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DET NORSKE VIDENSKAPS-AKADEMI I OSLO

GEOFYSISKE PUBLIKASJONER

GEOPHYSICA NORVEGICA

Vol. XXV. No. 6 February 1965

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OSLO 1965
UNIVERSITETSFORLAGET

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STUDIES ON THE EXCITATION OF N_2 AND N_2^+ BANDS IN AURORA

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FREMLAGT I VIDENSKAPS-AKADEMIETS MØTE DEN 22. MAI 1964 AV TANGEN

TRYKT MED BIDRAG FRA NORGES ALMENVITENSKAPELIGE FORSKNINGSRÅD

Summary. Some excitation mechanisms for N_2 and N_2^+ in aurora are discussed with emphasis on the time delays caused by secondary mechanisms. The N_2^+ First negative (0-1) band at 4278 A and one of the following bands: (A) the N_2^+ Meinel (4-1) band at 7037 A, (B) the First positive (5-2) band at 6705 A and (C) the Second positive (0-3) band at 4059 A emitted from active aurora were recorded simultaneously by a filter photometer. The observations are consistent with the view that the three latter bands may in part be excited by secondary mechanisms. The time delays caused by secondary mechanisms are compared with the corresponding time delay caused by an analogue *RC*-circuit indicating time constants of the order of one second.

1. Introduction. From the extensive observational work done on the auroral spectrum it is clear that important variations in its intensity distribution occur (cf. Chamberlain 1961). Some of the apparent variations are undoubtedly due to errors in the measurements; for example: variations are occasionally reported which should not occur, because the relative intensities in question depend only on transition probabilities, which cannot be affected under the existing conditions. The most pronounced variations in relative intensities are those of some forbidden emissions, such as the red [*OI*] lines 6300/64 Å, the green [*NI*] lines 5199/5201 Å and the Vegard-Kaplan [N_2]bands. It seems likely that most of the variation in the relative intensities of these lines and bands is due to collisional deactivation, since the excited states in question have rather long lifetimes against radiation (minutes to hours). For permitted radiations such deactivation cannot be important, because in the upper atmosphere the mean time between two gaskinetic collisions is much greater than the lifetime of the excited states. In agreement with this the reported variations in the relative intensities of permitted radiations are relatively small. But some of the reported variations seem to be real, and its explanation must be sought in the excitation mechanisms.

The variations in relative intensities is usually measured with spectrographs or with photoelectric scanning spectrometers. In the first case the exposure times are long (of the order of minutes), and in addition the use of photographic recording often results in serious errors. In the latter case the intensity may vary during the scanning of the spectrum, which usually lasts at least 10 sec. Averaging over several successive spectra again imply long effective exposure times. The absolute intensity of the aurora may change greatly in a second or so, intensity pulsations lasting less than a second are not uncommon. It is of interest to know if any change in relative intensity is associated with such abrupt variations in absolute intensity. As shown in sec. 2, this may yield some information on the nature of the excitation mechanisms.

In order to investigate this problem, a two-channel ("split-beam") filter photometer was used to measure aurora which varied rapidly in intensity. The relative intensity of any one of the First and Second positive N_2 bands, and of the Meinel N_2^+ bands, was compared with the First Negative N_2^+ bands. This work is reported in sec. 3. The results are consistent with the view that most of the excitation is due either to direct excitation by the primary particles impigning upon the atmosphere or to the secondary electrons which are ejected in collisions between the primaries and atmospheric molecules and atoms, but there also seems to be a certain contribution from slower processes.

2. Excitation mechanisms for N_2 and N_2^+ bands in aurora.

2.1. All evidence favours the view that most of the optical auroral emissions draw their energy, directly or indirectly, from fast primary electrons (and in some cases protons) which enter the atmosphere along the magnetic lines of force. We shall therefore first discuss the most direct excitation such particles can perform, i.e. excitation by the primaries or by the secondary electrons.

Denoting the primary particles (electrons or protons) by Y and the secondary electrons by e, this excitation of N_2 may be written:

$$N_2(X) + Y \text{ or } e \rightarrow N_2' + Y \text{ or } e, \qquad (1Ya \text{ or } 1\,ea)$$
$$\text{or } \rightarrow N_2^+ + e + Y \text{ or } e, \qquad (1Yb \text{ or } 1\,eb)$$
$$\text{or } \rightarrow N_2^{+\prime} + e + Y \text{ or } e, \qquad (1Yc \text{ or } 1\,ec)$$

where N_2' and $N_2^{+\prime}$ denotes excited molecules and ions respectively. The processes (1 *eb*), (1 *ec*) and similar processes with O_2, O or N produce tertiary electrons which again may participate in the same processes. We shall include also these in the term "secondary electrons". The average energy required to produce one ion pair in air is about 32 eV, which on the average leaves a little less than 20 eV kinetic energy for the ejected electrons. When secondary electrons are released through processes of the type (1*b*) and (*c*), they loose this energy rather rapidly through inelastic collisions with the atmospheric atoms and molecules. It was shown in an earlier paper (OMHOLT 1959b) that the energy of the secondary electrons decreased to 2 eV in less than 10^{-2} sec, provided the height in the atmosphere is less than about 140 km.

This can be seen more directly by considering the cross sections and densities in question. The cross section for inelastic collisions between electrons and oxygen atoms is of the order 5×17^{-17} cm^2 or higher (due to excitation of the state ^1D, 2 eV, and other states (cf. SEATON 1954). The electrons in question have velocities of about 10^8 cm/sec, so that a density of atomic oxygen of 2 . 10^{10} cm^{-3} is sufficient to make the time between two inelastic collisions less than 10^{-2} sec. This density occurs at an altitude of approximately 140 km. With all other excitation processes taken into account this time is reduced considerably. Since only a few inelastic collisions is sufficient to reduce the kinetic energy below the excitation potentials of the N_2 bands we may conclude that electron excitation of these bands occur within 10^{-2} sec after the ionization process in which the electron is released. For aurora at great heights this time may be exceeded.

Any one of the primary particles give up most of its energy within an altitude range of a scale height or so, say 10 km. Since typical velocities of primary electrons and protons are of the order 10^8 cm/sec or more, the major part of the energy of any one particle is in most cases given up in less than 10^{-2} sec. Again, for low-energetic primaries, causing aurora at great heights, this time may be exceeded.

The conclusion of these considerations is that most of the excitation resulting from any one primary particle, through any of the processes (1 *a*, *b*, *c*), is performed within a time interval which is less than 10^{-2} sec, provided the light occurs at normal auroral height (100-140 km). Further, this means that if the intensity (but not the energy and angular distribution) of the beam of primary particles vary rapidly, the various rates of excitation in question varies in phase, with a time shift of less than 10^{-2} sec between them. Again this is valid for aurora at normal heights only. For high aurora (above 150 km) it is not possible from these arguments to exclude that higher time shift occur, perhaps up to 0.1 sec.

If on the other hand systematic variations in the energy or angular distribution of the primaries occur, the situation is different. Such variations affect the height where the primaries are stopped. In this case the energy distribution of the secondaries also varies, not only because the energy spectrum of the newly ejected secondaries depends on the energy of the primaries, but also because the composition of the atmosphere varies with height. A change in the composition of the atmosphere affects the relative importance of the various collision processes. In this way the relative intensities between band systems or lines emitted from the same kind of molecules or atoms may change. It is reasonable that this may be the cause for much of the height variation in the relative intensities of the N_2 and N_2^+ bands.

Thus, with the hypothetized variation in energy or angular distribution one should expect variations in the relative intensities of the N_2 and N_2^+ bands.

2.2. At various times it has been advanced theories for the excitation of the auroral spectrum which include indirect excitation of various states. One argument for this is the differences between the auroral spectrum and laboratory spectra; another argument is the variations in the auroral spectrum. Most of the processes which have been advanced from time to time have been rejected (cf. BATES 1960, CHAMBERLAIN 1961). We shall here briefly discuss some processes which have been advanced more recently, and the consequences they may have for variations in the spectra of rapidly varying aurora.

MALVILLE (1959) has discussed the contribution from the process

$$N_2^+ + O^- \text{ (or } O_2^-) \rightarrow N_2(B^3\Pi) + O (\text{or } O_2) \tag{2}$$

to the excitation of the First Positive N_2 bands, particularly in type B aurora (red lower border, due to enhanced First Positive bands.) This process appears to have been proposed by MITRA (1943) and by GHOSH (1943).

GADSDEN (1961, 1962) has proposed a similar mechanism which may contribute to the excitation of the Second Positive N_2 bands:

$$N_2^+ + O^- \rightarrow N_2(C^3\Pi) + O(^1D) . \tag{3}$$

As is seen, this would also contribute to the emission of the red [OI] lines 6300/64.

The arguments for these processes are essentially based on variations in relative intensities between and within N_2 and N_2^+ band systems. We need not repeat this discussion here, but merely emphasize that the processes are highly speculative, and there is not yet any proof that they are of any importance. They are simply invoked to explain certain variations. For our investigations it is mainly of interest to see if these processes lead to any time lag or systematic intensity changes between various emissions from aurora which vary rapidly in intensity. For example, if a sudden onset of aurora occurs, it takes some time to build up a significant positive and negative ion density, and thus that part of the emission which is due to the processes (2) and (3) will build up gradually and not suddenly. Similarly, with a sudden interruption of the aurora the ion-concentrations will decay with their characteristic decay times, giving rise to a finite delay of the corresponding emission. It is very difficult to estimate these time delays with any accuracy because the reaction rates for all the processes governing the electron-ion content in the ionosphere at various heights are still very uncertain. However, certain limits may be estimated with reasonable accuracy.

To illustrate this we shall consider what happens to the electron-positive ion content when a very high rate of ionization suddenly starts. The continuity equation then reads:

$$\frac{dn_j}{dt} = c_j q - \alpha_j n_e n_j , \tag{4}$$

with

$$\alpha_j = \alpha_d + \lambda \alpha_i ,$$

$$n_e = \Sigma n_j / (1+\lambda) ,$$

and where n_j and n_e are the densities of the positive ions in question and electrons respectively, c_j is 0.2 for the sum of O^+ and O_2^+ and 0.8 for N_2^+, α_j the effective recombination coefficients, α_d and α_i the coefficients for dissociative recombination and recombination with negative ions, and λ the ratio between the densities of negative ions and electrons.

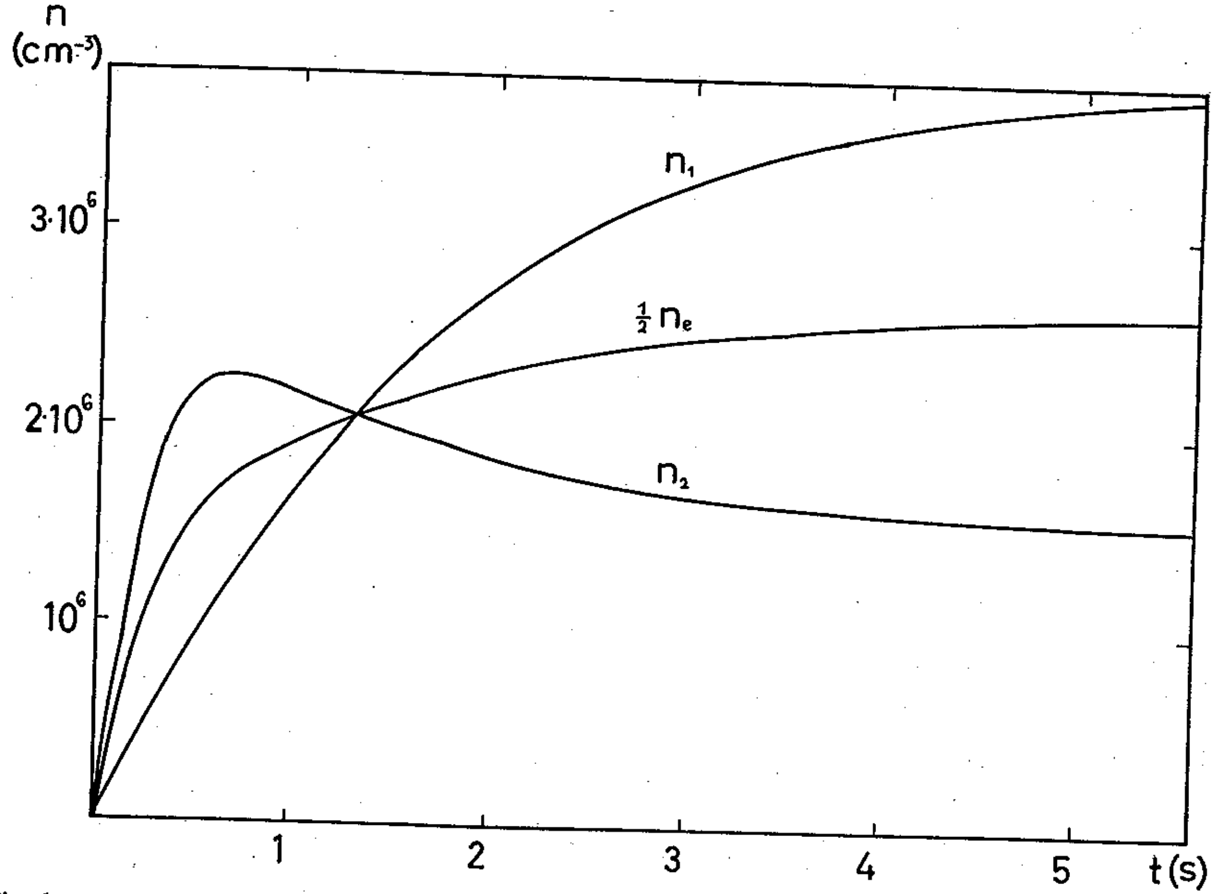

Fig. 1a. The concentration of N_2^+ ions (n_2), O^+ and O_2^+ ions (n_1) and electrons (n_e) as a function of time (t) when $q=0$ before $t=0$ and $q=10^7$ cm^{-3} s^{-1} after $t=0$.

A rate of ionization, q, of 10^7 cm^{-3}sec^{-1} is probably the upper limit for aurora (OMHOLT 1960). It is perhaps not too unrealistic to put the effective recombination coefficient for N_2^+ to 10^{-6}cm^{3}sec^{-1} or less and that for the sum of the O^+ and O_2^+ content to 10^{-7} cm^{3}sec^{-1} or less (NAWROCKI and PAPA 1961). Further, we put α_i, the coefficient for recombination between positive and negative ion, equal to α_d, and λ to be constant. With these assumptions some sample computations of $q(t)$ were made. q was chosen to be zero before $t=0$ and 10^7 cm^{-3}sec^{-1} after $t=0$. The resulting curves are plotted in Fig. 1a. As is seen, the N_2^+ curve rises rapidly to a maximum and then decreases slowly to its equilibrium value as n_e increases to its equilibrium value. Thus, in a dynamic process like this, the time constant for the electron density is governed largely by the slowest recombining ions, which contribute most to the equilibrium value. In the case shown in Fig. 1a the time constant for N_2^+ is only a few tenths of a second. The same is the case when q suddenly decreases to zero. For this case the curves shown in Fig. 1b apply.

With lower values of q the time constant becomes greater. Since $q=10^7$ cm^{-3}sec^{-1} and $\alpha(N_2^+)=10^{-6}$ cm^{3}sec^{-1} probably are upper limits, it seems likely that 0.1 sec is lower limit for the time lag between q and $n(N_2^+)$. Now, the total time lag between

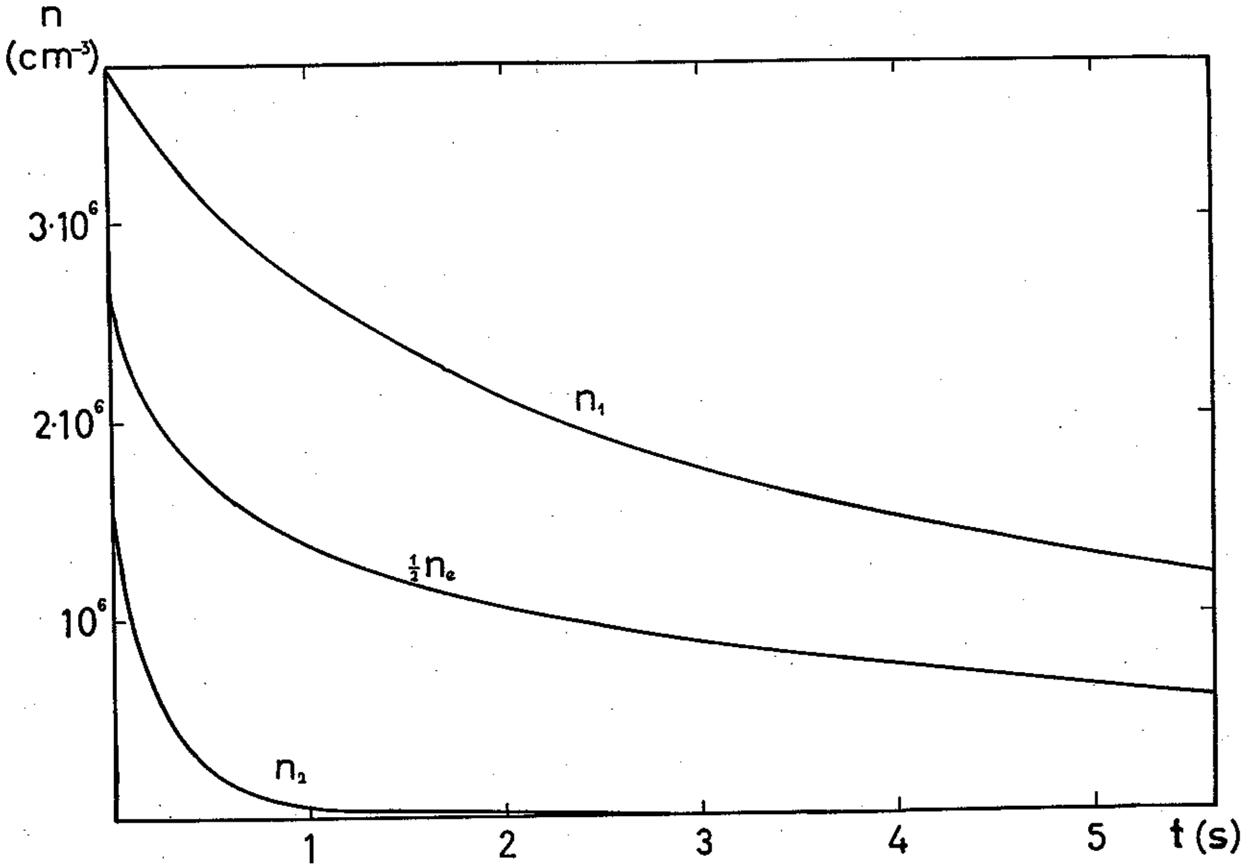

Fig. 1b. The concentration of N_2^+ ions (n_1), O^+ and O_2^+ ions (n_1) and electrons (n_e) as a function of time (t) when $q=10^7$ cm³ s^{-1} before $t=0$ and $q=0$ after $t=0$.

q and the processes (2) and (3) also depend on the time constant for the formation of O^- and O_2^-. If λ, the negative ion to electron ratio, is high and most of the recombination is between positive and negative ions, the time constant for the negative ion content is that for electrons. This is true whenever the formation and destruction of negative ions are so rapid that λ is effectively constant also through the initial periods in fig.s. 1a and 1b. If the processes are not that fast, the time constant for negative ions will be larger. Thus, again remembering that our example probably gives a lower limit to the time constant, 1 sec is a reasonable estimate for the lower limit of the time lag between q and the density of negative ions. Since this is much longer than that of N_2^+, it is the dominating one for the processes (2) and (3).

In consequence we must expect that the emission excited by processes (2) and (3) will be delayed relatively to those excited by process (1) corresponding to a time constant of one sec or more.

HUNTEN (1963) points out that the low concentration of N_2^+ ions at great heights indicates that other processes than recombination contribute to the removal of N_2^+ ions, such as charge transfer to O_2^+ and O^+. This would lower the time constant for N_2^+, but probably increase that of the negative ion and electron content.

2.3. There are also other excitation processes which could be considered, such as radiative recombination of N_2^+ and energy transfer from metastable states. Radiative recombination is thought to be of minor importance in the ionosphere, but should yield time constants of the same order of magnitude as with negative ions.

THOMPSON and WILLIAMS (1934) suggest that the process

$$N_2(a^1\Pi g)+N_2(X^1\Sigma g^+)\rightarrow N_2(X^1\Sigma g^+)+N_2(B^3\Pi g) \quad (5)$$

may be important in laboratory experiments. Since the lifetime of the $N_2(a)$ state is fairly short, 10^{-3} sec, and the process involves a change of the total spin, it is less likely to be imporant at the pressures experienced at auroral heigths. In general, energy transfer from metastable, excited atoms or molecules is not likely to be important for N_2^+, because the abundances of both N_2^+ and the metastable ones are relatively small, and a prohibitively large reaction coefficient would be required.

Magnetic disturbances observed during aurora indicates that strong currents occur in the ionosphere. It is not very likely that these currents contribute to the excitation of the optical emission (OMHOLT 1959b). If they do, however, the emission excited in this way does not follow the variations in the stream of primary particles. If the electric field is constant the current density at any place would follow the electron density. As we have seen, this would cause a definite time delay. If the electric field changes because of the changed currents, the energy distribution of the electrons and ions would change. Again all such changes would follow the build-up and destruction of the electrons and ions rather than the changes of intensity in the beam of primaries.

It has been pointed out earlier (OMHOLT 1959b) that the average ion energy should be substantially greater than the electron energy in an aurora if this is exposed to an external, horizontal electric field, giving rise to horizontal currents. This is because at the heights in question, electrons can form Hall-currents only, whereas the ions contribute to both Hall-currents and currents parallell to the electric field. The energy gain between two collisions for ions may perhaps amount to a few tenths of an electron volt. Even if an ion looses on the average about half of its energy per collision the average ion energy may not be negligible.

The excitation of the Meinel bands from $N_2^+(X)$ requires only a couple of eV, and it would thus be energetically possible for the ions to "excite themselves" in collisions with the atmospheric particles. Although the relevant cross-sections probably are very small (MASSEY and BURHOP 1952), this possibility should perhaps not entirely be ruled out.

3. Observations. The observations were made with a two-channel photometer described earlier (OMHOLT 1959a). The essential feature of this photometer is that it measures the intensity of any two emission lines or bands in the aurora appearing within a circular area of about 1° diameter in the sky. The appropriate emissions are isolated by intereference filters. The half-width of the filters used were about 50 A. The intensities were recorded by EMI photomultipliers and the photo currents were

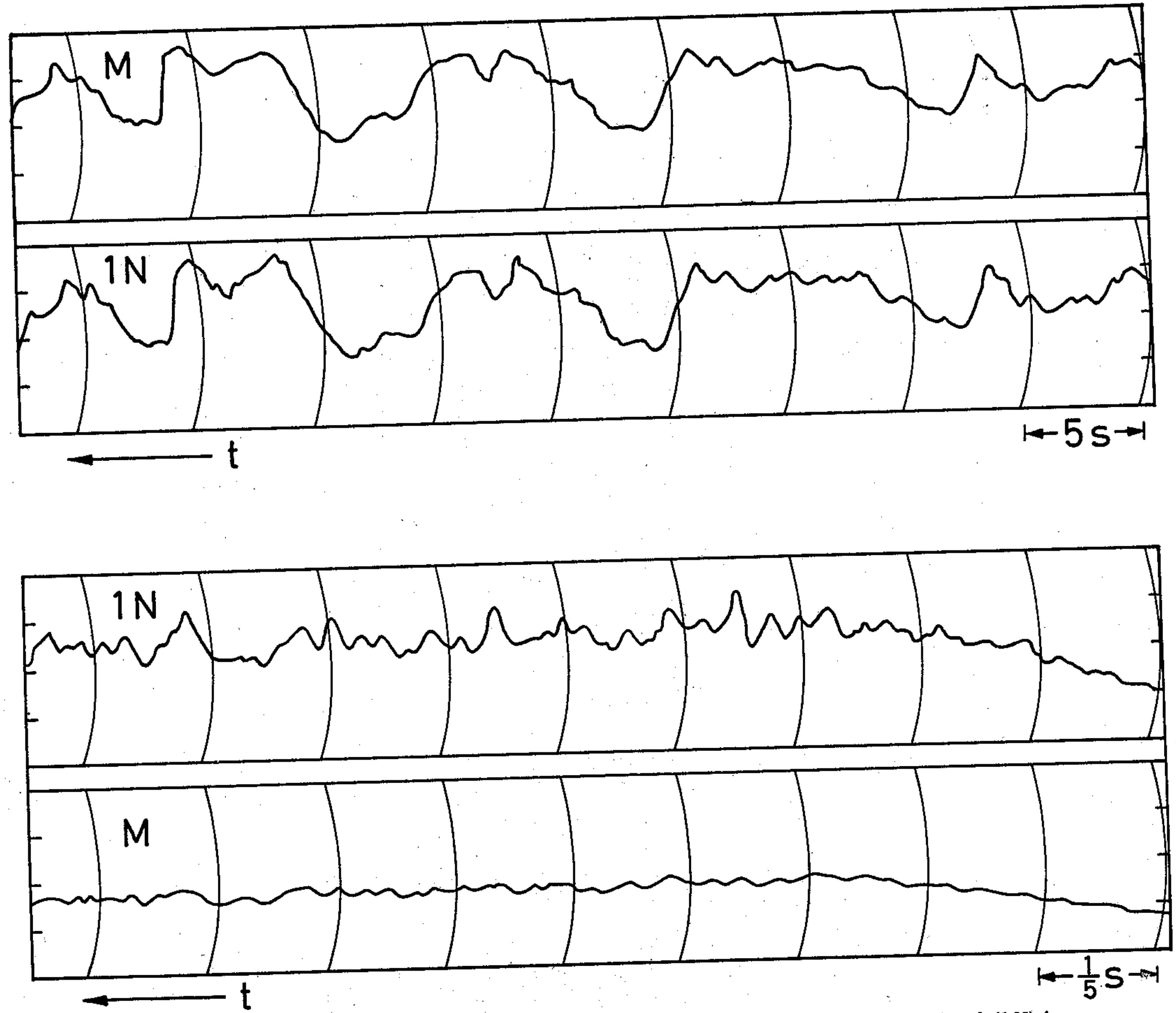

Fig. 2. Records of intensity variations in the Meinel band (M) and the First negative band ($1N$) in rayed arcs. The lower figure is from the extraordinary rapid variations mentioned in the text.

amplified and recorded by a Brush recorder. The photometer can be pointed in any direction and also be moved during the record.

During the observations simultaneous records were made of the N_2^+ First Negative (0—1) band at 4278 A and one of the following bands:

(A) The N_2^+ Meinel (4—1) band at 7037 A,
(B) the First Positive (5—2) band at 6705 A, or
(C) the Second Positive (0—3) band at 4059 A.

Observations of active aurora were made with the photometer kept in a fixed direction towards the auroral display, thus recording the intensity variations at one particular spot. Homogeneous aurora was recorded by scanning the photometer across quiet forms. The intensities and intensity variations quoted in this paper were all derived by subtracting the lowest level of luminosity during the record. Thus any background of scattered auroral light, auroral glow or light from the night sky was automatically compensated for. All observations were corrected for atmospheric extinction. Since extinction correction for extended light sources are rather uncertain for zenith distances above 80°, the observations were limited to zenith distances below this limit. An example of a record is shown in Fig. 2.

4. Analysis of observations. The first step in the analysis was to investigate whether there was any measurable time shift between the peaks in the two intensity curves. This would mean that there is a significant delay in the emission of the one band compared to the other. During rapidly varying aurora, giving rise to short light pulses, such time shift is possible to measure. When the variations are slower the peak of the pulses are difficult to establish with a sufficient accuracy, consequently the absolute error in the time shift is large. It should also be mentioned that noise level (shot noise) introduces some errors in the individual measurements.

It has turned out that all the three band systems: The Meinel bands, the First positive bands and the Second positive bands were slightly delayed compared to the standard reference band system, the First negative N_2^+ bands. The time delays for light pulses with half-widths of the order of magnitude 1 sec are given in Table 1. The Meinel bands and the First positive bands were also measured in aurora which showed extraordinary rapid variations, with half-widths of light pulses even less than 1/10 of a second. In these extremely short light pulses no significant time delays were observable.

During this analysis it was noted that the intensity ratio between any one of the three bands in question and the First negative bands was greater in slow light pulses than in the rapid ones. Still greater was this ratio in homogenous aurora. In Table 1 are also given the intensity ratio between the three band systems and the First negative band on arbitrary scales for light pulses with half-width about or less than 1 sec, light pulses with half-widths greater than 1 sec and for homogeneous aurora.

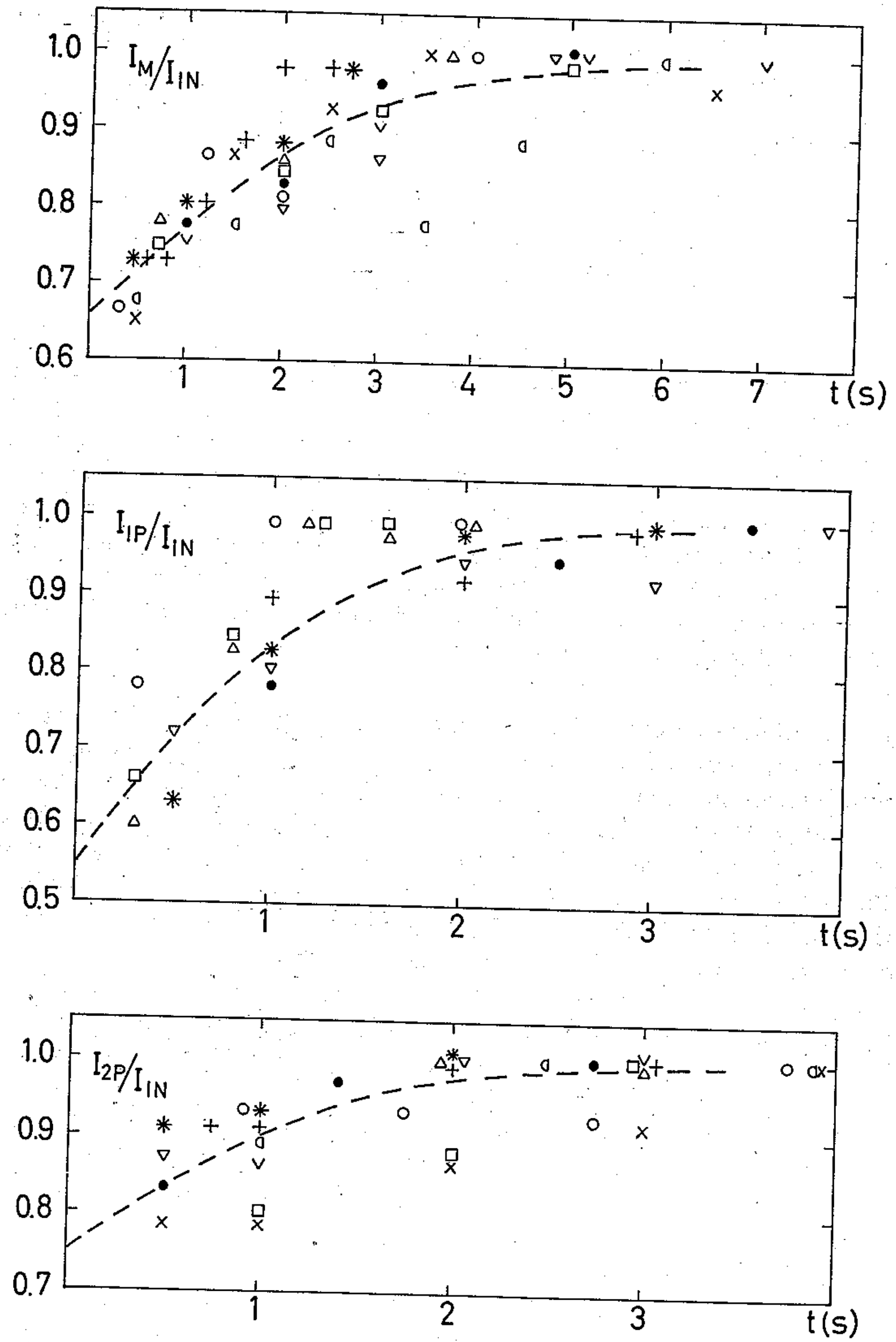

Fig. 3. The intensity ratio between the Meinel band and the First negative band, I_M/I_{1N}, the First positive band and the First negative band, I_{1P}/I_{1N}, and between the Second positive band and the First negative band, I_{2P}/I_{1N}, as a function of time elapsed from the start of the measured light pulses. The results from the various pulses are indicated by different signs.

Table 1. *Time delay Δt of intensity peaks and relative intensity ratios r for the Meinel bands (M), First positive bands (1P) and Second positive bands (2P) relative to the First negative bands. r_1 and r_2 are for pulses of half-width less than one sec and a few seconds respectively and r_3 for quiet aurora.*

	M	1P	2P
$\Delta t(10^{-3}$sec)	22±7	18±8	15±7
r_1..........	66±2	82±4	75±4
r_2..........	77±5	97±4	88±3
r_3..........	100	100	100

These systematic variations in the intensity ratios are understandable from analogy with electric RC-circuits. Feeding a parallell RC-circuit with a varying current, gives current through the resistor which is not only phase shiftet compared to the feeding current, but also have a damping, increasing with the time constant of the circuit and with the frequency of the feeding current. Any secondary mechanism in the excitation prosess may be imagined to have a function similar to a condensor in such a circuit. This is discussed in more detail in section 5.

In want of a mathematical model for the excitation mechanisms and emissions, it is difficult to analyse the records in detail. To proceed with the analysis and get some more information on these intensity ratio variations a number of pulses which lasted for a few seconds were selected. In these light pulses the intensity ratio between any one of the three band systems and the First negative band was measured as a function of time elapsed from the start of the light pulse. To eliminate errors due to the shot noise the intensities were integrated over short time intervals (of the order of 1 sec) before the intensity ratio was formed. The result for the three band systems are given in Figure 3. The intensities are on the same arbitrary scale as in Table 1.

As is seen there are systematic variations in the intensity ratios, in the same direction as indicated by the data in Table 1. Although the scatter in the individual measurements is considerable, the variations is undoubtedly significant. The curve drawn on the figures are of the form

$$I = I_0(1 - k\exp(-t/\tau)).$$

The time constant τ is of the order one second for the First positive bands and Second positive bands, and two seconds for the Meinel bands.

Without any detailed interpretation of the curves it seems reasonable to conclude that both the time delay between the peaks and these systematic variations in the intensity ratio is due to the influence of secondary excitation mechanisms. Assuming as a hypothesis that the First negative bands are excited without any time delay compared to the primary particle stream, it is reasonable that the intensity ratio in Figures 3 for $t=0$ is proportional to that part of the excitation which is due directly to the primary particles or secondary electrons. The difference between this ratio and that for quiet forms is then proportional to that part of the excitation which is due to secondary mechanisms with a time delay. This implies that of the total excitation rate for the Meinel bands, First positive bands and Second positive bands respectively 35%, 45% and 25% are due to secondary mechanisms. To understand the significance of these curves and of the data given in Table 1, it may be illuminating to discuss an analogue *RC*-circuit. This will be done in the next section.

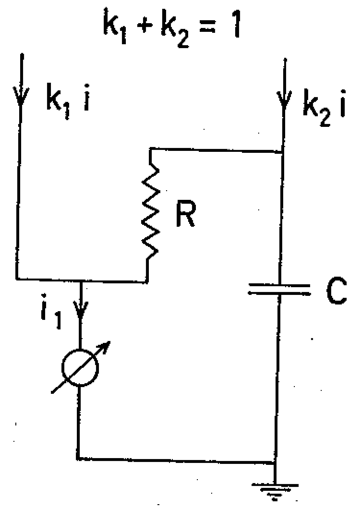

Fig. 4. An analogue *RC*-circuit.

5. An analogue RC-circuit. To illustrate the effect of indirect excitation mechanisms we have chosen an electric analogue *RC*-circuit fed by currents, as shown in Fig. 4. Here $k_1 i$ signifies the direct excitation in phase with the primary particle intensity, $k_2 i$ the formation of active particles leading to subsequent excitation of the band in question, and with $k_1 + k_2 = 1$. The charging of the capacitor C signifies the building up of a density of active particles, and the discharge current through R the removal of such particles by excitation. The total current i_1 then signifies the total rate of excitation. With $C = 0$ there is no accumulation of active particles, no time delay and $i_1 = i$.

If the circuit is fed by a current

$$i = I + i_0 \sin \omega t \tag{1}$$

the total current i_1 is given by

$$i_1 = I + i_0 D \sin(\omega t - \phi) \tag{2}$$

where the damping constant D and the phase shift ϕ are given by

$$D^2 = (1 + k_1 \omega^2 \tau^2)/(1 + \omega^2 \tau^2) \tag{3}$$

and

$$\tan \phi = k_2 \omega \tau / (1 + k_1 \omega^2 \tau^2)\,, \tag{4}$$

and where $\tau = RC$.

For rapid variations (ω large) we have:

$$\phi \approx \frac{k_2}{2\pi k_1 \tau} \cdot T \tag{5}$$

and for slow variations (ω small):

$$\phi \approx 2\pi k_2 \tau \cdot \frac{1}{T} \tag{6}$$

where $T = 2\pi/\omega$.

The time lag between the peaks of the two currents is

$$\Delta t = \frac{\phi}{2\pi} \cdot T\,. \tag{7}$$

If the circuit is fed by a step current with $i=0$ for $t>0$ and $i=i_0$ for $t>0$, then we obtain

$$i_1=i_0(1-k_2\exp(-t/\tau)). \tag{8}$$

Consider now the curves in Fig. 3. These are derived not from step-functions in the excitation, but from pulses with a definite rise time of the order of seconds. This means that with step-functions in the excitation the time constant of the experimental functions would be somewhat shorter, but still of the same order of magnitude. Let us adopt $\tau=1$ sec as representative for all three curves. Further, we adopt the values $k_2=1/3$ and $k_1=2/3$ as representative.

Let us now turn back to the rapid variations and the results in Table 1. The pulses on which the time-lag measurements were based have a half-width of the order half a sec. With the "excitation function" (1) and $I=i_0$ this correspond to $T\approx 1$ sec and $\omega\approx 6$ sec^{-1}. Putting $\tau=1$ sec equations (3), (7) and (4) now yield $\triangle t=15\times 10^{-3}$ sec and $D=0.8$. D is the ratio between the peak to peak value of i_1 compared to the peak to peak value of i. It is thus equivalent of the ratio r_2 given in Table 1. For very slow variations $D=1$, and D approaches 0.67 with decreasing T. $\omega=6$ is sufficiently large to make eq. (5) valid, and from eq. (7) is then seen that $\triangle t$ approaches zero as T^2 with decreasing T.

As immediately seen, these values of $\triangle t$ and D are in reasonable agreement with the data given in Table 1, the crudeness of the analogue model taken into account.

6. Conclusions. It is obvious that the computations on the analogue RC-model only serve illustrative purposes: to show the significance of time delays compared to amplitude variations. In certain special cases it may be very accurate. For example, if the First positive bands should be excited directly and in addition through process (5) discussed in section 2, then the equation governing this emission would be exactly the same as those giving the current i_1 in our analogue circuit. The lifetime of the metastable $N_2(a^1\Pi g)$ molecules would then replace the time constant $\tau=RC$. But for processes like (2) and (3) in section 2 one would need an analogue circuit with two condensors to signify the building up of densities of positive and negative ions.

Although our measurements are rather crude, and the interpretation tentative, it is difficult to escape the conclusion that secondary excitation mechanisms contribute to the excitation of the Meinel bands, the First positive bands and the Second positive bands with an appreciable, although not major fraction. These secondary processes seem to have time constants of the order of magnitude one second. But it should also be born in mind that this interpretation is based on the assumption that the First negative bands are emitted in phase with the intensity of the primary particles. This is only a hypothesis, which may not be true. If secondary mechanisms with appreciable time delay also contribute to the excitation of the First negative bands, the importance and time constant of the secondary prosesses contributing to the excitation of the other band systems would increase.

It is not, from the present material, possible to distinguish between the various processes proposed in section 2. It is desireable to repeat the measurements with photometers with more light-gathering power to get curves of higher accuracy. It might then be possible to get a detailed analysis of the curves and compare them with various mathematical models based on the processes discussed in section 2.

Also, it should not be excluded that the observed time shift may be due to systematic variations of the energy and penetration depth of the primary particles during such pulses of increased particle precipitation.

Acknowledgement: The research reported in this paper has been supported in part by the: AIR FORCE CAMBRIDGE RESEARCH LABORATORIES, OAR, under Contract AF 61(052)-680 through the European Office of Aerospace Research, United States Air Force.

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