas for vibrational – and rotational spectra, the following suggestions of these formulas might be :

Vibrational spectra :  $I_v = C f(\lambda) \exp((-D_0) / kT_v) / (\exp h \nu_v / k T_v) - 1$

where  $\Delta G(v)_{\text{mean}} = D_0$  and  $h \nu_v = G(v)^1 - G(v)^{11}$

This formula has only been studied on the “Planck term” and demands future work for the whole formula.

Rotational spectra :  $I_r = C f(\lambda) \exp((-G_v) / kT_r) / (\exp h \nu_r / k T_r) - 1$

where  $\Delta F_v(J)_{\text{mean}} = G(v)$  and  $h \nu_r = F^1(J) - F^{11}(J)$

where J = rotational quantum number. This formula is not yet studied and it demands a lot of future work.

**Table II**

Element	<u>Aurora emissions used</u>		Spin
	Wavelength	Transition	
OI	5577	$2^1D - 2^1S$	$\Delta S = 0$
OI	6300	$2^3P - 2^1D$	$\Delta S \neq 0$
OI	6364	$2^3P - 2^1D$	$\Delta S \neq 0$
NI	5200	$2^4S - 2^2D$	$\Delta S \neq 0$
$N_2^+$	4278	0 - 1	
$N_2^+$	4709	0 - 2	
$N_2^+$	5228	0 - 3	
$N_2$	6187	4 - 0	
$O_2^+$	5296	2 - 0	
$O_2^+$	6026	0 - 0	

**Table III**

Nightglow emissions used

Element	Filter (Å)	Spectral range (Å)	Bandhead or line (Å)	Vibr. data	Systems
OI	5580	115	5577	-	$^1D - ^1S$
OI	6300	130	6300	-	$^3P - ^1D$
OH	6700	-	6862	(7 - 2)	Meinel
OH	6300	130	6256	(9 - 3)	"
$O_2^+$	5260	120	5296	(2 - 0)	1N, b → a
$N_2^+$	4400	570	4710	(0 - 2)	1N, B → X
$N_2^+$	3670	350	3914	(0 - 0)	1N, B → X

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**Figures**

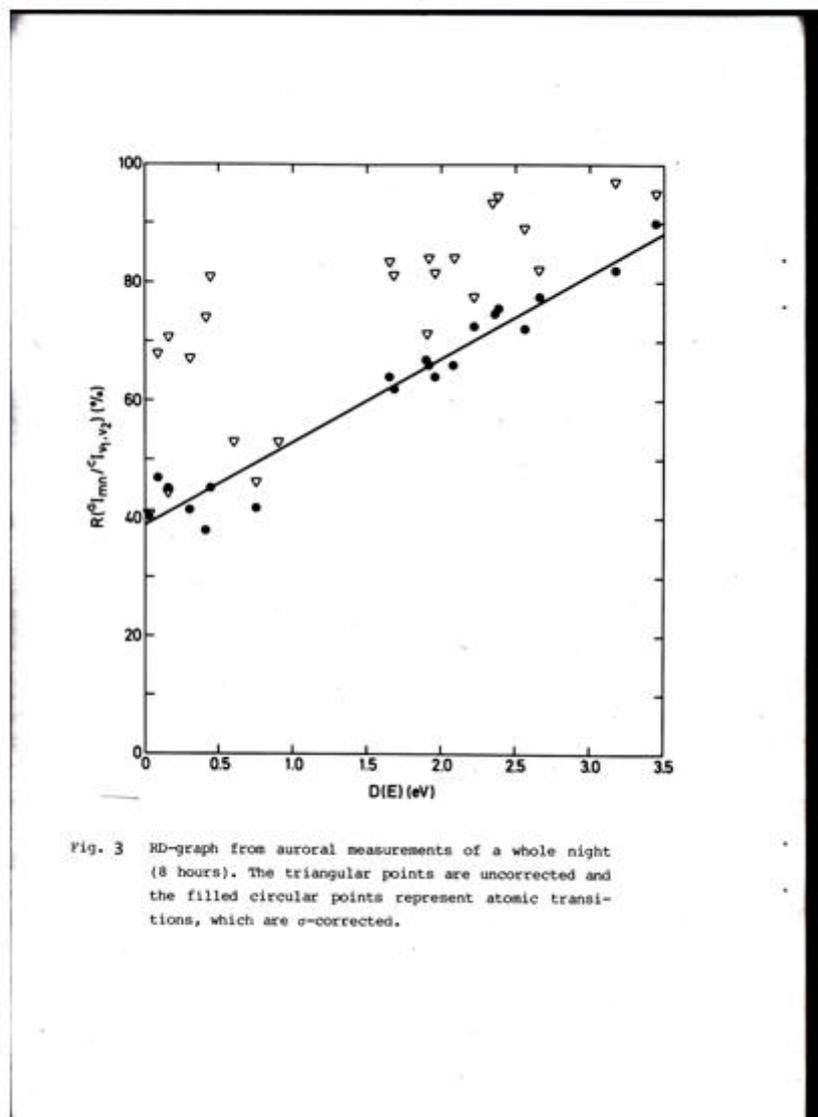


Fig. 3 HD-graph from auroral measurements of a whole night (8 hours). The triangular points are uncorrected and the filled circular points represent atomic transitions, which are  $\sigma$ -corrected.

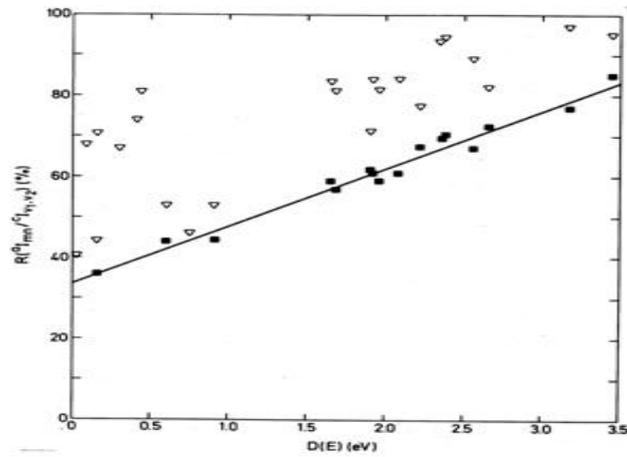


Fig. 4 RD-graph from auroral measurements of a whole night (8 hours). The triangular points are the same as in Fig. 3. The filled squares represent atomic and molecular transitions, which both are  $\sigma$ -corrected.

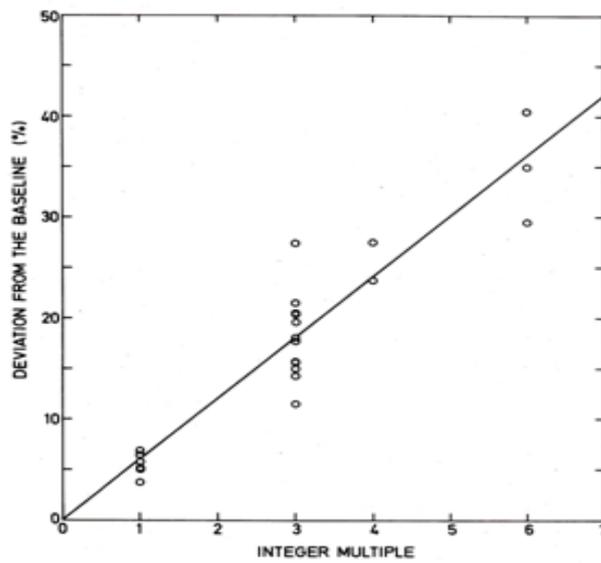


Fig. 5  $\sigma$ -plot for the atomic transitions in Fig. 3. The deviations from the "baseline" in the RD-graph plotted versus an integer number.

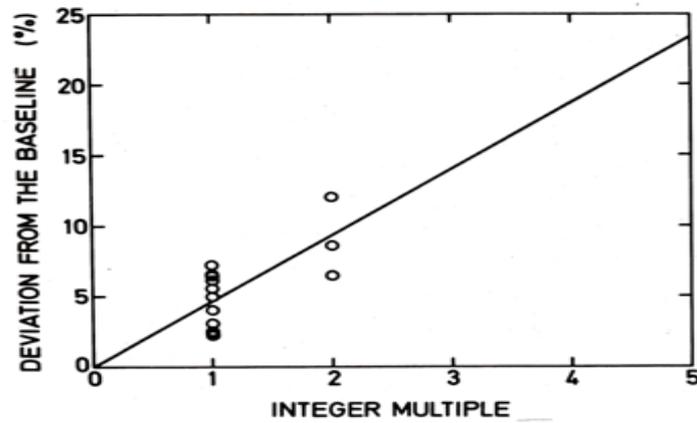


Fig 6  $\sigma$ -plot for the molecular transitions in Fig. 4 The deviations from the "baseline" in the RD-graph plotted versus an integer number.

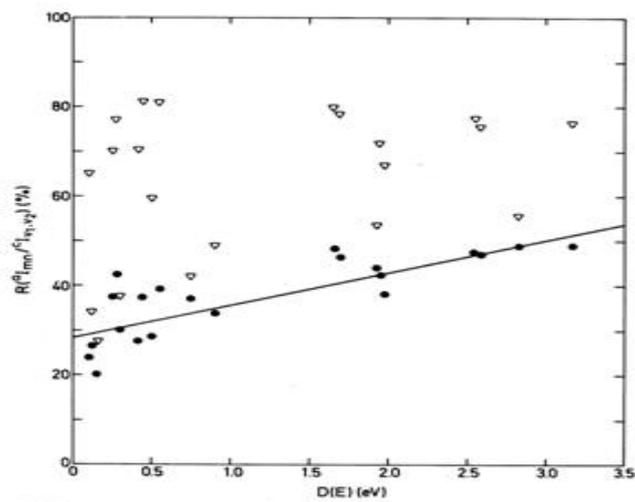


Fig. 7 RD-graph from a strong auroral event. The filled circles represent atomic and molecular transitions, which both are  $\sigma$ -corrected.

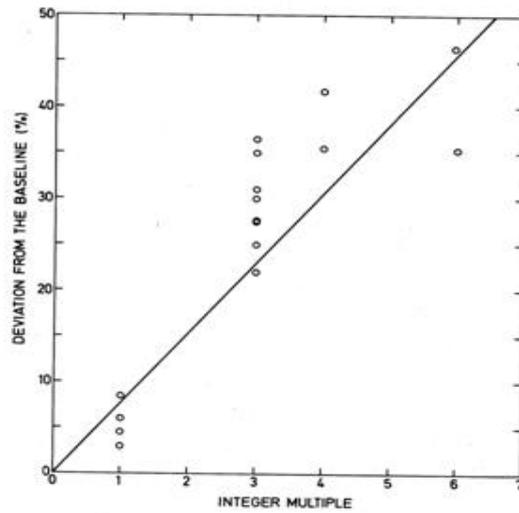


Fig. 8 e-plot for the atomic transitions from the same strong auroral event.

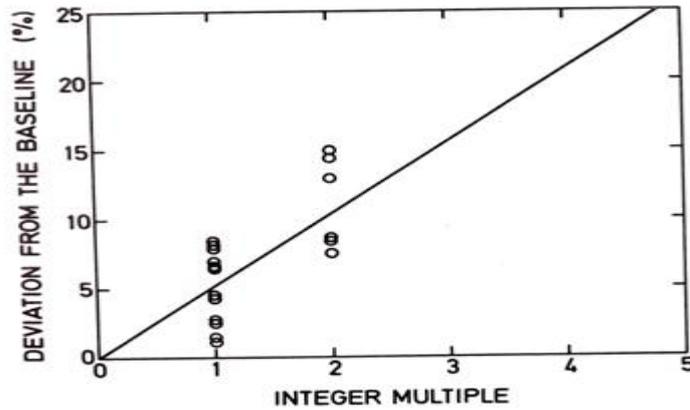


Fig. 9 e-plot for the molecular transitions from the same strong auroral event.

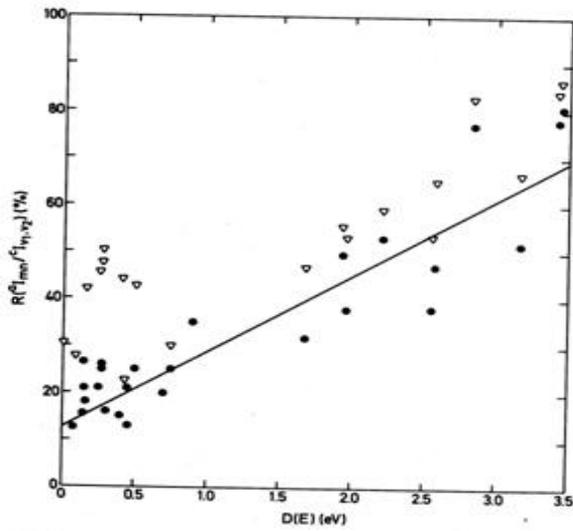


Fig 10 MD-graph from the calm auroral period. The filled circles represent atomic and molecular transitions, which both are  $\sigma$ -corrected.

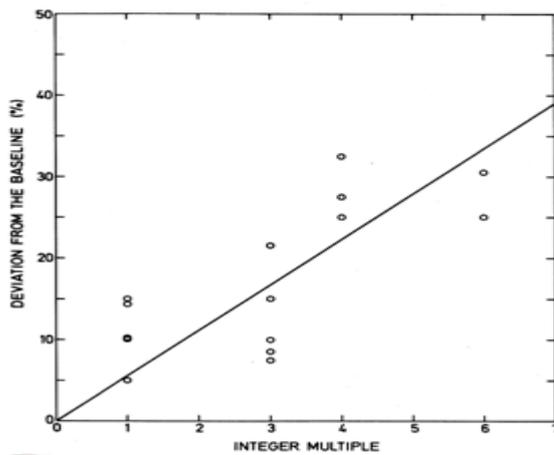


Fig. 11  $\sigma$ -plot for the atomic transitions from the calm auroral period.

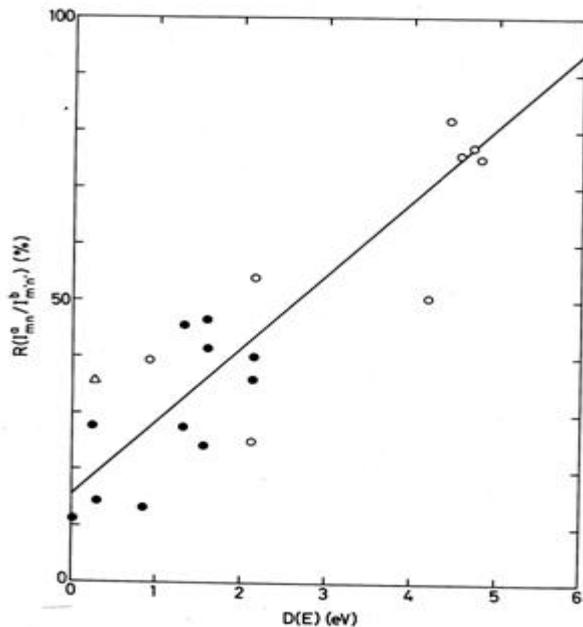


Fig 12. KD-plot from nightglow measurements (Barbier) over a period of three years. Filled circles constitute points from vibrational - vibrational spectra and unfilled circles constitute points from vibrational-atomic spectra.

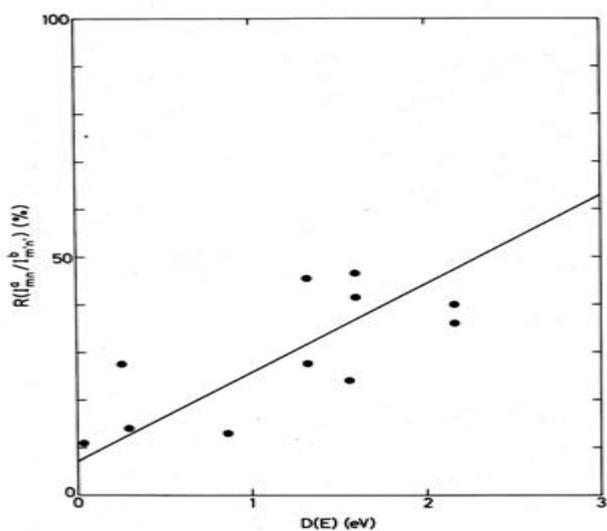


Fig 13. KD-plot from nightglow measurements over a period of three years, where only vibrational spectra have been studied.

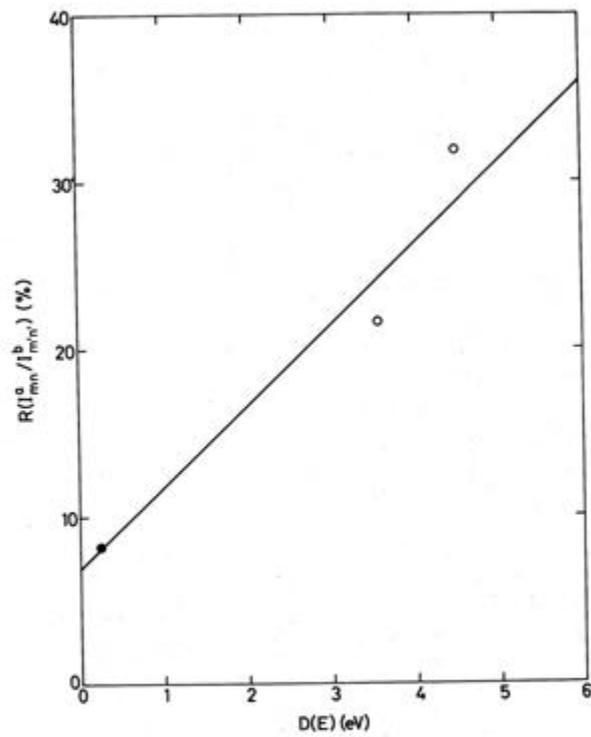


Fig 14. KD-plot from nightglow measurements over a period of one year (Kao and Kulkarni).