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A new method of organizing spectral line intensity ratio fluctuations of auroral emissions

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Abstract

In this paper a new kind of linearization effect between the atmospheric auroral emissions is presented. The same kind of linearization effect has previously been found in nightglow emissions from photometer measurements and in the spectrochemical field from studies of optical light sources. Linear graphs have been obtained for atomic spectral lines and vibrational bandspectra 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 auroral emissions, where linear graphs have been obtained on different auroral occasions. By doing such studies of auroral light it is possible to see the importance of the inelastic scattering cross section 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 that are active in the different auroral phases.

Keywords: Auroral spectroscopy.

1. Introduction

Auroral spectroscopy has been developed in the cause of more than a century, since the early pioneer work of Ångström (1869). Only in the recent decade, 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 by Chamberlain (1961) provides most of the fundamental concept required to model the spectroscopic aurora, and the book of Omholt (1971) updates some formulas as many numerical parameters. A fairly good and detailed review of questions concerning optical emissions of aurora is given in a book of Wallance-Jones (1974).

In a paper by Rees et al. (1974) the effect of various electron energy spectra on the photon emission rates of three auroral 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 auroral electron fluxes and these spectroscopic emissions. The model studied there includes two major sources of atomic and molecular excitation; 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 $O(^1D)$ state.

In another paper by Sharp et al. (1979), auroral optical emission rates, thermal ion and electron densities, and low energy electron fluxes were measured in an IBC I aurora by a 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_2 $(A^3\Sigma)$ 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 mechanisms for the auroral red and green oxygen lines OI 6300 Å and OI 5577 Å in the auroral spectrum. This is rather ironical because these emissions are the most prominent emissions in the whole auroral 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 auroral processes.

In this paper a new method of analysis has been used in a study of auroral emission with a spectrophotometer situated at the Lycksele Ionospheric 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 (Thelin 1984) and serves as a ground for this auroral investigation. From the beginning this kind of analysis has been used for studying an intensity formula in optical emission spectroscopy by using various kinds of light sources in combination with a versatile image dissector echélle spectrometer system (IDES). The theoretical treatment of this linearization effect has earlier been presented in a theoretical paper by Yngström and Thelin (1983) and in a newer version of the theory by Yngström (1985). The new analysis method of treating spectral line ratio fluctuations has been presented in two spectrochemical papers by Thelin (1983 and 1985). A more extended version of this method of analysis concerning intensity ratio fluctuations is given by Thelin (1986 a and b). This new analysis method has recently been complemented by a still newer analysis method by Thelin and Yngström (1986) based on studies of absolute intensities from standard tables and showing the same intensity formula.

Table I

Experimental parameters used

Spectrophotometer: SP 1
Grating: Bausch and Lomb, 1200 rates/mm, 10 x 12 cm
Spectral range used: 4200 - 6400 Å
Resolution (1:st order): 1 Å
Entrance slit: 0.5 mm
Time/registration: 4 min (measuring time)
Time/registration (total): 5 min

Experimental

In this investigation a spectrophotometer SP 1 was used, with photoelectric registration and a 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 experimental parameters and spectral emissions used can be seen in Tables I and II. A spectrogram of the observed spectral region including the emissions studied can be seen in Fig. 1.

Results and discussion

This paper includes an analysis method (RD-graph) similar to the one in the spectrochemical papers 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 repeatingly witn a versatile spectrometer system.

The same method of analysis was also used when analysing spectral line ratio fluctuations in the nightglow emissions in a paper by Thelin (1984). 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 analysing and combining atomic and molecular spectra.

According to the new method of analysis, Thelin (1986) a linear
expression was achieved when $d({}^{a}I_{mn}/{}^{b}I_{m'n'}) / ({}^{a}I_{mn}/{}^{b}I_{m'n'})$ was plotted versus $D(E) = |{}^{a}J-{}^{b}J+{}^{a}h\nu_{mn}-{}^{b}h\nu_{m'n'}|$ according to the formula:

$$\frac{d({}^{a}I_{mn}/{}^{b}I_{m'n'})}{({}^{a}I_{mn}/{}^{b}I_{m'n'})} = \frac{d({}^{a}C_{mn}/{}^{b}C_{m'n'})}{({}^{a}C_{mn}/{}^{b}C_{m'n'})} + \frac{1}{kT} \cdot \frac{dT}{T} \cdot D(E) \qquad (1)$$

when 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->n, and m'->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, which has been demonstrated in detail in that 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 auroral emissions have been studied. By using intensity ratios, the effects due to 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

$$d\ ({}^{c}I_{v_1,v_2} / {}^{d}I_{v_3,v_4}) / ({}^{c}I_{v_1,v_2} / {}^{d}I_{v_3,v_4})$$

versus

$$D(E) = \left|({}^{c}G'(v_1) - {}^{c}G''(v_2) - {}^{d}G'(v_3) + {}^{d}G''(v_4))\right| \quad (2)$$

which constitutes the total photon exponent at the study of two 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 Herzberg (1950):

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

v is here the vibrational quantum number, and ω_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

$$d\ ({}^{a}I_{mn} / {}^{c}I_{v_1,v_2}) / ({}^{a}I_{mn} / {}^{c}I_{v_1,v_2})$$

versus $D(E) = |((^aE_m - {}^aE_n) - C\,(^cG'(v_1) - {}^cG''(v_2)))|$

where the expression (3) 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 idea is in agreement with the results recently published by Thelin and Yngström (1986), 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 measurement. 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 a spectrophotometer run at the geophysical observatory at Lycksele and can be seen in an RD-graph in Fig. (2) from auroral measurements of a whole night (19.00-03.00 LT, 21/2-1973). According to this graph (triangular points), the points here are much more spread than in an RD-graph of the nightglow emissions.

A logical explanation of this phenomenon could be the influence of the inelastic scattering cross section of incident thermal electrons. According to a paper by Henry et al. (1969), this cross section of the process

$$O(^3P) + e \rightarrow O(^1D) + e$$

is equal to the product of transition probability (A_{nm}) and an electron energy function f(E) according to equation (4):

$$\sigma = A_{nm} \cdot f(E) \qquad (4)$$

A similar approach has earlier been given by Suckerwer (1971), 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 σ. 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 an 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 nonexponential part (C-factor ratio fluctuation) of equation 1. This can be seen clearly when studying the auroral 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. 2. The σ-dependence of these atomic emissions is proportional to E^{-1}, E^{-3}, E^{-3}, and E^{-3} respectively. Corresponding σ-values of the diatomic molecules follow an E^{-1} ln E dependence according to an experimental paper by Borst et al. (1970), 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 σ is situated at much higher energies (~ 100 eV) compared to the cross sections of the atoms. By combining different emissions as in the nightglow paper, there will be different additional contributions to the auroral RD-graphs. In this RD-graph auroral emissions have been studied at repeated registrations with a spectrophotometer during a whole night (8 hours).

For the spinforbidden transitions with $\Delta S \neq 0$, the σ-dependence is E^{-3}, which means that the σ-fluctuation will be $|d\sigma/\sigma| = 3 \cdot |dE/E|$. For the spin allowed transitions with $\Delta S = 0$, this σ-dependence is E^{-1}, which means that $|d\sigma/\sigma| = |dE/E|$. For example, by combining two such alternatives with the cross sections σ_1 and σ_2 in an RD-graph, there will be contribution from $d(\sigma_1/\sigma_2) / (\sigma_1/\sigma_2) = |d\sigma_1/\sigma_1| + |d\sigma_2/\sigma_2|$. This means that for example $d(\sigma_{5577}/\sigma_{6300}) / (\sigma_{5577}/\sigma_{6300}) = 4 \cdot |dE/E|$ and $d(\sigma_{6300}/\sigma_{6364}) / (\sigma_{6300}/\sigma_{6364}) = 6\ |dE/E|$. This means that the σ-ratio fluctuations

$$|d\sigma/\sigma| = n \cdot |dE/E| \qquad (5)\ n = \text{integer number}$$

are integer multiples of $|dE/E|$. Corresponding σ-fluctuation from the diatomic molecules is

$$|d\sigma/\sigma| = |(1 - 1/\ln E)\ dE/E| \qquad (6)$$

where the $(1 - 1/\ln E) \approx 1$ 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 to 4 and 6 respectively. Therefore, it is possible to find a straight line, where these σ-ratio fluctuations are subtracted from the observed triangular points of Fig. 2. This has been done for the atomic transitions in Fig. 2, where the circular black points are "σ-corrected" for the atomic transitions. Corresponding σ-correction has also been done for the diatomic molecules, which can be seen in Fig.3 (quadratic points). This means that in Fig. 3 σ-correction has been done for both atomic- and molecular transitions. To really see the separation between the σ-correction of atoms and molecules the line of Fig. 3 has been put in as a dashed line in Fig. 2, which really shows that these lines are moved parallelly to each other. 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. 2 and the linear graph, a kind of "σ-plot" can be arranged for the atomic transitions. This can be seen in Fig. 4 where the deviation of the triangular points from the "baseline" in Fig. 2, has been plotted versus the integer multiple of $|dE/E|$. What is clearly seen from Fig. 4 is that this graph is really a straight line supporting the idea of σ-dependence in the auroral 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 σ-plot for the molecular emissions, there are only two possible "integer" multiple combinations (1 and 2) possibly depending on whether there is one or two molecular emissions in this intensity ratio. Due to equ (6) these "integer" multiples are (1 - 1/lnE) and 2 (1 - 1/lnE) depending on the mean value of the energy E of the interacting electrons. Such a σ-plot for the molecular transitions is seen in Fig. 5. By comparing the slopes in Figs. 4 and 5, it is possible to determine E by using equations (5) and (6). 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 auroral event of 2 hours. This can be seen in Fig. 6, where as in Fig. 2 the triangular points are situated above the linear "baseline" (filled points), which is σ-corrected for the atomic transitions. What is clearly seen when comparing Figs. 6 and 2 is that the mean temperature in Fig. 6 is raised for the atoms and molecules, because the slope is less than in Fig. 2. This is because of the fact that the slope of an RD-graph is $(\frac{1}{kT} \cdot \frac{dT}{T})$, which means that the slope of the baseline decreases with increasing mean temperature. By making similar σ-plot as Figs 4 and 5 for this strong auroral event, very interesting results concerning the difference between atoms and molecules can be achieved. This can be seen in Figs. 7 and 8, where it is easily seen that the slope of Fig. 7 for the atoms was increased compared to Fig. 4, while the slope of Fig. 8 for the molecules was almost unchanged compared to Fig. 5. By comparing the slopes in Figs. 7 and 8 it seems to be possible to determine the mean energy of the interacting electrons by using equations 1 and 2, 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 auroral event. This means that during the strong auroral event of two hours 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 auroral 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 (> 50 eV) Borst (1970). This result also fits well with the excitation cross sections for oxygen, which are situated between (3-12) eV) with the mean value ≈ 7 eV, which has been reported in a paper by (Sharp et al. 1979).

After this strong auroral activity (of two 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 Fig. 9, where the "baselines" for atoms (filled line) and molecules (dashed line) are marked. It can be observed that the slope of these lines has increased compared to Fig. 6 because of a temperature decrease of the atoms and molecules during this calm recovery phase. The σ-plot of the atoms of this recovery phase can be seen in Fig. 10. Obviously there is a great difference between this σ-plot and the one in Fig. 7, which indicates an important auroral lightmechanism: the σ-dependence. The slope of the line in Fig. 10 is obviously more like the line in Fig. 4, 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. 9 and 2 is that the intercept with the R-axis is much lower for Fig. 9 (around 12%) than for Fig. 2 (around 39%). The explanation of this is that the fluctuations in number density ratios of atoms, molecules, and electrons are much less in Fig. 9 than in Fig. 2, which is natural to suggest. According to the spectrochemical papers, the number densities are included in the nonexponential part of equation 1, 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 "oldfashioned" equipment with rather few spectral emissions used. If for example photon counting equipment and more emission should be used, more accurate plots would probably be obtained.

By using the differencies of the upper states in equ 2, instead of the differencies 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 auroral emissions is mainly the dependence of the σ-term of the auroral emissions. One can simplify it by saying that the RD-graphs of the nightglow emissions have a similar appearance to the baseline of Fig. 3. There are, of cource differences in the number density ratio fluctuations, too, but they are not so great compared to the σ-ratio fluctuations.

As was mentioned above, there are many examples in the literature announcing the importance of the real low energy electrons in explaining auroral emissions. One of these papers is a paper by Rees (1974). 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. 7. 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 Dalgarno (1969), and the expressions for electron loss due to vibrational excitation have been used by Rees et al. (1967) and Dalgarno et al. (1968). 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. 6 and 7 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 studies by Rees and Roble (1975) of the number of quanta of the OI 6300 Å, OI 5577 Å and N_2^+ 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_2^+ 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).

Conclusion

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

The RD-graphs also make it possible to see the difference between nightglow and auroral processes clearly. A contributor to the auroral light seems to be the electron-atom inelastic scattering cross sections (σ) of suprathermal electrons in the energy range <50 eV. According to the energy function of equation (4), this investigation also shows that the spinflip is very important for the explanations of the auroral emissions. For the electron-molecule scattering cross sections the corresponding electron energies are situated in the energy range >50 eV. The mean electron energy of the Maxwell distribution has been calculated to be around 20 eV during a whole night of auroral activities.

What has been observed during a strong auroral event is a cooling process for the electron plasma (from about 20 to about 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.

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TABLE II

Emissions used

Element	Wavelength(Å)	Transition	Spin
OI	5577	$2^1D - 2^1S$	$\Delta S=0$
OI	6300	$2^3P - 2^1D$	$\Delta S\neq0$
OI	6364	$2^3P - 2^1D$	$\Delta S\neq0$
NI	5200	$2^4S - 2^2D$	$\Delta S\neq0$
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	

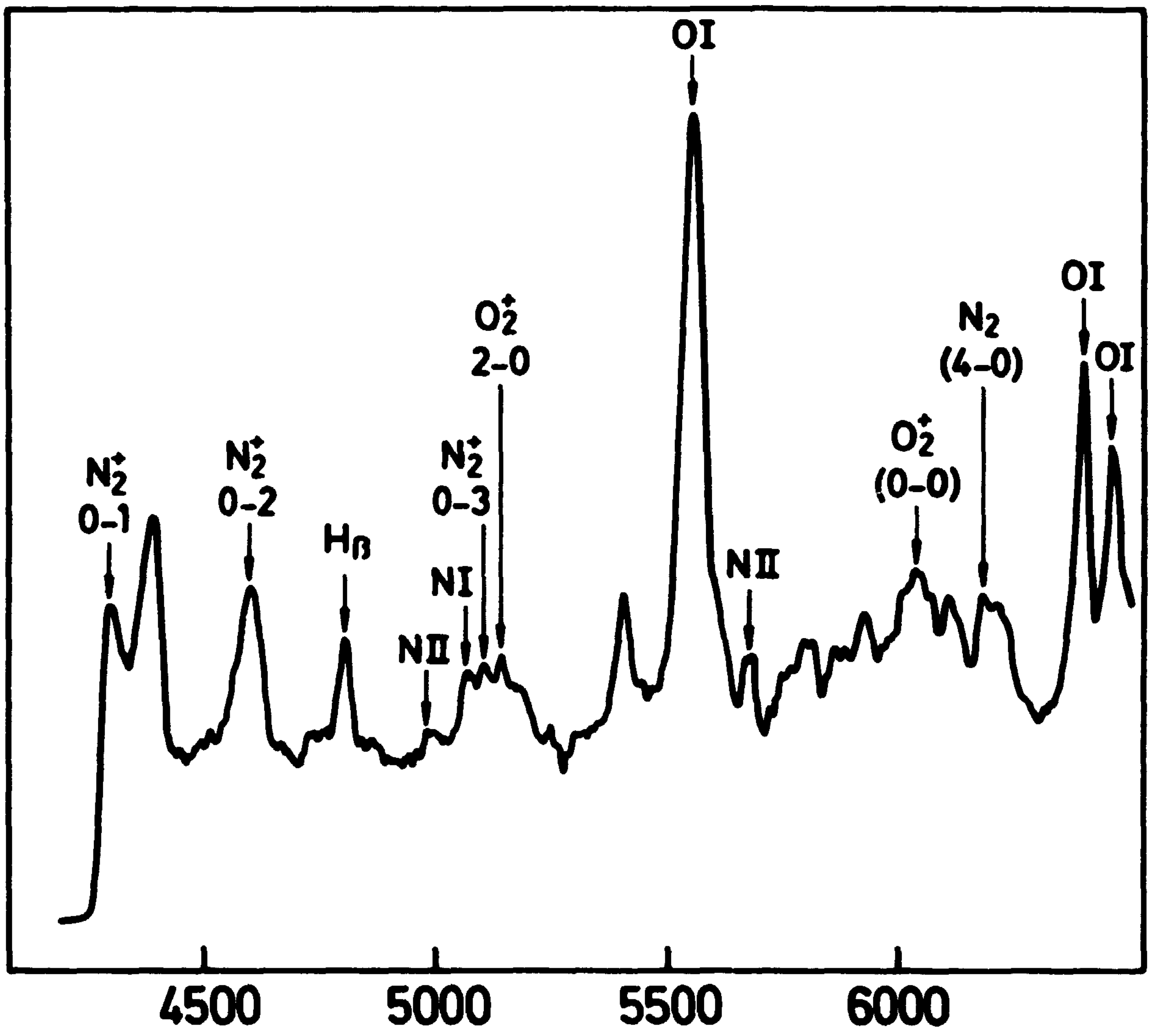

Fig. 1 Spectrogram of the observed spectral region 4200-6400 Å.

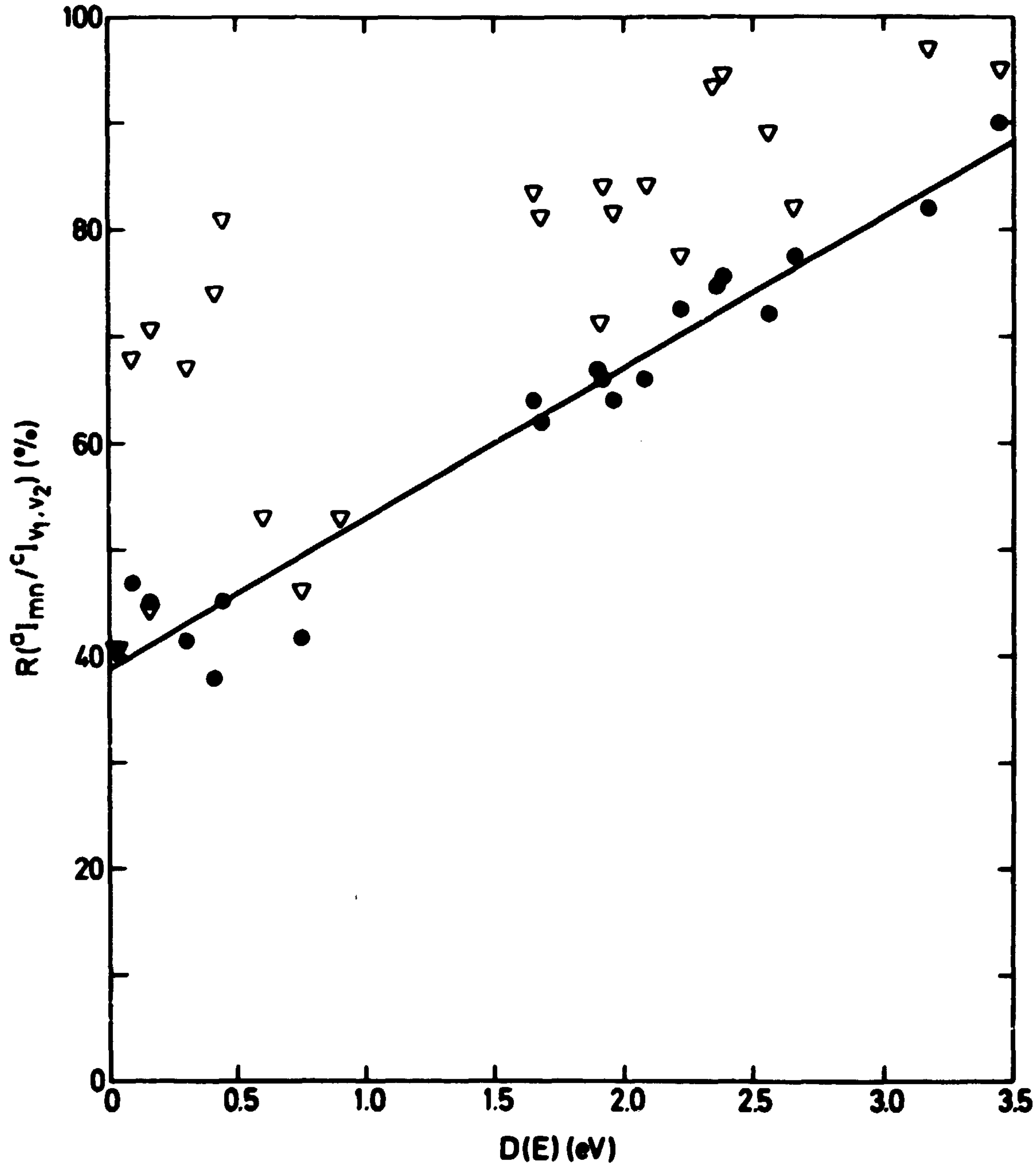

Fig. 2 RD-graph from auroral measurements of a whole night (8 hours). The triangular points are uncorrected and the filled circular points represent atomic transitions, which are σ-corrected.

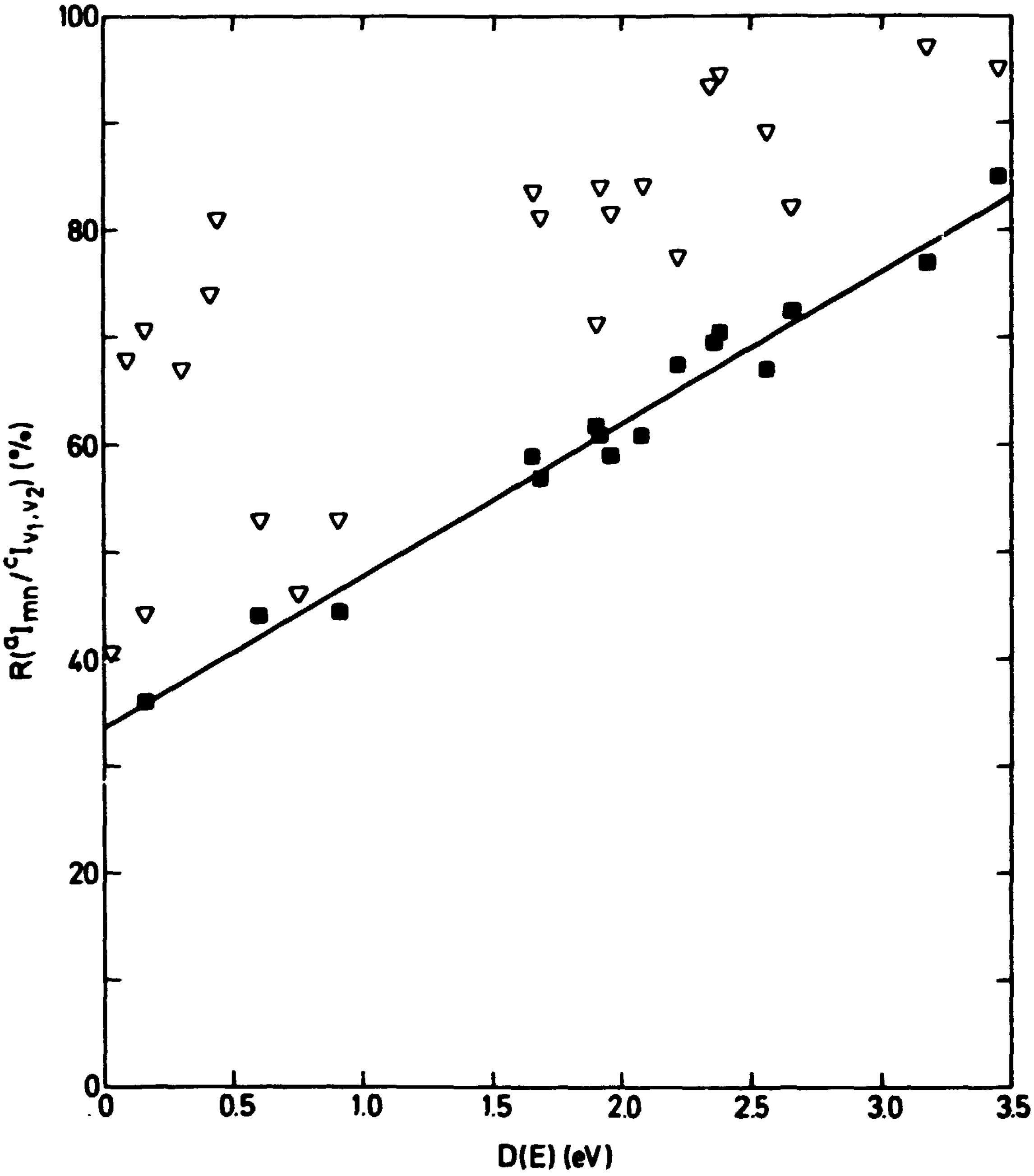

Fig.3 RD-graph from auroral measurements of a whole night (8 hours). The triangular points are the same as in Fig. 2. The filled squares represent atomic and molecular transitions, which both are σ-corrected.

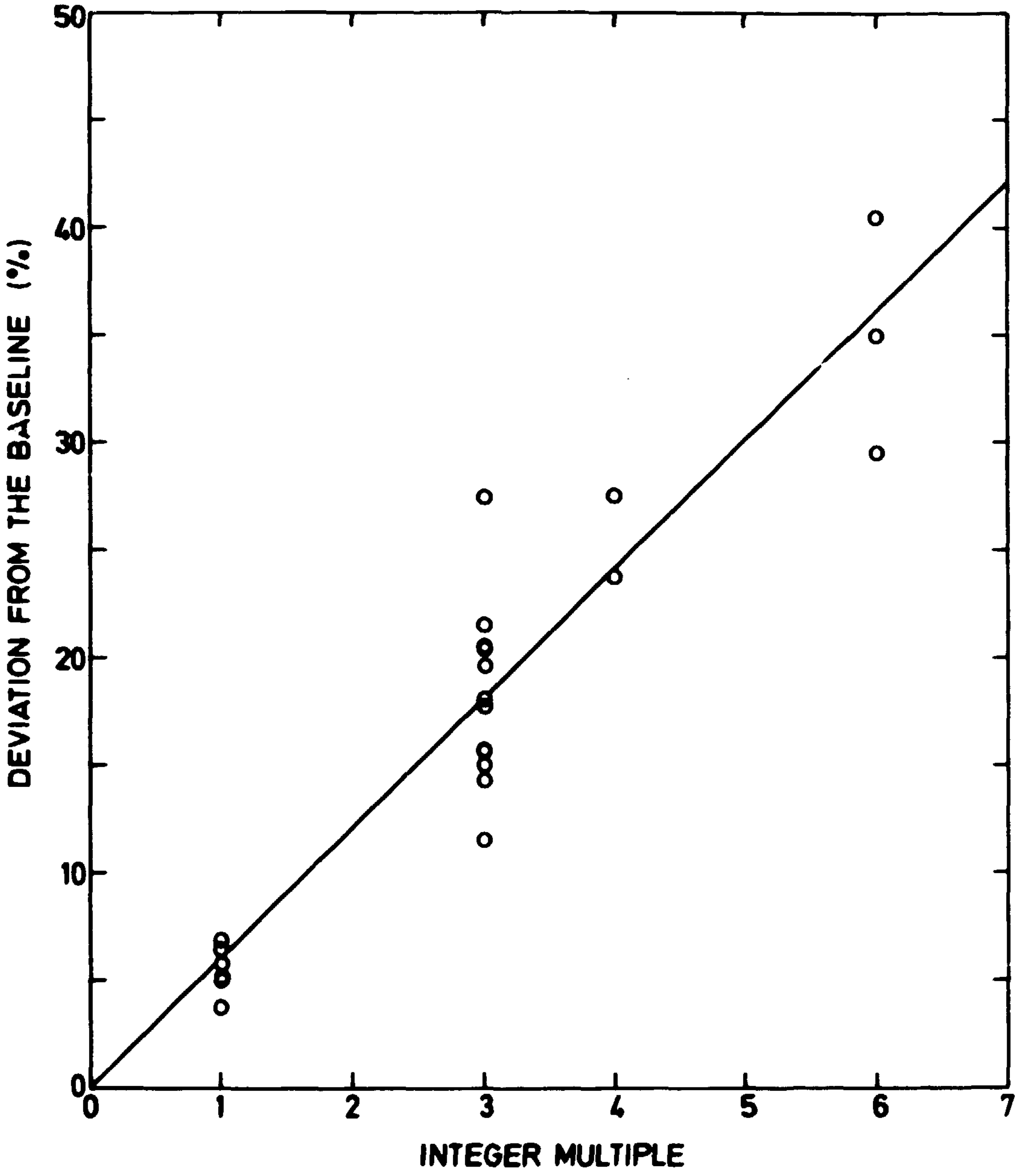

Fig. 4 σ-plot for the atomic transitions in Fig. 2. The deviations from the "baseline" in the RD-graph plotted versus an integer number.

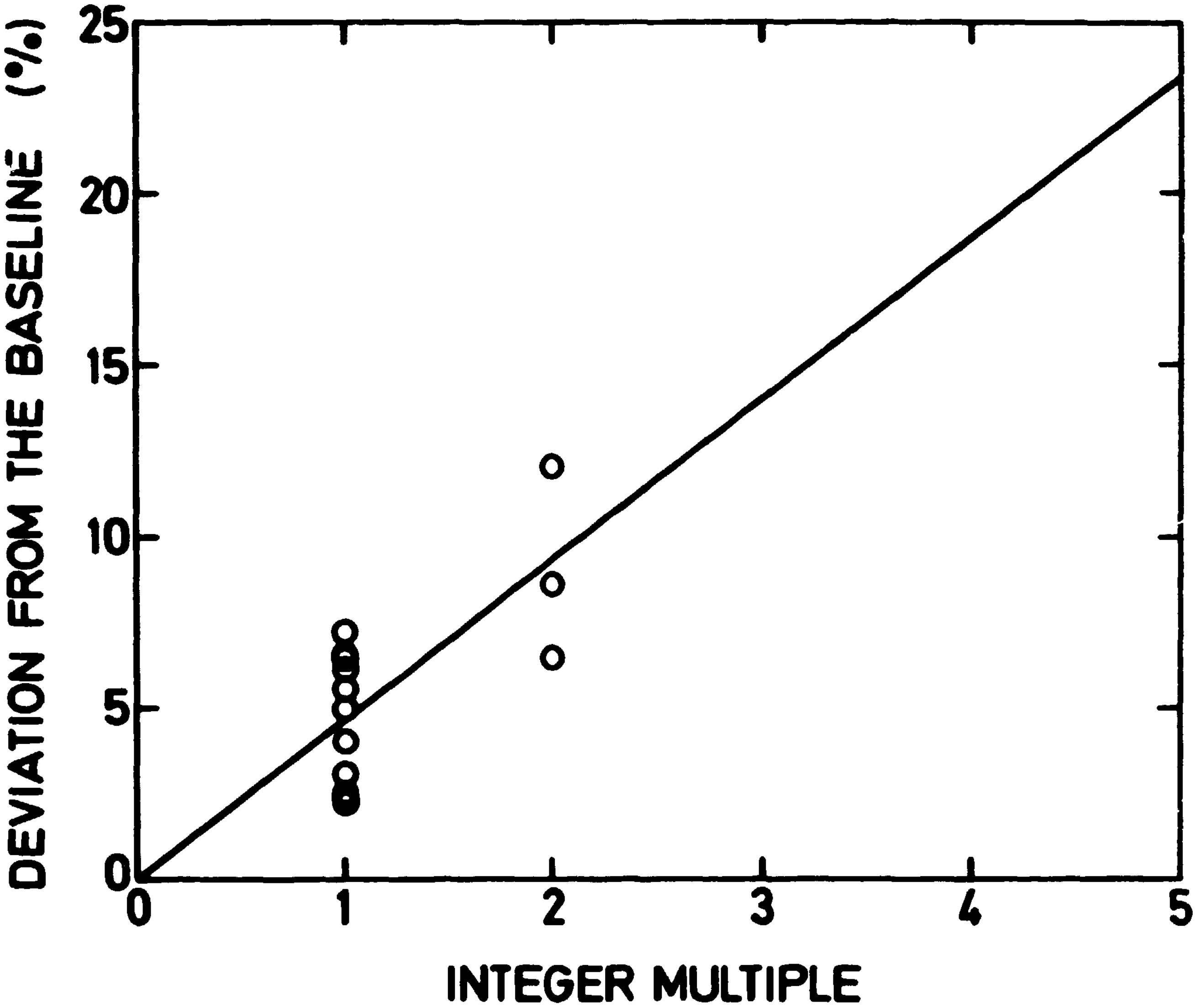

Fig. 5 σ-plot for the molecular transitions in Fig. 3. The deviations from the "baseline" in the RD-graph plotted versus an integer number.

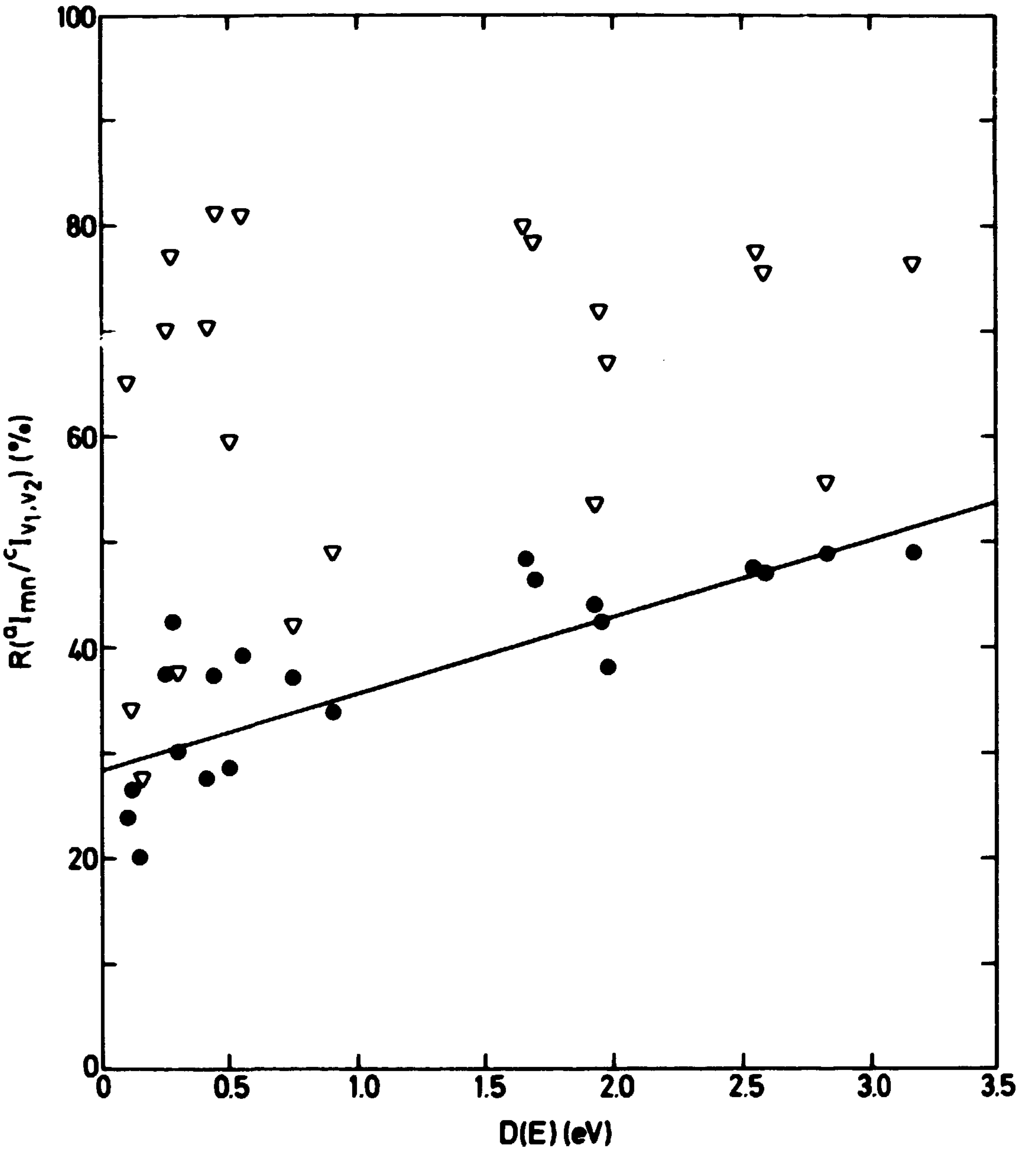

Fig. 6 RD-graph from a strong auroral event. The filled circles represent atomic and molecular transitions, which both are σ-corrected.

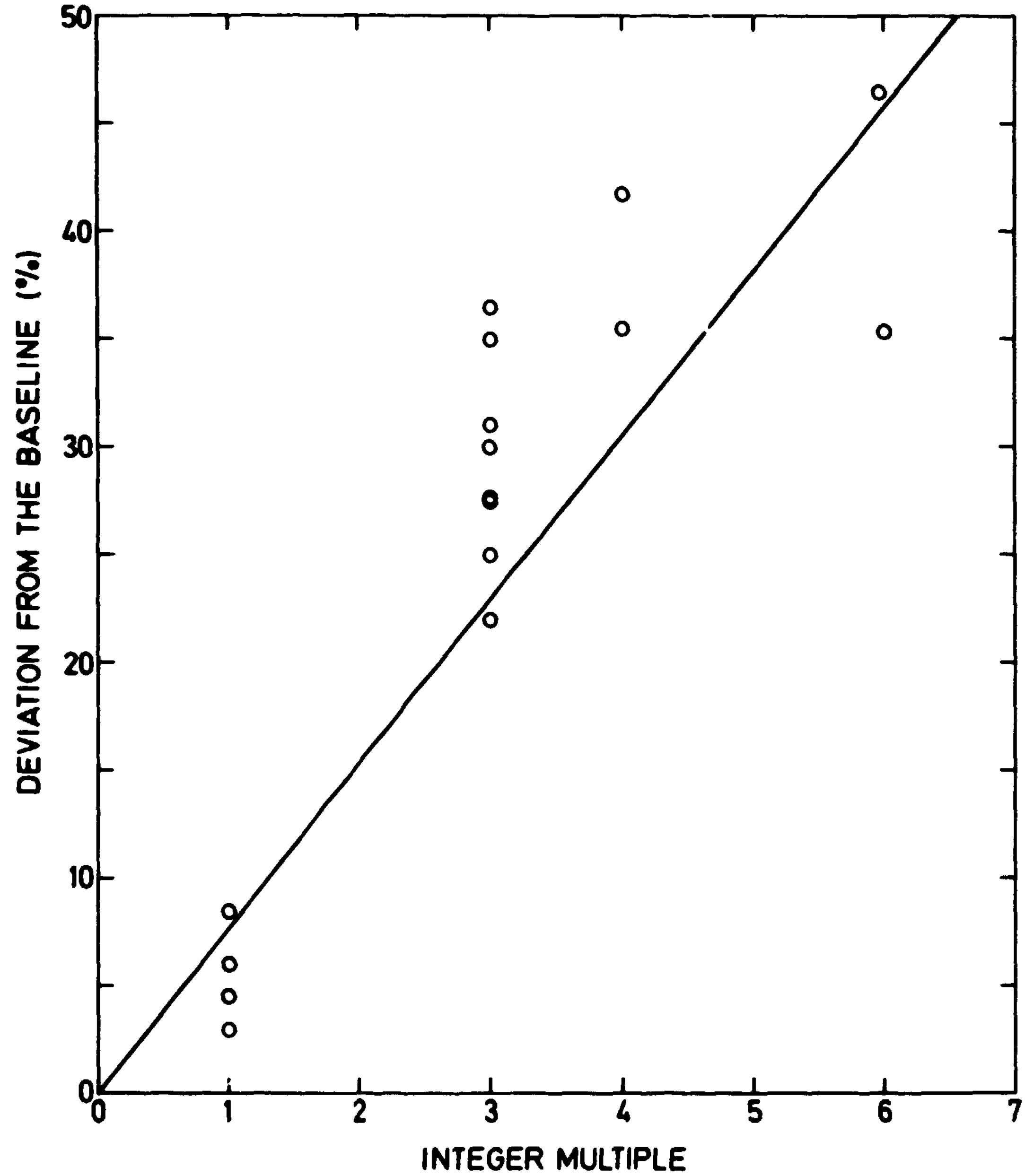

Fig. 7 σ-plot for the atomic transitions from the same strong auroral event.

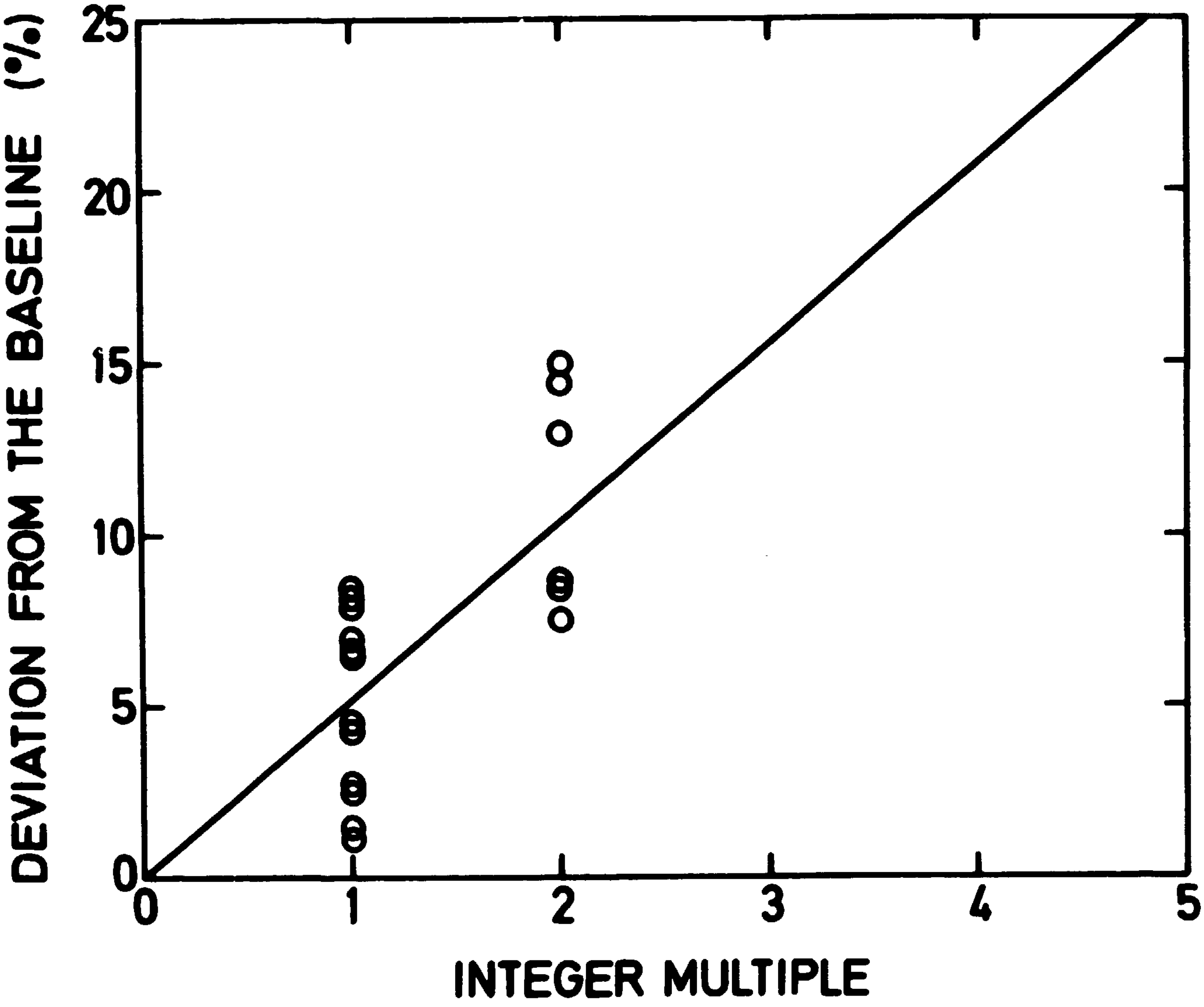

Fig. 8 σ-plot for the molecular transitions from the same strong auroral event.

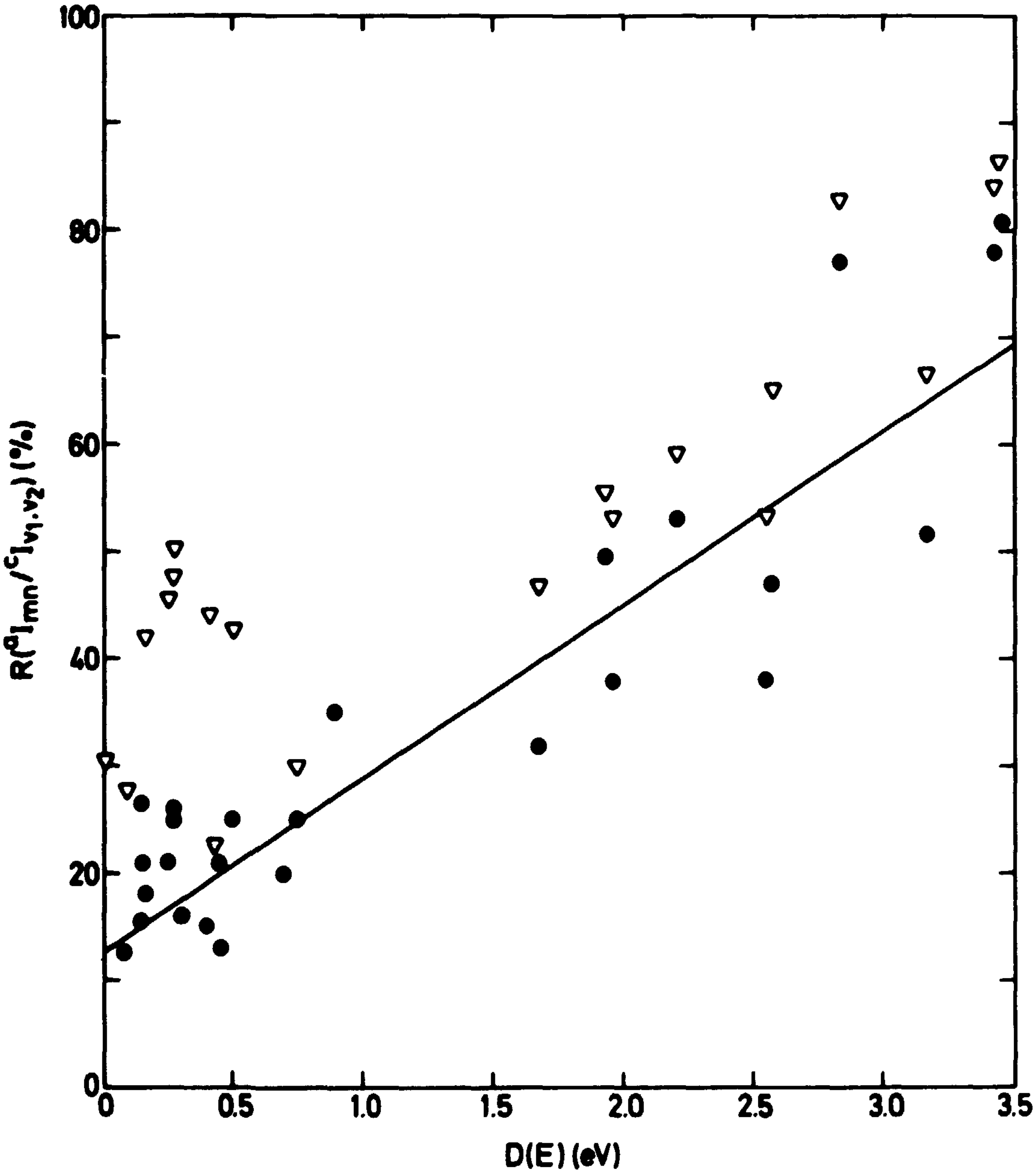

Fig. 9 RD-graph from the calm auroral period. The filled circles represent atomic and molecular transitions, which both are σ-corrected.

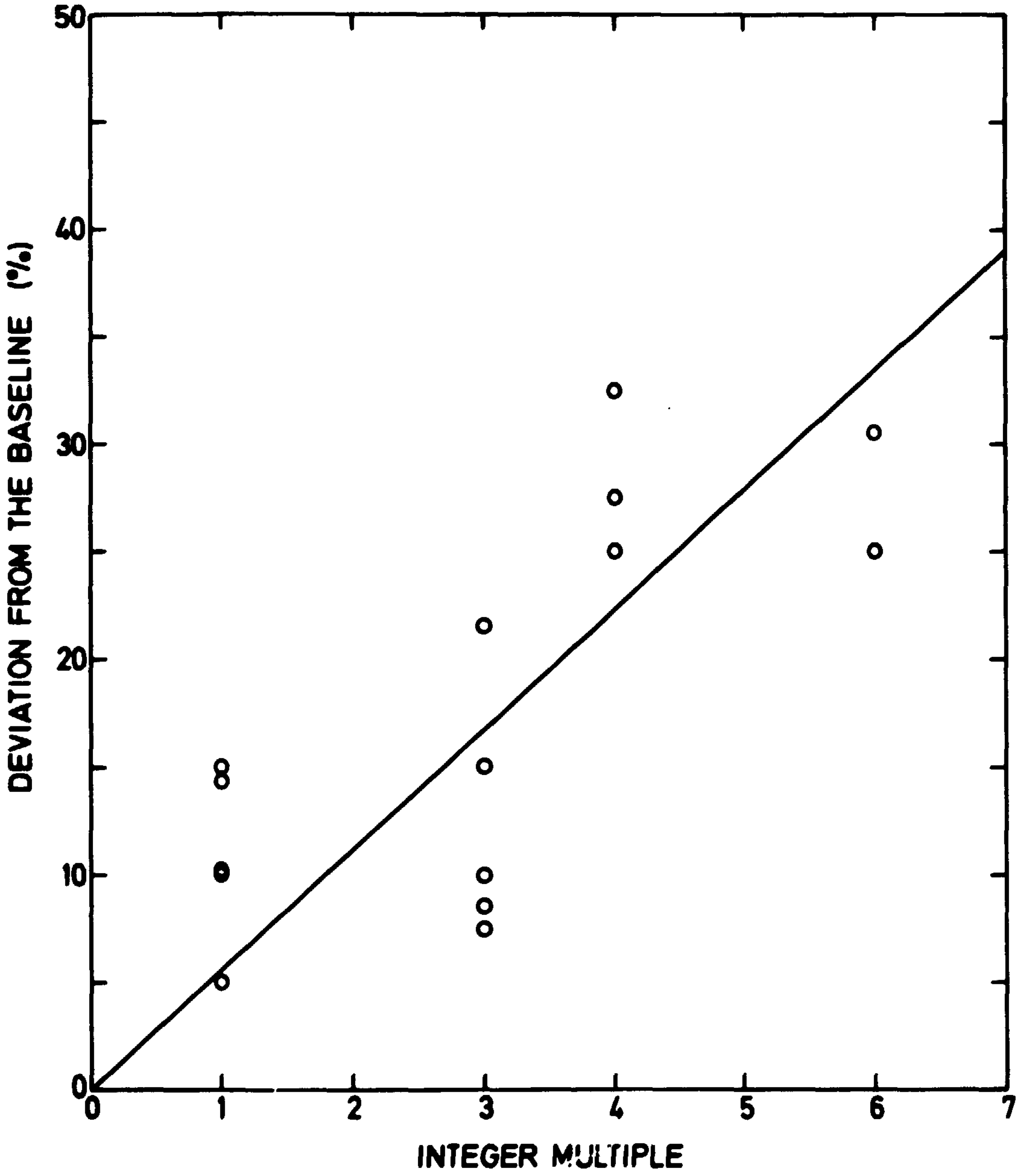

Fig. 10 σ-plot for the atomic transitions from the calm auroral period.