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Ground-based photometric observations of the type A aurora of 17-18 december 1971*

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RESUME. – *Des observations au sol ont été effectuées pendant l'événement du 17 au 18 décembre 1971 depuis la Norvège septentrionale, à l'aide d'un photomètre à filtre incliné qui enregistre les intensités de N_2^+ 1.Neg., Hβ, λ6 300 OI, et λ5 200 NI. Le rapport élevé de λ6 300/N_2^+.Neg. permet de classer cet événement parmi les aurores de type A. Le rapport λ6 300/λ5 200 varie pendant la nuit mais reste supérieur aux valeurs habituelles de 20 environ. Les observations sont compatibles avec la présence d'un flux électronique mou (500 eV) et qui est à l'origine de l'intensification de la raie rouge. Ce qui est en accord avec un modèle d'aurore. On trouve aussi que $N(^2D°)$ est dé-activé par des collisions avec électrons à un taux prédit par les calculs théoriques. Une limite supérieure de 40 secondes environ est déduite pour le temps de vie effectif du $N(^2D°)$, quoiqu'aucun rapport simple ne donne une bonne corrélation avec les observations.*

ABSTRACT. – *Ground-based observations have been made during the event of 17 - 18 Dec. 1971 from northern Norway, using a tilting-filter photometer monitoring the intensities of N_2^+ 1.Neg., H_β, λ6 300 OI and λ5 200 NI. The high λ6 300/N_2^+ 1. Neg. ratio classes this event among type A auroras. The λ6 300/λ5 200 ratio varies during the night and remains higher than the usual value of nearly 20. These observations are compatible with a soft electron flux (≅ 500 eV) as the origin of the red line enhancement as illustrated by comparison with a model aurora. It is also found that $N(^2D°)$ is deactivated by collisions with electrons at a rate foreseen by theoretical calculations. An upper limit of about 40 seconds is derived for the $N(^2D°)$ effective lifetime, though no simple relationship gives a good fit to the observations.*

Introduction

The event under consideration occurred during the development of a planetary magnetic storm which followed two sudden commencements: the first one took place on December 16, 1971, at 19.05 U.T.; the second, on the following day at 14.18 U.T. The magnetic disturbance reached its peak on the afternoon of the 17 th when K_p reached a value of 7_+. The activity then slowly decreased and gradually returned to normal conditions.

The observations reported here were performed in northern Norway and concern photometric data

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(**) Aspirant of the Belgian Foundation for Scientific Research (FNRS).

collected during the main and recovery phases of the storm (Dec. 17, 19.45 to Dec. 18, 03.30 UT). They show some of the spectral features which are typical of auroras associated with major magnetic storms notably by the unusually high λ 6 300 intensity recorded. The occurrence of such type-A red auroras has been often observed simultaneously with the development of major magnetic storms (e.g. Belon and Clark, 1959 ; Meriwither et al. 1970 ; Mc Ewen and Sivjee, 1972). Figure 1 (a) and (b) present traces of the magnetic activity of the horizontal component measured for the same period of time as our observations. The magnetogram shown in Figure 1 (a) was recorded in Tromsö (70°N, 19°E) which is situated about 60 km NW from the optical station where the photometric measurements were made. The second trace (fig. 1 (b)) was recorded in a mid-latitude station (Dourbes : 50°N, 5°E) and is displayed with the same time scale. A jump is clearly seen at 14.18 hrs. on both traces, indicating the sudden commencement of the storm.

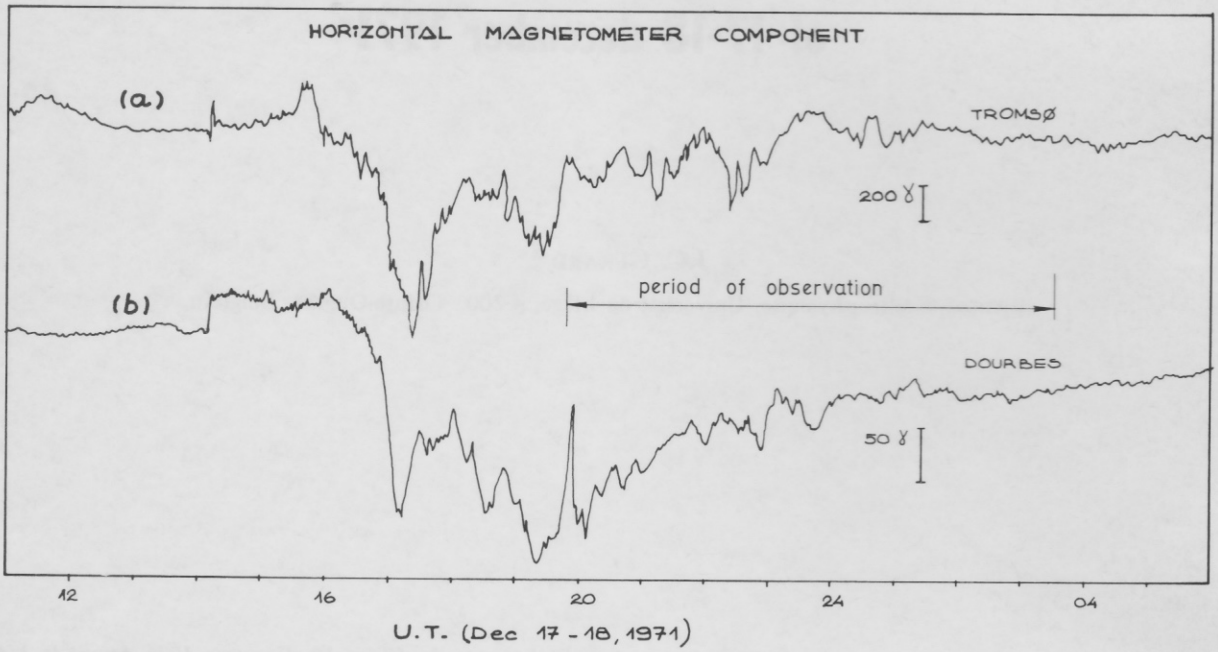


Fig. 1

Magnetograms recorded in Tromsö (70°N, 19°E) and Dourbes (50°N, 5°E) during the 17 - 18 Dec. 1971 magnetic storm.

The disturbance reached a maximum of about 1 100 gammas at high latitude and 210 gammas at mid-latitude, thus classing this event among major magnetic storms.

The equipment

Ground-based observations of the aurora have been made from Skibotn, Norway (Inv. Lat. 66°N) during the period December 9 to 20, 1971, The instrument used consisted of a four-channel tilting filter photometer operated in the pulse-counting mode. The photometer was looking zenithwards with a field of view reaching about 2 degrees. The frequence of tilting could be changed from 0 to 3 min^{-1}. The latter speed was actually used for all the measurements reported here. The instrument sensitivity was determined by measuring its response to a calibrated diffuse source. A more detailed description of the equipment and operation mode is given by Gérard and Harang (1973), who reported in that paper on the results of the other nights of the period of observation.

The observations

The photometer was monitoring the intensity of the features listed in Table I.

The N_2^+ 1. Neg. Syst. intensity provides an estimate of the total amount of precipitated energy (~5.10^{-4} 4 278 Å photon/eV). The hydrogen H_β line intensity depends on the precipitated proton flux. The λ 6 300 OI and λ 5 200 NI emission lines are due to forbidden transitions with radiative lifetimes of 110 sec and 26 hrs. respectively.

Table I

Features observed with the four-channel tilting filter photometer

λ (A)	Feature	Lifetime
4 278	(0-1) N_2^+ 1 Neg. Syst.	Allowed transition
4 861	Balmer β	" "
6 300	[OI] : $^3p - {}^1D$	~ 110 sec.
5 200	[NI] : $^4S° - {}^2D°$	~ 26 hrs.

Depending on the altitude considered, the $O(^1D)$ term is populated by various processes : secondary and thermal electron collisions with the ground-term $O(^3P)$, dissociative recombination of O_2^+. The $N(^2D°)$ production is mainly accounted for by the reaction :

$$NO^+ + e \rightarrow N(^2D) + O$$

which is also responsible for the weak ($\simeq$ 1R) λ 5 200 nightglow. Both excited states are efficiently depopulated by collisions with neutral species. The intensity of these lines is thus governed by excitation mechanisms and quenching ; they provide useful information regarding ionospheric conditions and the altitude of the emission region.

The observations normally started as soon as the atmosphere was dark enough and lasted until sunrise. However, due to unfavorable meteorological conditions, no measurements have been made during this storm until Dec. 17 at 18.00 U.T. On account of some trouble experienced with the magnetic recorder, no valuable data were recorded until 19.40 U.T. The period of time during which the observations reported hereunder were made, the sky was moonless and remained clear.

The intensity measured in the four channels is plotted as a function of time on logarithmic scale in Figure 2.

The experimental points are distant by 100 seconds from each other. Visual inspection of the display revealed that the upper part of the rays were clearly reddish during most of the night, thus exceeding the visual threshold of about 10 kR. A corona formed at about 00.30 and lasted for a few minutes. These particular aspects, together with the high 6 300/4 278 ratio observed, permits the identification of the display as a type-A aurora. Throughout the night structured forms appeared and faded with various morphology. However, rayed arcs dominated over the other forms and even during the early morning hours (~ 3.30 U.T.) pulsations remained absent.

Regarding the location of the observations, the station was in the statistical oval for $Q = 3$ during the period of measurements. The global morphology in the entire oval and polar cap has been determined at 02.19 U.T. by an ISIS II scanning survey of the northern polar regions (Anger and Lui, 1973). These data indicate that *at this particular time,* we were observing just near the equatorward edge of a "diffuse zone" of aurora.

Intensity ratios

Some spectral characteristics are remarkable in this display as illustrated in Figure 2.

1/ The H_β intensity is occasionally relatively high, reaching values as large as 200 R, indicating the presence of an important proton flux. The measured λ 4 278/H_β intensity ratio varies between 138 and 5.7. This ratio yields an estimate of the proton contribution to the ionization rate. Eather (1968) has determined experimental intensity ratios in hydrogen aurora for pure proton excitation. His λ 3 914/H_β is 3.3 to 5.7. Consequently, the fraction of proton excitation in these observations is estimated to vary between 4 and 100 percent.

Similarly, a λ 5 300/H_β ratio of about 3 is expected in a pure proton aurora, which is to be compared to the lowest value of 14 observed during this particular night. The conclusion can thus be drawn that, even during the proton-rich phases of the event, most of the 6 300 OI emission is not due to the direct effect of proton precipitation.

2/ The λ 6 300/λ 4 278 ratio is enhanced with respect to other nights : a maximum of 7 being reached at about 19.50 U.T. This corresponds to an enhancement by a factor 14 with respect to "normal" aurora, for a λ 4 278 N_2^+ brightness of 1.1 kR. The λ 6 300 Å intensity got as high as 12 kR, a value quite considerable compared to those observed during other nights. This fact, together with the duration of the red line enhancement, confirms that this event is a type-A aurora.

3/ The λ 6 300 OI/λ 5 200 NI ratio was unusually high, ranging between 84 and 30. This ratio has been shown to keep a constant value close to 20 in other displays, independently of the auroral brightness (Gérard and Harang, 1973). During this event, on the contrary, it is variable : Figure 3 shows its variation as a function of the λ 6 300 brightness. Open circles correspond to the experimental points plotted in Figure 2 (1 point every 100 sec.), whereas

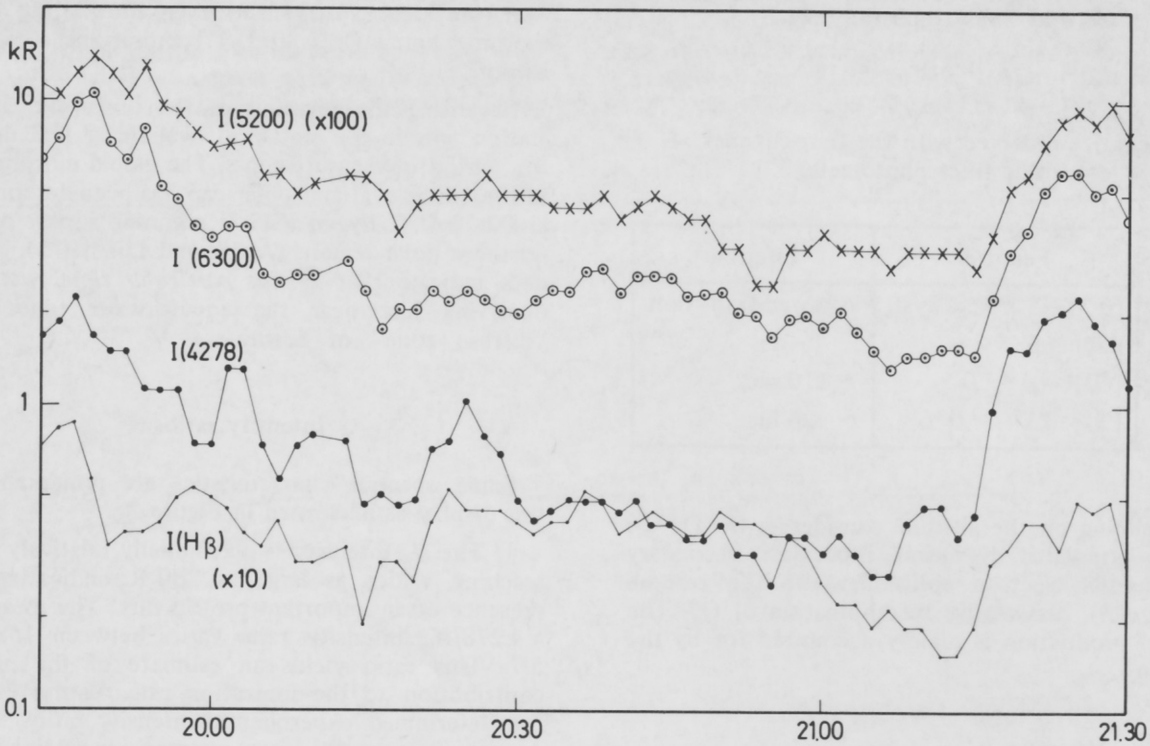

kR
10
1
0.1
I(5200) (x100)
I (6300)
I(4278)
I(Hβ)
(x10)
20.00
20.30
21.00
21.30

Fig. 2a

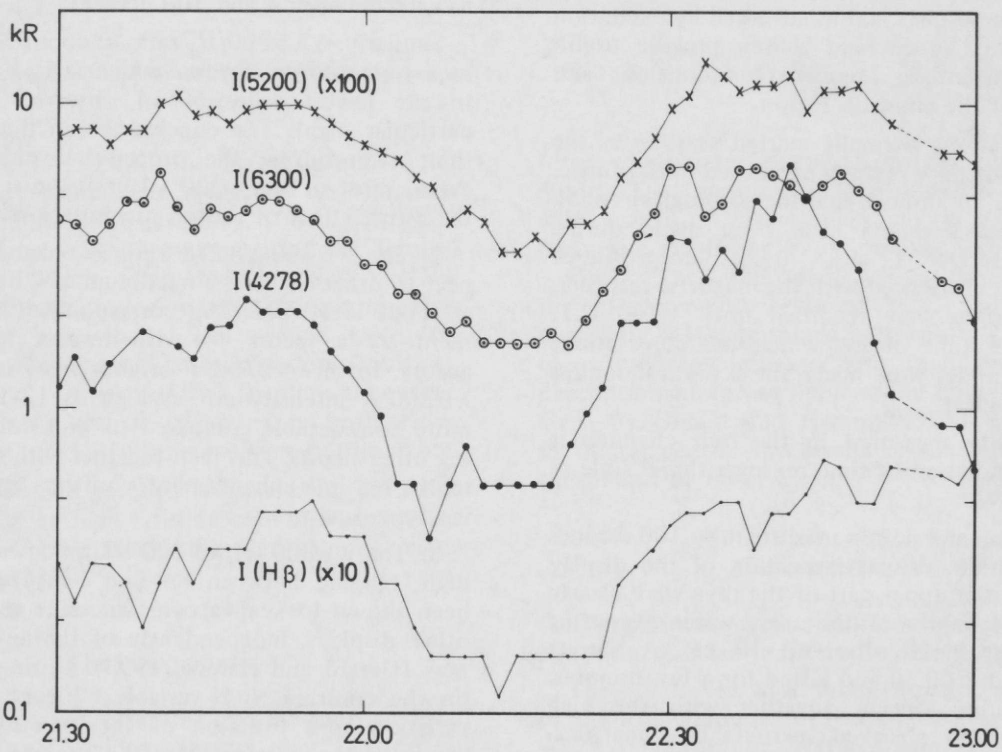
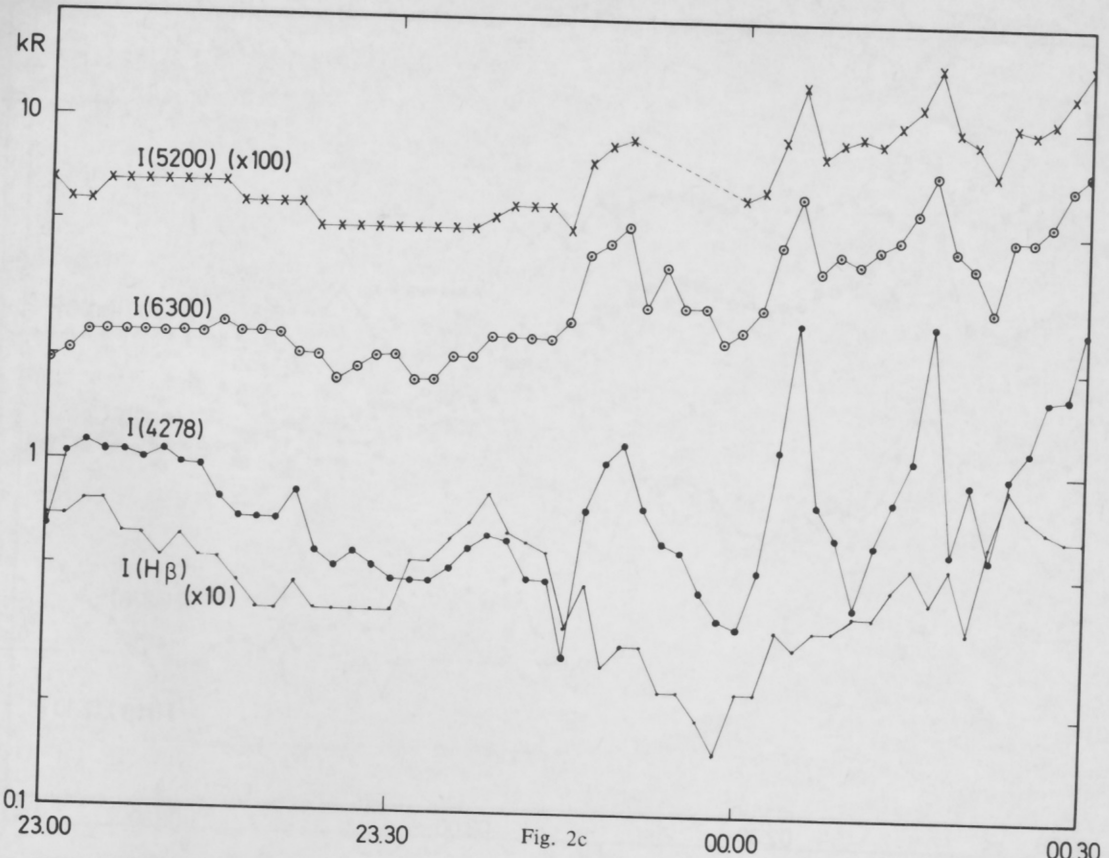
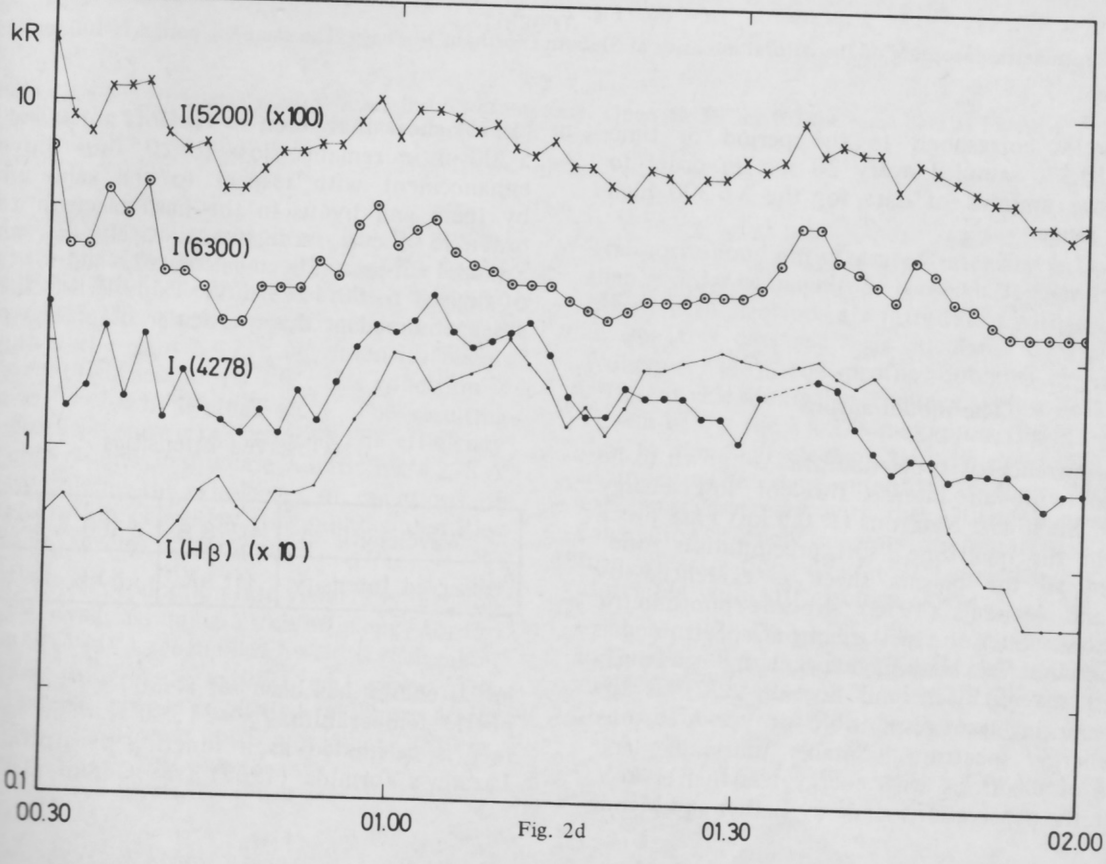

kR
10
1
0.1
I(5200) (x100)
I(6300)
I(4278)
I (Hβ) (x10)
21.30
22.00
22.30
23.00

Fig. 2b



kR
10
1
0.1
I(5200) (x100)
I(6300)
I(4278)
I(Hβ)
(x10)
23.00
23.30
00.00
00.30

Fig. 2c



kR
10
1
0.1
I(5200) (x100)
I(6300)
I(4278)
I(Hβ) (x 10)
00.30
01.00
01.30
02.00

Fig. 2d

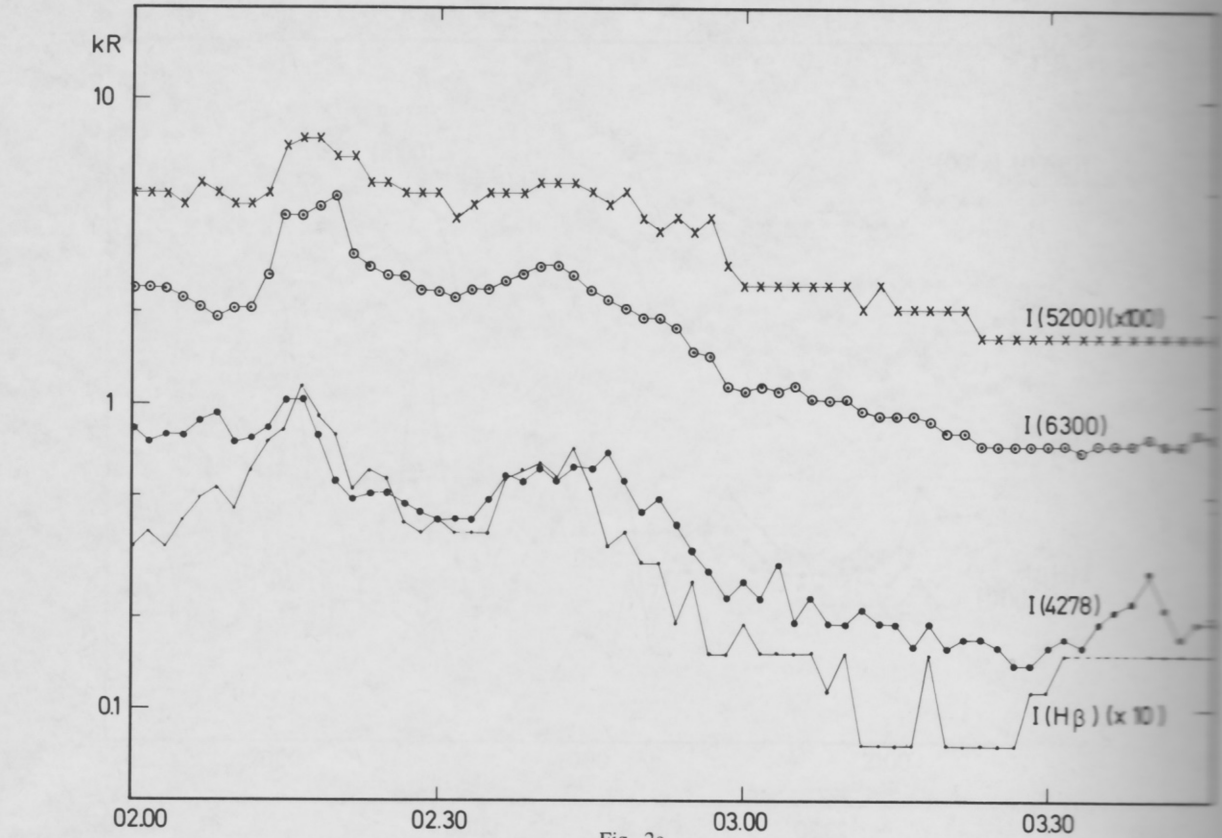


Fig. 2e

Fig. 2

Photometric recording of the auroral intensity at Skibotn (northern Norway). The sampling period is 100

closed circles correspond to the period of time 19.42 – 19.57, sampled every 20 sec. in order to increase the amount of data for the λ 6 300 high intensity range.

The model aurora

The occurrence of type-A auroras is known to be associated with an intense flux of low energy electrons. Such soft electrons (≅ 0.5 keV) are precipitated in the nighttime "soft precipitation zone" connected to the plasma sheet as evidenced by Eather and Mende's (1972) airborne photometric observations. Such a soft electron spectrum has been measured by sounding rocket and positively identified by Mc Ewen and Sivjee (1972) as the primary exciting agent responsible for type-A auroras. Their energy spectrum contains unusually large amounts of electrons with energy less than 1 keV. However, the observations made by Eather and Mende (1971) show that, even in the soft zone, the 5 200 ratio remains close to 20, thus enhancement with respect to the by them and by us in the hard electron order to discuss more quantitatively a model aurora has been calculated, of highest 6 300/4 278 ratio. Table II lists the sities observed at that particular time. The

Table II

Observed Intensities

Wavelength	4 278 Å	6 300 Å	[illegible]
Observed Intensity	1.1 kR	8 kR	[illegible]

initial energy has been set at 500 eV and the pheric temperature $T_\infty = 1\,200$°K. The rate is calculated as a function of altitude, Lazarev's formula (1967) (see Gérard,

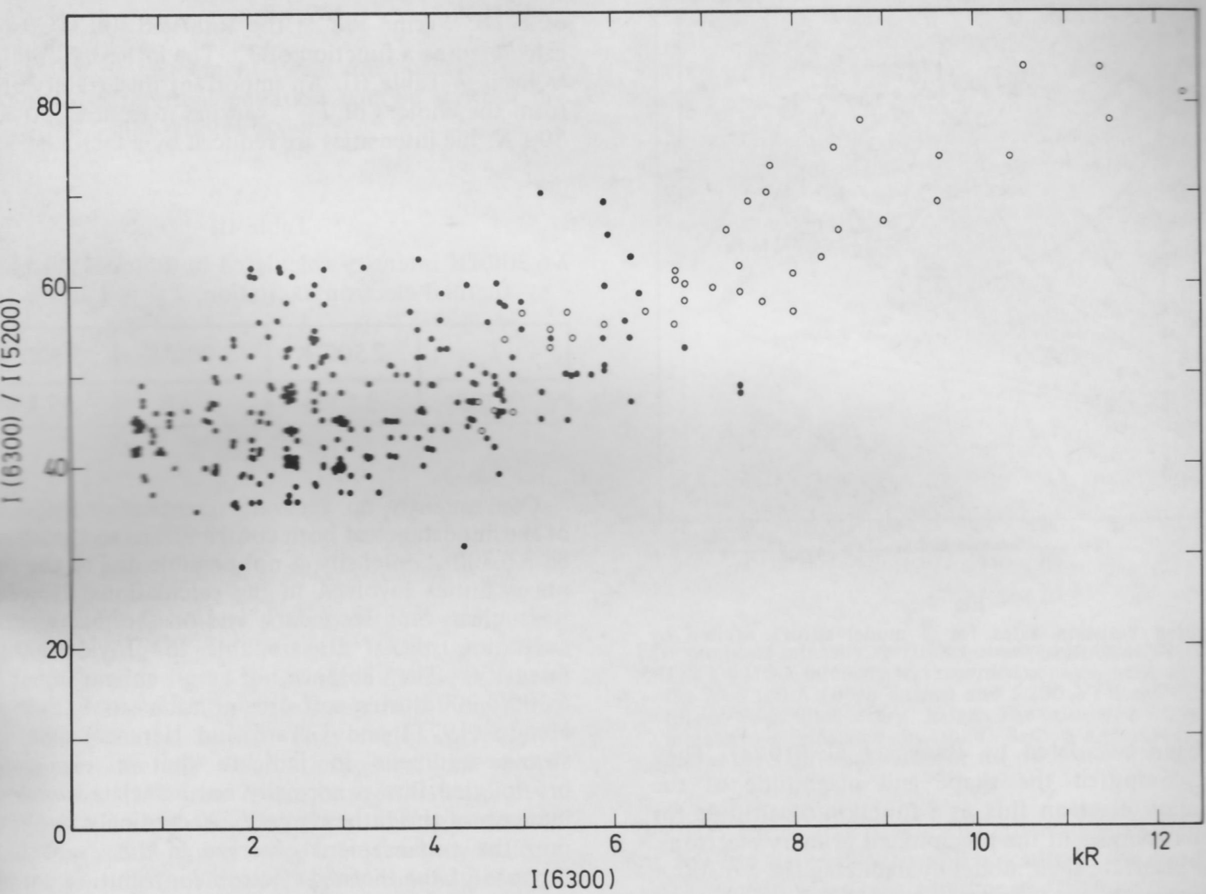


Fig. 3

The λ 6 300 OI/λ 5 200 NI intensity ratio versus the 6 300 intensity. Open circles are for the same data as Figure 1, closed circles correspond to the 19.42 - 19.57 period of time sampled each 20 sec.

Jacchia (1971)'s model atmosphere. The λ 4 278 N_2^+ emission rate profile is then derived under the assumption that one λ 4 278 photon is emitted for fifty N_2 ionizations. The monoenergetic incident flux is adjusted until the slant λ 4 278 N_2^+ intensity equals the observed brightness of 1.1 kR ; this condition is reached for $F = 7 \times 10^9$ cm^{-2} . sec^{-1}. The resulting emission profile is shown in Figure 4. The efficiency of energy conversion is in this case 3.3 10^3 eV/4 278 Å photon. By solving the whole set of equations of steady state in ion chemistry, the number densities of each ionic species is computed.

The λ 5 200 NI production rate yielded by reaction (1) can be derived, assuming a unit efficiency for the production of $(N^2D°)$. Quenching by O_2 is then taken into account using $k = 5 \times 10^{-12}$ cm^3 sec^{-1}. The resulting emission profile is plotted in Figure 4 and shows monotonic increase up to more than 300 km.

The corresponding integrated intensity is then more than 1 order of magnitude too high. If quenching collisions with electrons are introduced with a constant of 3×10^{-9} cm^3 sec^{-1} as calculated by Henry and William (1968), the profile obtained is radically different. Paradoxically it shows then a peak nearly 10 km below the λ 4 278 maximum, this effect being due to the high electron density present at higher altitudes. The slant intensity is then 120 R, in excellent agreement with the 130 R observed. This calculation strongly suggests the importance of electron deactivation of $N(^2D°)$, particularly when associated with soft electron fluxes.

The λ 6 300 OI production rate can be essentially ascribed to secondary and thermal electron excitation above 250 km (Rees et al., 1967). The contribution of the direct excitation by secondary electrons :

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

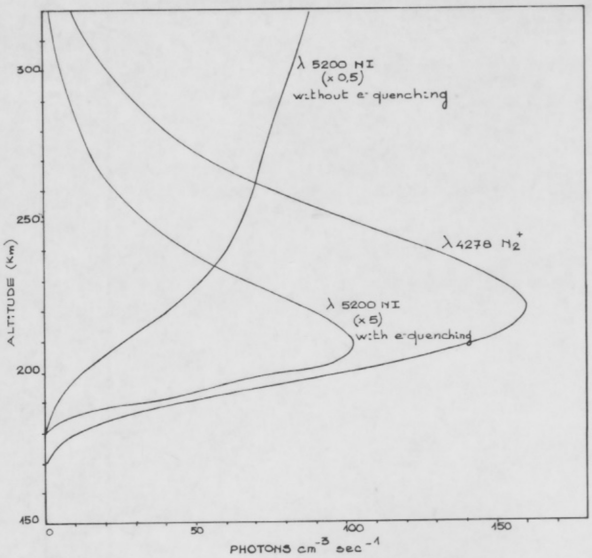


Fig. 4

Computed emission rates for a model aurora excited by 500 eV electrons.

has been calculated by Banks et al. (1974). They have computed the shape and magnitude of the secondary electron flux as a function of altitude for various energies of the precipitated primary electrons. They illustrate their model by deducing the λ 6 300 *A* emission rate for primary energies E. varying from 0.42 to 10 keV. Using $T_\infty = 1\,000°K$, $E° = 0.42$ keV and the deactivation coefficient k_{N2} $(O^1D) = 6.5$ 10^{-11} cm^3 sec^{-1}, their calculated slant λ 6 300 *A* brightness is nearly 13 kR, provided a precipitated primary flux of 7 x 10^9 cm^{-2} sec^{-1} is used as determined previously. Incidentally, according to Banks et als' model, the theoretical N_2^+ λ 4 278 *A* intensity corresponding to the flux is 1.2 kR, in good agreement with the observed one of 1.1 kR. Large relative errors in the calculated secondary flux are expected in the energy range 2 – 5 eV where the $O(^1D)$ electron excitation cross-section is sharply peaked. These uncertainties may lead to overestimating the contribution of the secondary electron $O(^1D)$ production.

The thermal electron production can be evaluated using :

$$n_{th}(6\,300) = \alpha_{th} \cdot n(O) \cdot N_e \text{ cm}^{-3} \text{ sec}^{-1},$$

where n_{th} (6 300) is the $O(^1D)$ production rate, $n(O)$ and N_e the atomic oxygen and electron densities respectively and α_{th} is a steep function of T_e given by Rees et al. (1967). Assuming that $O(^1D)$ is quenched by N_2 with a rate constant k_{N2} (O^1D) of 8 10^{-11} cm^3 sec^{-1}, the total λ 6 300 OI can be calculated as a function of T_e. The intensity obtained is given in Table III. An important uncertainty arises from the choices of T_∞ : varying it from 1 200°K to 800°K, the intensities are reduced by a factor of 3.6.

Table III

λ 6 300 OI intensity calculated in a model aurora for thermal electron excitation, T_∞ = 1 200°K

T_e	2 500°K	3 000°K	3 500°K
I_{th} (6 300)	3.5 kR	19 kR	59 kR

Consequently an accurate quantitative discussion of the importance of both contributions to the observed λ 6 300 *A* intensity is not possible due to the large uncertainties involved in the calculations. However, it is clear that secondary and/or thermal electron excitation of $O(^1D)$ are able to provide enough intensity. The absence of any enhancement of 6 300/5 200 during soft precipitations in Eather and Mende (1971) and Gérard and Harang's data is a strong argument to indicate that a low energy precipitated flux is normally not associated with any increase of this intensity ratio. Accordingly, we interpret the enhancement observed in this event to an increase of the thermal electron contribution coupled with an unusually high altitude $N(^2D°)$ deactivation by electrons.

The $N(^2D)$ effective lifetime

The analysis by various authors of fast temporal variations of the auroral intensity has provided estimates of the effective lifetime τ of $O(^1S)$. This method can be used here to derive an upper limit to the value of τ in the case of $N(^2D)$. The equation connecting the $N(^2D)$ number density to its production rate η is :

$$\frac{dn(^2D)}{dt} = \eta(^2D) - \frac{n(^2D)}{\tau},$$

which also defines the parameter τ.

The usual approximation made for the excitation of $O(^1S)$ is to take :

$$\eta \propto I(4\,278),$$

i.e. to assume that the production rate is proportional to the ionization rate. It is found empirically that this assumption holds no more for $N(^2D)$ and that a relationship of the type :

$$\eta \,\alpha\, (I(4\,278))^{1/2}$$

gives a better agreement with the observations. The above differential equation can be written in term of the 5 200 A intensity :

$$\tau \frac{dI}{dt} = f(t) - I\,,$$

which has the solution :

$$I(t) = I(t_0)\, e^{-\Delta t/\tau} + \frac{e^{-\Delta t/\tau}}{\tau} \int_{t_0}^{t} f(t')\; e^{\Delta t'/\tau}\, dt'$$

with :

$$\Delta t = t - t_0$$

and :

$$\Delta t' = t' - t_0$$

This equation has been solved with a computer, using $f(t)\,\alpha \sqrt{I(4\,278)}$. The result is illustrated for two pulsations at figure 5 for three different values of τ. These observations were made in the direction of the geographical zenith. They really correspond to temporal intensity fluctuations since the aurora was diffuse at this time. It can be seen that a perfect agreement between the theoretical and experimental (closed circles) curves cannot be reached, indicating that no single effective lifetime can be deduced using a simple differential equation. However, an upper limit of about 40 seconds can be derived from the amplitude of the modulation. On the other hand, $\tau \simeq 0$ best fits the third pulsation of figure 5, observed between t_0 + 210 and 240 seconds. This illustrates the complexity of the $N(^2D)$ chemistry. The parameter τ can be written as :

$$\tau = (A_{5\,200} + \sum_i k_i\, n(X_i))^{-1}$$

where k_i are the rates of quenching of $N(^2D)$ by the species X_i. The deactivating agents to be considered are O_2 ($k = 5 \times 10^{-12}$ cm^3 . sec^{-1} electrons ($K = 3 \times 10^{-9}$ cm^3 . sec^{-1}) and NO. The rate coefficient of the reaction

$$N(^4S) + NO \rightarrow N_2 + 0\,,$$

has been estimated at $1{,}5 \times 10^{-12}\ T^{1/2}$ cm^3 . sec^{-1} by Nicolet (1970) and is likely to be close to that of $N(^2D)$. Taking the bulk ot 5 200 A emission to be situated at 210 km and using $\eta(O_2) = 1.8 \times 10^8$ cm^{-3} and $\eta(e) = 10^6$ cm^{-3},

$$\tau^{-1} \cong 3.2 \times 10^{-3} + 5 \times 10^{-11}\, \eta(NO)$$

The observed value $\tau^{-1} \cong 2.5 \times 10^{-2}$ sec^{-1} is only explained if the nitric oxide density exceeds

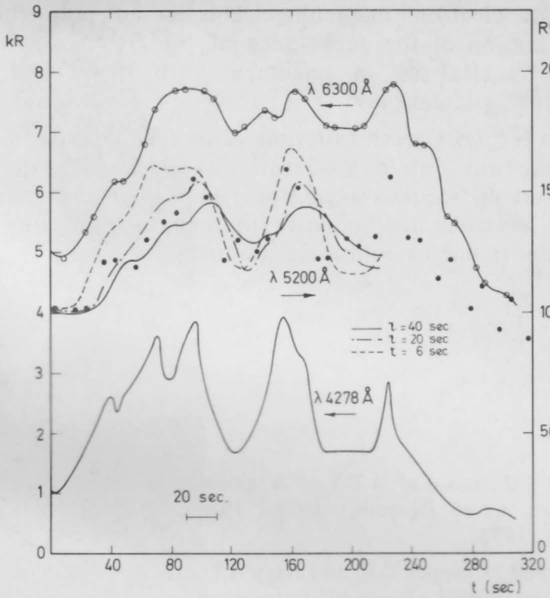


Fig. 5

Fast temporal intensity variations observed in three channels. The λ 4 278 A intensity was recorded continuously, whereas the λλ 6 300 A (open circles) and 5 200 A (closed circles) filters were tilted every 20 sec. The calculated λ 5 200 A intensity is indicated by solid, dashed and dot-dashed curves for 3 different values of the parameter τ.

5×10^8 cm^{-3} at 210 km. Whether such an amount of NO can be reached is still a controversial question since recent mass-spectrometer measurements have indicated that the NO abundance in the aurora cannot be interpreted in terms of the conventional ion chemistry.

Conclusions

The study of the photometric measurements made during the main and recovery phases of the event of 17 – 18 Dec. 1971 has revealed various features confirming or providing supplementary information regarding previous descriptions of the auroral spectrum during major magnetic storms. The outstanding characteristics of the aurora are essentially :

– a significant H_β intensity giving a proton excitation contribution reaching occasionally nearly 100 %.

– a high λ 6 300 OI/1. Neg. N_2^+ ratio characterizing type-A red auroras

– a 6 300/5 200 ratio higher than the usual nearly constant value. All these observations are compatible with the assumption that the essential part of the ionization is due to a soft electron (≅ 500 eV) spectrum. The considerable electron density reached between 200 and 400 kms has the twofold effect of enhancing the $O(^1D)$ thermal production and reducing by a considerable factor the λ 5 200 NI intensity through electron quenching. This is an indirect confirmation of the importance of $N(^2D)$ deactivation by electrons in agreement with Henry and William's calculation.

The $N(^2D)$ effective lifetime cannot be derived in a simple way but the observations yield an estimate of about 40 seconds as an upper limit. This value is much less than the radiative lifetime and indicates the importance of collisional deactivation.

Acknowledgments

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