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Variations in the Auroral Spectrum at the Latitude of the Polar Cleft

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Abstract. During the period November 23 to December 7, 1975 simultaneous photometric and spectrometric auroral measurements were performed for 250 h on the latitude of the polar cleft from Ny-Aalesund. The auroral green and red lines were observed all the time. During certain periods around local geomagnetic noon the intensity of the red line increased even when the intensity of the green line decreased. This was taken as an optical signature of the polar cleft. In the spectral range between the auroral green line and the hydrogen Balmer line H_β the NI doublet at 5200 Å was the dominating emission, occurring in 65% of the spectra, especially strong within the polar cleft. The peak 5200 Å intensity of averaged spectra seldom exceeded 100 R whereas the peak of 6300 Å was several kR.

The H_β was found in 30% of the averaged spectra. Its intensity was mostly below 20 R, and showed a weak correlation with the degree of "completeness" of the cleft. The 5200 Å and 6300 Å emissions are generated mainly by low-energy electron precipitation at high altitudes where the emission rate can be comparable with the quenching rate of the long-lived, metastable emitting states. Low-energy protons have a low efficiency for generating H_β photons which is believed to be the main reason for the low H_β intensity.

Key words: NI 5200 Å emission – Intensity ratios – Production and quenching rates – Dayside aurora – Polar cleft.

1. Introduction

The only accessible site where the sky is dark during the winter and yet near the locus of the daytime aurora is found on Svalbard. There Norway operates an auroral research station in Ny-Aalesund (78.9° N, 11.9° E, geographic, and 75.9° N, 114.7° E corr. geomagnetic coordinates) (Fig. 1). Ny-Aalesund is supposed to traverse the polar cleft at low and moderate magnetic activity (Feldstein,

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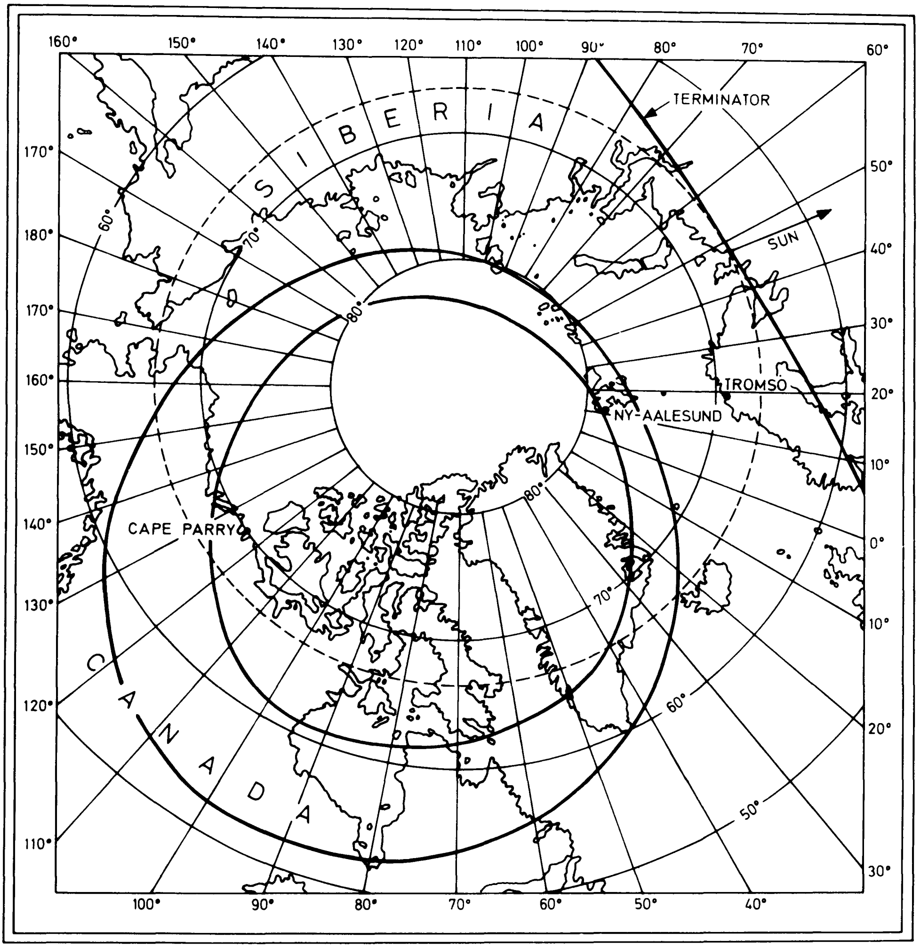

Fig. 1. The north polar region showing the sunrise-sunset line (terminator) at winter-solstice with respect to Ny-Aalesund at local geomagnetic noon and an approximate location of the auroral oval for a moderately disturbed period (Feldstein, 1966)

1966; Starkov and Feldstein, 1968). Local magnetic noon is at 0845 UT. With southward interplanetary magnetic field the latitudinal extent of the cleft region can be relatively long, $\Delta\lambda \sim 12$ h (Zaitzeva and Pudovkin, 1976), and Ny-Aalesund is expected to be within the cleft for several hours per day, depending on the level of geomagnetic activity.

In conjunction with the International Magnetospheric Study an expedition to Ny-Aalesund was undertaken during the period November 20 to December 12, 1975. Auroral optical and radio drift measurements were coordinated with passes of ISIS-2, and the purpose of the campaign was to study the daytime aurora by simultaneous ground-based and space observations (Berkey and Harang, 1976). A complete data analysis is underway.

Ground-based photometric and spectrometric measurements were performed from November 23 to December 8. In this report characteristic auroral features obtained from analysis of photo- and spectrometer data will be given.

2. Measurements and Analysis

The instruments used in this work were one scanning spectrometer and five fixed interference filter photometers. The spectrometer, called SP4 and described elsewhere (Stoffregen et al., 1971), had a spectral resolution of 30 Å and made in 4 min one wavelength scan between 4800 Å and 5800 Å. The photometers were constructed to measure the auroral emissions at 4861 Å (H_β), 5577 Å, 6300 Å, and the continuum around 5400 Å, where the FWHM of the interference filters was 30 Å. The sensitivity threshold of SP4 and the photometers were 10 R and 1 R, respectively. The photometers had a circular field of view with a full angle of 5°, whereas the spectrometer had a rectangular field of view $\sim 0.3° \times 3°$. The measurements were performed towards zenith. The instruments were calibrated in absolute units, and the data stored on digital tape.

During this campaign the solar depression angle, Sd, was always greater than 9°, which allowed continuous measurements in the zenith direction. Local noon shifted from 1104 UT to 1109 UT during the period of observations, and then, especially in November, the shorter wavelength observations were disturbed by sunlight, multiply scattered by air molecules and aerosol particles in the lower atmosphere (Henriksen et al., 1977).

The sky background, originating from airglow, scattered sunlight and extraterrestrial sources, was estimated from the photometric measurements. Around local noon the contribution from multiply scattered sunlight dominated. The baseline of the recorded radiance was estimated for each quarter of an hour by taking the lowest value within that interval. The sampling rate of the radiance was one per second. This method of obtaining the sky background intensity on the wavelengths of the auroral green and red lines at 5577 Å and 6300 Å was less reliable since at Ny-Aalesund there was an almost continuous auroral activity during daytime. The obvious improvement here is the use of a polarizing filter which, however, was not available for the present expedition.

The sky background estimated for the day of November 24 is shown in Figure 2. Since Sd is less than 15°, the intensity maximum around local noon is due to multiply scattered sunlight. The deviations from a smooth curve are most probably caused by auroral enhancements. During the afternoon the intensity drops to a few R/Å, which is the estimated sky background value. The relatively high intensity before noon is explained by a misty sky in combination with weak moonlight.

A better estimate of the sky background as a function of Sd is obtained from a statistic analysis of all the data during the period (Henriksen et al., 1977). This is used in the present study to find the auroral intensities at 4861 Å, 5200 Å, 5577 Å, and 6300 Å.

A sample SP4 scan taken close to local noon is shown in Figure 3, showing the increase of the scattered light intensity towards shorter wavelengths. A

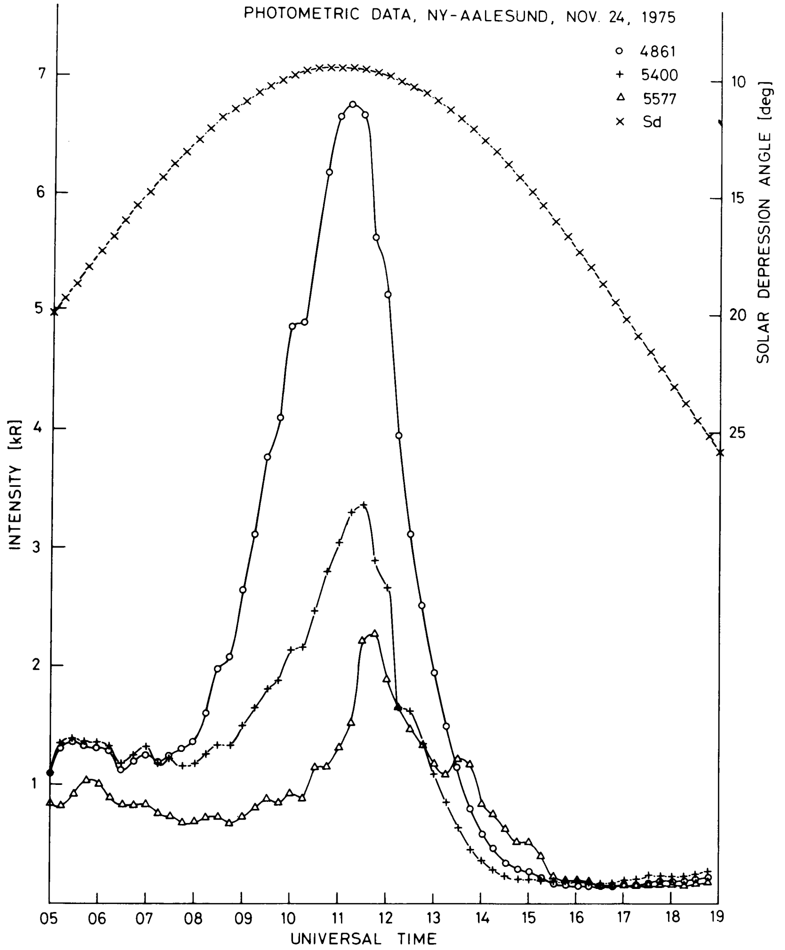

Fig. 2. The minimum intensity measured by photometers and calculations of Sd during daytime. The moon was low, and before 10 UT the sky was misty, clearing up later

small enhancement is seen at 5200 Å, but from this example it is hard to decide its significance as a real spectral feature. Signal averaging has accordingly been performed adding eight scans together, giving one spectrum each 32 min, and then a significant emission appears at 5200 Å. An example of the averaged data is shown in Figure 4. The strongest emissions between OI 5577 Å and H_β 4861 Å is then one at 5200 Å, which is likely to be the NI($^4S-^2D$) doublet. This is supported by recent spectrometric measurements in Alaska by Sivjee and Romick (1976), which show that the only emission within 30 Å of 5200 Å is the N_2^+ first negative band (0,3) with P-bandhead at 5228 Å. Preliminary spectrometric measurements in Tromsø give further evidence that the NI(^2D) 5200 Å emission with the doublet lines at 5198.5 Å and 5200.7 Å is a dominating auroral feature around 5200 Å. In Figure 5 an example of these new measure-

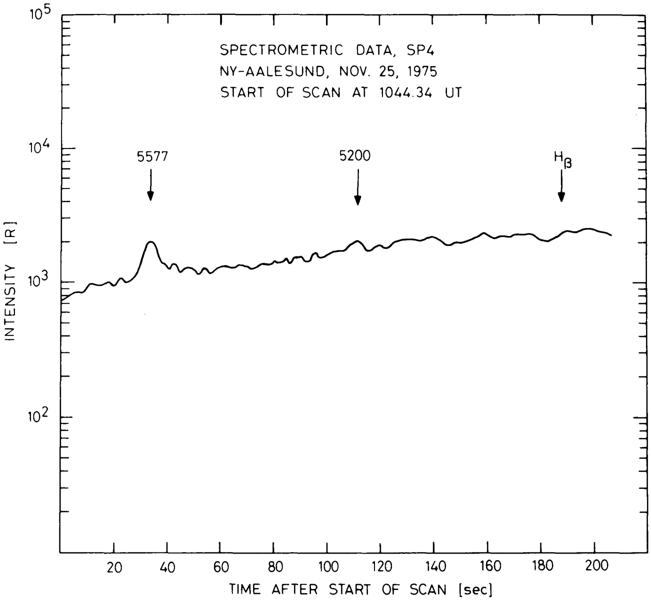

Fig. 3. The spectrum between 4800 Å and 5800 Å. In this case the auroral green line is a dominating feature, 5200 Å is weak, and no H_β is observed. Total duration of each scan is 4 min

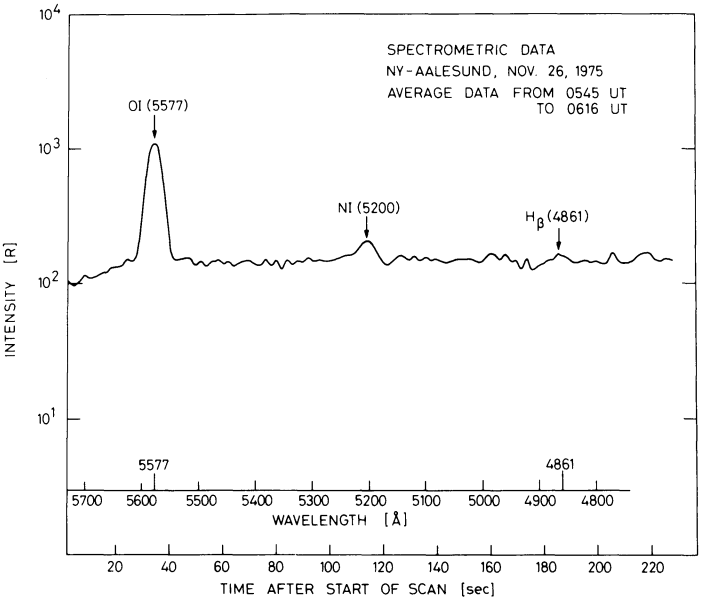

Fig. 4. Averaged spectrum obtained from 8 single scans. The emissions 5577 Å, 5200 Å, and H_β 4861 Å appear with characteristic intensities in the polar cleft aurora, 1 kR, 60 R, and 20 R, respectively

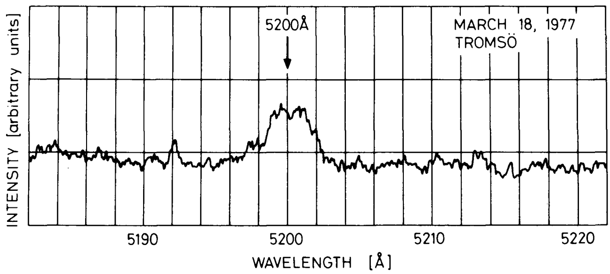

Fig. 5. Preliminary observation of spectral range around 5200 Å with a resolving power of 2 Å/cm. The NI 5200 Å doublet is on the point of being resolved. This observation is made with an improved spectrometer used in the January 78 campaign

ments is given. This recording is obtained at local geomagnetic midnight with the spectrometer at an elevation angle of 20°, pointing towards north into a diffuse auroral glow. Since the bulk of the 5200 Å emission originates from altitudes above 200 km, it is likely that the main emission region in this case was located within the polar cap, and therefore related to similar ionospheric conditions as in Ny-Aalesund.

The intensities of the auroral emissions at 4861 Å, 5200 Å, and 5577 Å are obtained from the averaged spectra, and the intensity of the 6300 Å emission is derived from the photometric measurements. The resulting averaged auroral intensities are presented and discussed below.

3. The Observational Results

A total of 467 averaged scans are analyzed, and the 5577 Å emission is clearly seen in every one. The averaged 5577 Å and 6300 Å intensities are plotted in Figures 6 and 7. For most of the time the 6300 Å emission is the strongest feature which is specific for high latitude aurora. Especially during intensity enhancements around local geomagnetic noon the 6300 Å line shows the strongest increase with maximum averaged intensities around 4 kR. The 6300 Å emission is regarded as an optical polar cleft signature (Shepherd et al., 1976). In several cases the 5577 Å intensity exceeds the 6300 Å intensity and must be due to bursts of more energetic electrons than those ~100 eV characteristic of the polar cleft (Doering et al., 1976). At lower latitudes, in the auroral zone, the 5577 Å emission is normally stronger than the 6300 Å emission, and the reversal of this intensity ratio seems to be inherent with the aurora in the polar cleft and the polar cap.

The NI 5200 Å emission is found to be a significant feature of the auroral spectrum of the polar cleft and within the polar cap. It is clearly identified in 302 averaged spectra. The 5200 Å intensity of the spectra has been plotted in Figures 8 and 9. Only in rare cases does the intensity exceed 100 R. The intensity variations of 5200 Å are similar to those of 6300 Å, but the intensities are more than ten times lower. On the basis of the similarity of the intensity

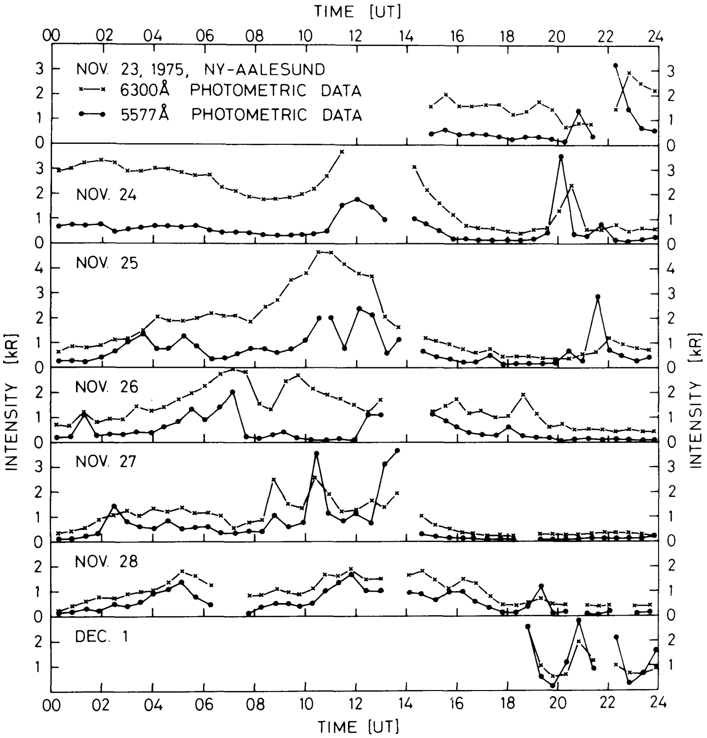

Fig. 6. Intensity of 5577 Å and 6300 Å obtained from spectrometer and photometer data for the period from Nov. 23 to Dec. 1, 1975 at Ny-Aalesund. The marks are at the start of each interval

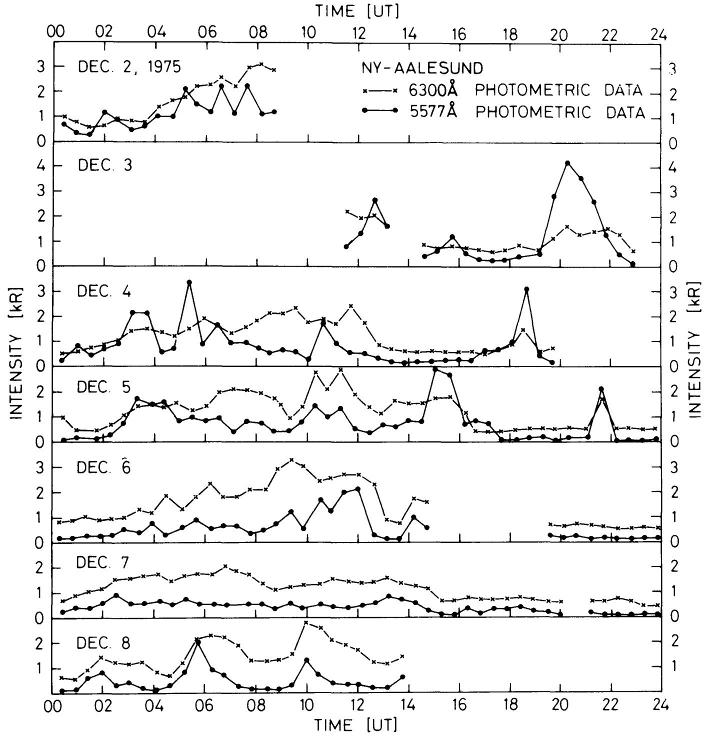

Fig. 7. Intensity of 5577 Å and 6300 Å obtained from spectrometer and photometer data for the period from Dec. 2 to Dec. 8, 1975 at Ny-Aalesund

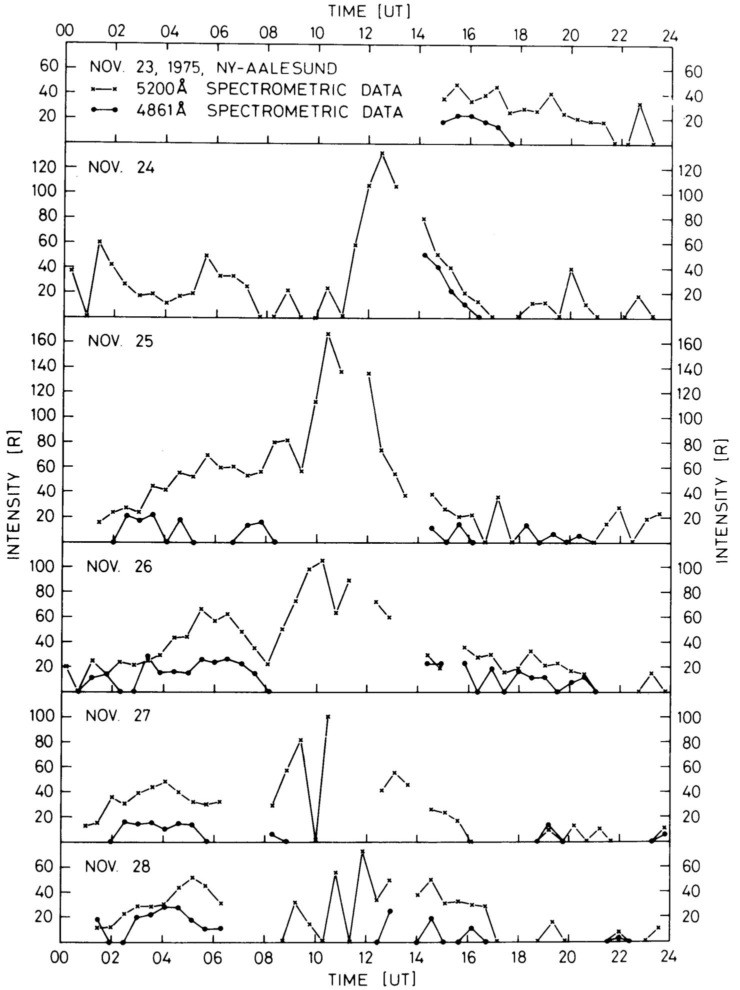

Fig. 8. Intensity of 5200 Å and 4861 Å obtained from averaged spectra for the period from Nov. 23 to Nov. 28, 1975. The observations were performed at Ny-Aalesund, using the SP4 spectrometer

variations and the quenching characteristics, the former can be regarded as another optical signature of the polar cleft.

The averaged H_β intensity is plotted in Figures 8 and 9 together with the 5200 Å measurements. From these diagrams it can be seen that the H_β in general is weaker than the 5200 Å emission. The averaged H_β intensity is mostly below 20 R and exceeds only a few times the 5200 Å intensity. The H_β emission can be identified in 140 of the averaged spectra. It occurs most frequently in the morning sector, and is therefore considered a less good indicator of the completeness of the polar cleft which is expected to be centered around geomagnetic noon. However, the increased background around local noon, at least in November, makes it difficult to detect H_β intensities of about 20 R.

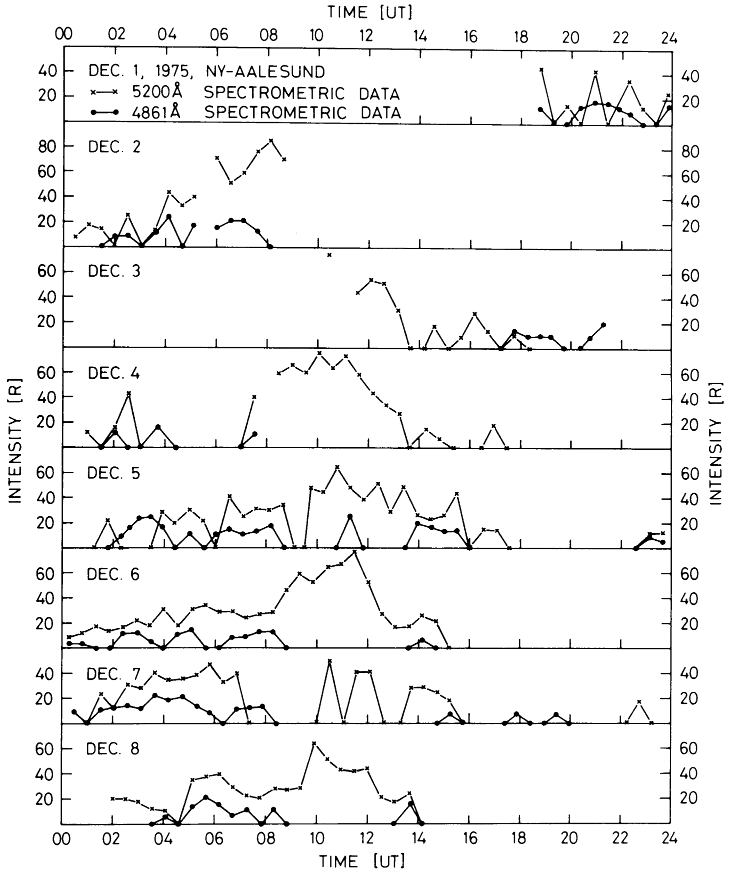

Fig. 9. Intensity of 5200 Å and 4861 Å obtained from averaged spectra for the period from Dec. 1 to Dec. 8, 1975 at Ny-Aalesund

The occurrence frequencies of this emission can accordingly be higher than our measurements show.

4. Excitation and Temporal Variations of the Observed Emissions

The H_β emission is due to an allowed transition in the neutral hydrogen atom. Within aurora the excited H atoms are mainly produced by neutralization of precipitated protons and collisional excitation of energetic neutral hydrogen atoms as the particles penetrate into the atmosphere (Omholt, 1971). Additional processes like dissociative excitation of hydrogen atoms by electron impact on H_2 and H_2O (Vroom and de Heer, 1969) are of minor importance. Therefore the H_β emission can be used as a monitor of proton precipitation.

Using satellites, high fluxes of low energy protons with characteristic energy below 1 keV have been detected and interpreted as a signature of the polar cleft (Heikkila et al., 1972; Doering et al., 1976). However, the efficiency of these protons to produce H_β is very low, less than 0.1 photon per proton (Eather, 1967). Therefore observed fluxes around 10^8 protons/(cm^2 sr keV s) (Sivjee and Hultqvist, 1975) may generate less than 10 R of H_β, indicating that the H_β output due to the characteristic polar cleft protons is small, and frequently escaped detection by our instruments.

The auroral emissions at 5577 Å and 6300 Å are due to forbidden transitions in the oxygen atom, $O(^1D-^1S)$ and $O(^3P-^1D)$. The auroral excitation of the $O(^1D)$ atoms is probably a superposition of several direct and indirect processes, and because of its low excitation energy of 1.96 eV, the same and additional sources as for the $O(^1S)$ atoms (Henriksen, 1974) can contribute. The most important additional process can be dissociative recombination of NO^+ ions, and it may account for the dominating 6300 Å intensity.

In the twilight $O(^1D)$ atoms are also produced by photodissociation of O_2 in the Schumann-Runge continuum (Noxon and Johanson, 1972). During our campaign the photodissociative contribution to the observed 6300 Å intensity was of minor importance since Sd remained $>9°$. The maximum photodissociative contribution is about 100 R, and therefore this excitation source can not account for the enhanced intensities around local noon.

The 5200 Å emission is due to the forbidden transition $N(^4S-^2D)$. The excitation energy of the ^2D state is 2.38 eV, and a number of indirect processes can contribute (Strobel et al., 1976; Frederick and Rusch, 1977). These processes comprise dissociative excitation of N_2 by photons and fast electrons, dissociative recombination of NO^+, and the reactions

$$N^+ + O_2 \rightarrow N(^2D) + O_2^+$$

and

$$N_2^+ + O \rightarrow N(^2D) + NO^+ .$$

The indirect excitation processes can be initiated both by electron and proton precipitation, and the observed 5200 Å, 5577 Å, and 6300 Å intensities may in principle also be partly generated by low-energy proton precipitation, but is considered to be of minor importance. A detailed analysis of the excitation sources is underways.

Examining the individual spectrometer scans which lasted for 4 min, one can frequently find intensity variations greater than 90% from scan to scan. These variations which are considered real indicate that the effective lifetime of the $N(^2D)$ atoms can be shorter than 4 min. The photometric records of 6300 Å contain 90% intensity variation within a few seconds, reflecting the magnitude of the effective $O(^1D)$ lifetime. The natural lifetime of the upper states of the 5200 Å, 5577 Å, and 6300 Å emissions are 26 h (Wiese et al., 1966), 0.8 s (Sinanoglu, 1970), and 110 s (Garstang, 1951), respectively.

In comparison the 5577 Å line can be considered as an instantaneous emission. When the effective lifetime is drastically shortened, the effect is due to collisional quenching which is analysed below.

5. Production Rate and Collisional Deactivation

When the atmospheric number density is sufficiently high, collisional deactivation, or quenching, is the main loss mechanism of the excited species. This mechanism is particularly important for ^{2}D and ^{1}D metastable states.

The height variation of the ratio between the emission and the quenching rates of excited atoms can be given by the expression

$$r_j = A_j / \sum_x d_j(x) n(x,h),$$

where $d_j(x)$ is the quenching coefficient for excited state j by species x with density $n(x,h)$ at height h. A_j is the sum of the radiative probabilities from state j.

Molecular nitrogen is regarded to be the dominating quenching agent of the O(^{1}D) state (Zipf, 1969). Using the N_2 number density $n(N_2, h)$ versus altitude from the CIRA mean atmosphere (1972), $A = 0.0091\ s^{-1}$ (Garstang, 1951), and $d(N_2) = 6 \cdot 10^{-11}\ cm^3/s$ (Zipf, 1969), the ^{1}D effective lifetime altitude profile is calculated and illustrated in Figure 10. This figure demonstrates that around 200 km 95% of the excited O(^{1}D) atoms are quenched, and an effective lifetime of a few seconds appears.

The energy of the auroral electrons penetrating down to 200 km is estimated to be a few hundred eV (Rees, 1963; Banks et al., 1974), typical energies of polar cleft electrons. As the diurnal variation of the 6300 Å emission differs considerably from the behaviour of H_β, it gives further evidence that the main part of the O(^{1}D) excitation is due to low-energy electron precipitation. The collisional quenching of the O(^{1}S) atoms is below 10% above 150 km (Henriksen, 1975), and therefore the excitation rate of the O(^{1}D) atoms generally exceeds the excitation rate of the O(^{1}S) atoms by at least an order of magnitude within the polar cleft.

Recent investigations find that for the N(^{2}D) atoms, atomic oxygen is the major quenching agent between 140 km and 220 km with a rate coefficient of $1 \cdot 10^{-12}\ cm^3\ s^{-1}$ (Strobel et al., 1976). Below 140 km collision with O_2 is the main loss process with rate coefficient of $7 \cdot 10^{-12}\ cm^3\ s^{-1}$, and above 220 km the quenching rate due to thermal electrons becomes the dominating loss mechanism. Using the quenching rate $5 \cdot 10^{-10}\ (T_e/300)^{1/2}\ cm^3\ s^{-1}$, the steady-state electron densities, and electron temperatures obtained by Frederick and Rusch (1977), the calculated electron quenching does not exceed the other loss mechanisms below 300 km. The effective lifetime τ and the emission to quenching ratio r have been calculated, using O, and O_2 number densities of the CIRA mean atmosphere (1972). The results are illustrated in Figure 11. The spectrometric records of 5200 Å infer that the effective lifetime can be at least as short as 4 min, a value which is obtained at 220 km. At this altitude less than 1% of the N(^{2}D) excitation leads to 5200 Å radiation.

Using our data, we estimate that in the cleft the production of the N(^{2}D) atoms generally is of the same order of magnitude as the production of the

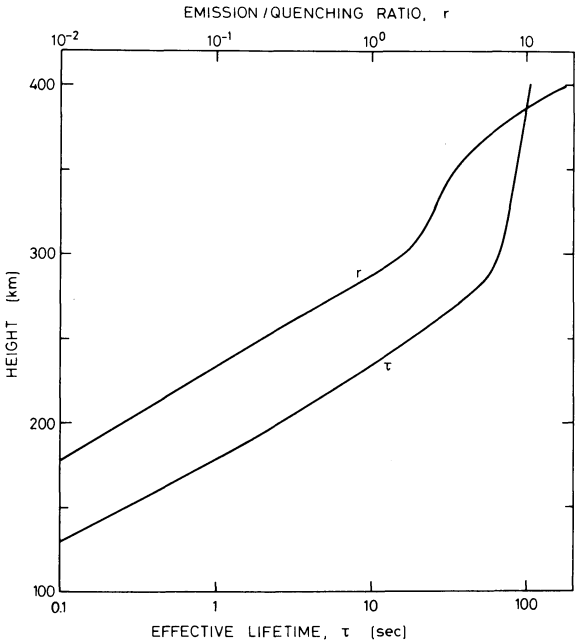

Fig. 10. The effective lifetime τ of the O(^{1}D) atoms and the ratio of emission to quenching r versus height

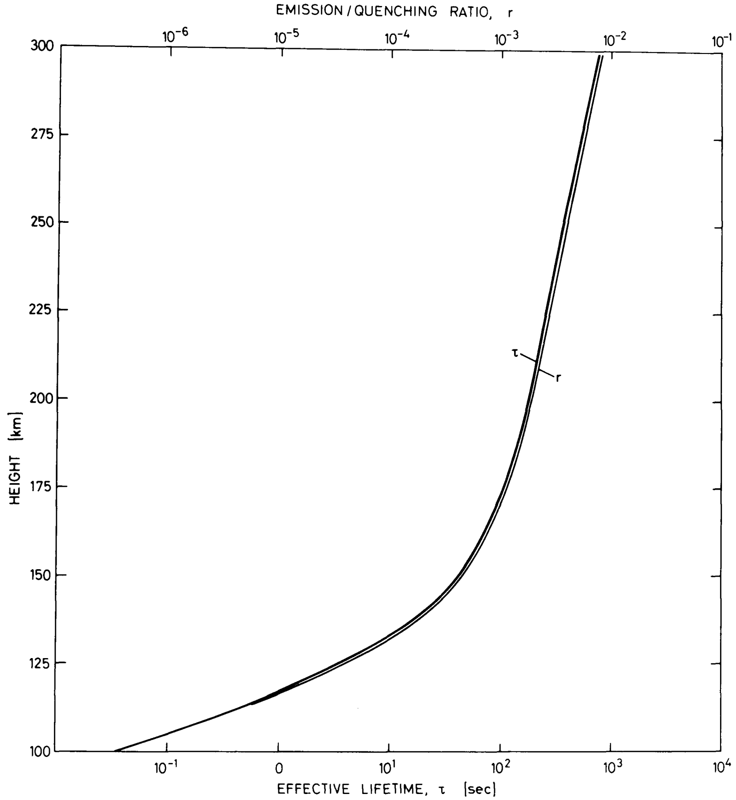

Fig. 11. The effective lifetime τ of the N(^{2}D) atoms and the ratio of emission to quenching r versus height

$O(^1S)$ atoms. The diurnal variation of the 5200 Å emission indicates that the main part of the production is due to low-energy electrons as for the $O(^1D)$ species.

Direct rocket-measurements in the polar cleft show that the emission height of 6300 Å can be found between 200 km and 235 km, and 5200 Å is emitted from altitudes above 235 km (Shepherd et al., 1976). The results of these experiments are in accord with the present work.

6. Conclusions and Future Work

The above discussed enhancements of the 5200 Å and 6300 Å features lead to the conclusion that the [NI] emission is another optical signature of the polar cleft aurora. The H_β intensity is relatively low, and it does not seem to be correlated with the 5200 Å and 6300 Å emissions, and remains low around local geomagnetic noon when Ny-Aalesund is expected to be within the polar cleft. Satellite particle measurements indicate that the particle precipitation is dominated by low-energy protons and electrons, probably of direct-entry origin. The enhanced intensity of the 6300 Å line is due to low-energy electron precipitation, and the low-energy protons may give only minor contributions to both 5200 Å and 6300 Å intensities.

The present set of data is not sufficient to predict adequately the location of the auroral oval at various levels of geomagnetic activity. Improved spectrometric observations, however, can be used to map the location of the dayside auroral oval, the polar cleft, and to identify the coupling mechanisms between the ionosphere and the magnetosphere.

A new campaign to Ny-Aalesund took place during January 1978, with an extended spectrometric observation programme. An improved spectrometer with a spectral resolution of 2 Å was included for the purpose of identifying the possible HeI 5876 Å emission from zenith and its expected Doppler shift of a few Ångströms towards shorter wavelengths. The wavelength region 5876 Å ± 10 Å was systematically explored, and weak intensity enhancements identified.

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