# SUBSTORMS DURING THE IMS PERIOD OBSERVED BY SOUNDING ROCKETS

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***Abstract*:** Experimental results obtained by the sounding rockets at Syowa Station, Antarctica, are briefly summarized. The electron density profiles in auroras were measured by the rockets which penetrated into intensely bright (~30 k$R$ for OI 5577 Å), bright (~10 k$R$) and weak (~5 k$R$) auroras. The $E$-region electron density amounts to $\sim 1.2\times10^6$ el/cm$^3$, $\sim 5.0\times10^5$ el/cm$^3$ and $\sim 6.0\times10^4$ el/cm$^3$ for intensely bright, bright and weak auroras respectively, while it is $\sim 6.0\times10^3$ el/cm$^3$ for no aurora during the night. The electron density in the $D$-region beneath the lower boundary of an intensely bright arc (75–98 km in altitude) is also considerably enhanced, up to $0.7–1.0\times10^6$ el/cm$^3$.

In bright auroral arcs, the electric field becomes small and points in the equatorward direction, whereas it becomes large with the predominant westward direction in the near space outside of a bright auroral arc. The electric field fluctuations (up to 240 Hz in frequency) are greatly enhanced in auroras over a wide frequency range, at altitudes of 100–120 km.

Various kinds of VLF and HF emissions are observed in the auroral ionosphere. Characteristics of these emissions and their relations to the precipitating electron flux are discussed.

## 1. Introduction

During the IMS period, 19 sounding rockets (seven S-310JA type rockets, max altitude ($h_{max}$)=230 km and twelve S-210JA type rockets $h_{max}$=130 km) were launched into auroras from Syowa Station (Geomag. lat.=70.0°, Geomag. long.=79.4°), Antarctica, at various stages of polar substorms. Through the successful rocket flights, significant physical quantities in auroras were measured: namely, 19 profiles of the electron density and temperature in the ionosphere, 11 energy spectra of precipitating electrons, 15 frequency spectra of VLF and HF plasma waves and 4 vertical profiles of electric and magnetic fields. These rocket data have been analyzed and compared with coordinated ground-based observation data, for the study of polar substorms. In this report, the experimental results of some of these rocketborne studies will be briefly summarized.

## 2. Electron Number Density within Auroras

Up to date, 22 sounding rockets have been launched at Syowa Station for the purpose of measuring the electron number density profile during the night time in the southern auroral ionosphere. The peak height of 17 rockets of the S-210JA type is about 130 km, whereas that of 5 rockets of the S-310JA type is about 220 km. In Figs. 1 and 2, the electron density profiles obtained by the S-210JA type (17 cases in total) and those obtained by the S-310JA type (5 cases in total) are separately summarized.

Practically, it was difficult to put a sounding rocket into a bright auroral arc or band even when the auroral activity as a whole was very strong and the overhead sky was covered with a number of auroral arcs. Among 15 time trials to shoot auroral arcs with a S-210JA or a S-310JA type rocket carrying an electron-probe, two S-210JA and four S-310JA rockets were able to penetrate a bright auroral arc. All other rockets passed some distance away from or through a weak aurora close to a bright auroral arc.

A S-310JA-7 rocket was launched from Syowa Station at 19h15m50s (UT) on March 27, 1978 just before the beginning of an intense substorm. The azimuthal direction of the rocket ground track was 338° (22° westward from the geo-

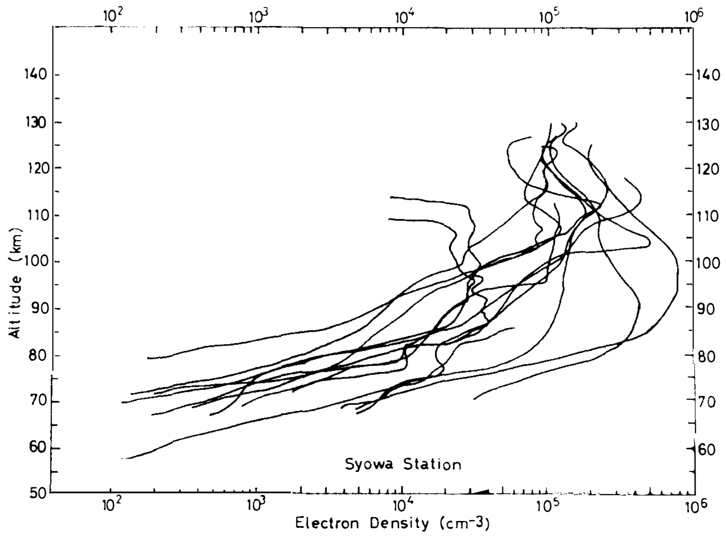


*Fig. 1. The vertical profiles of electron density along the flight orbits of S-210JA type sounding rockets during night hours (Original data provided by MIYAZAKI).*

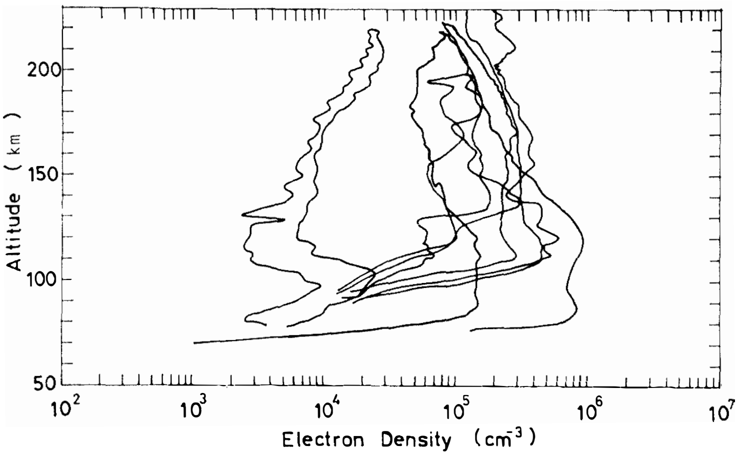


*Fig. 2. The vertical profiles of electron density along the flight orbits of S-310JA type sounding rockets during night hours (Original data provided by OYA and MIYAZAKI).*

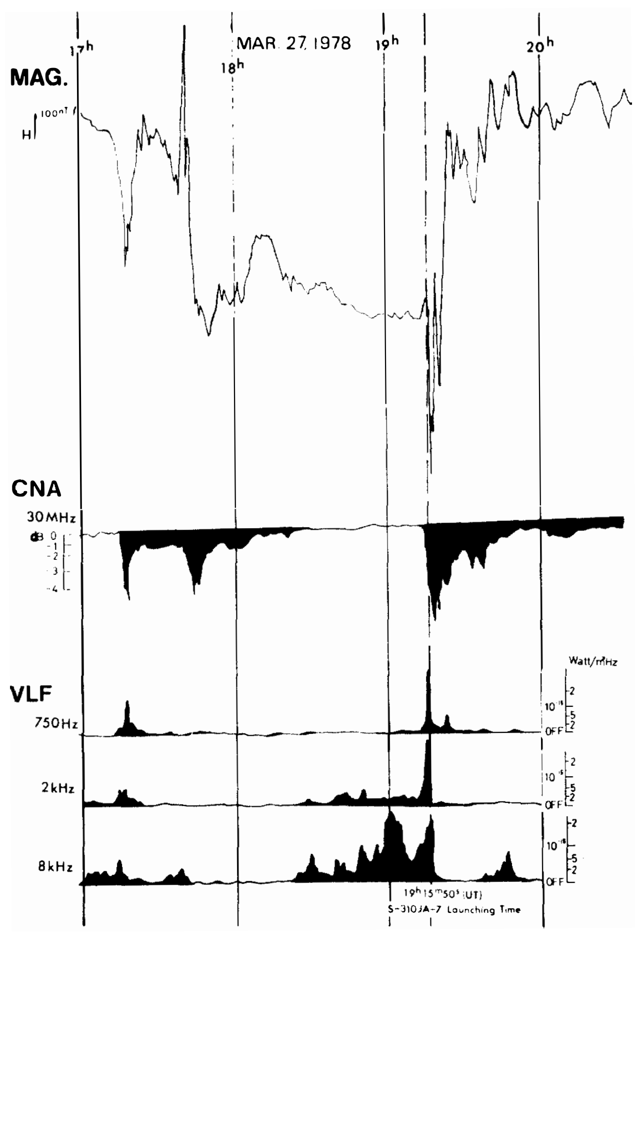


*Fig. 3. Records of geomagnetic H component, 30 MHz cosmic noise absorption and VLF emissions during the flight of S-310JA-7.*

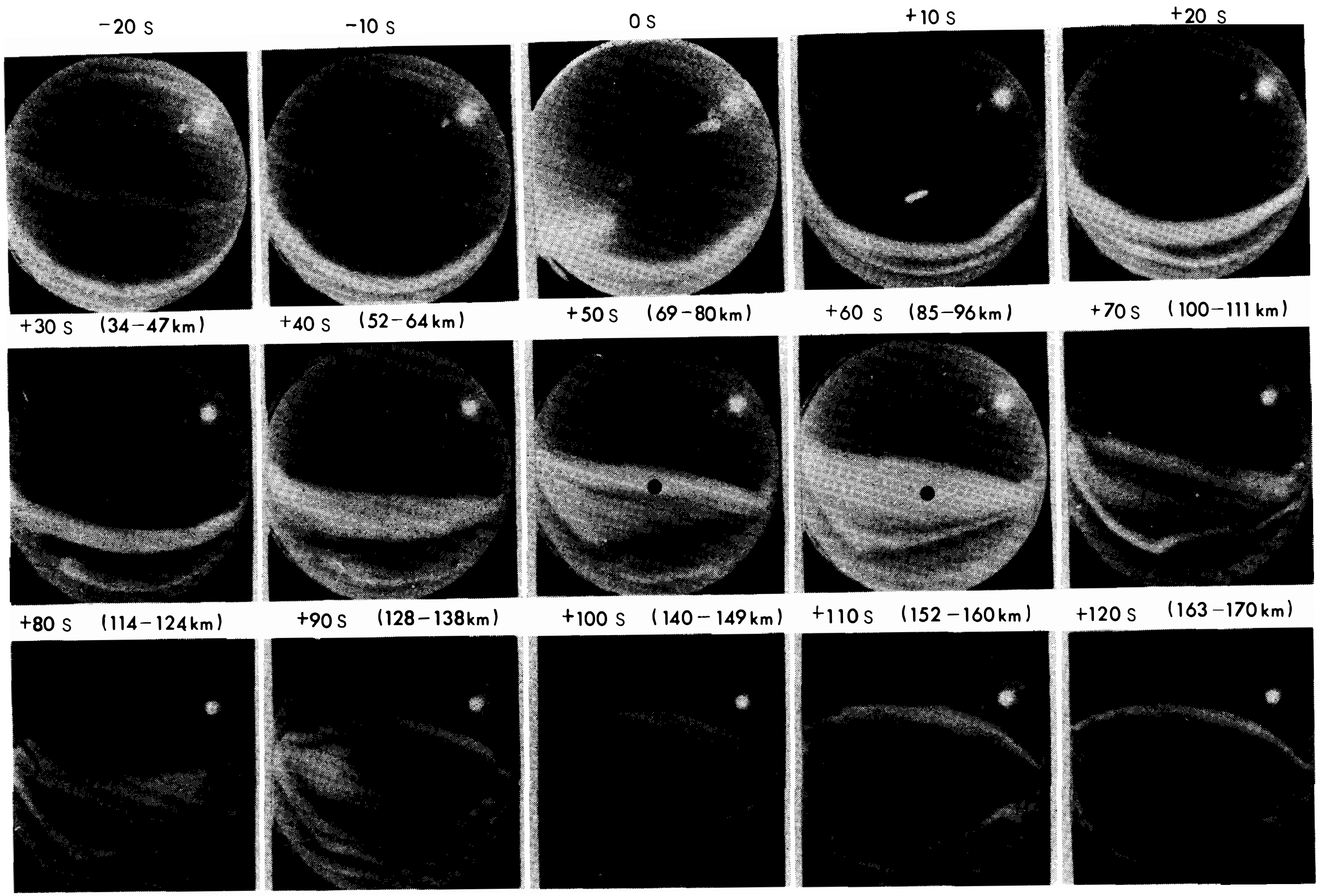


*Fig. 4. All-sky camera photographs taken at every 10 s at Syowa Station during the S-310JA-7 rocket flight. Orientation of the all-sky camera photographs: top is the geomagnetic south (poleward) and bottom is the north (equatorward). Black circles on the photographs show the rocket position at the same time.*

magnetic north). The records of the geomagnetic $H$ component, 30 MHz cosmic noise absorption and VLF emissions (750 Hz, 2 kHz and 8 kHz) during the rocket flight time are shown in Fig. 3. The launching time is indicated by a dashed line. The all-sky camera photographs in Fig. 4 show a sudden brightening of an auroral arc near the geomagnetic northern horizon of Syowa Station about 20 s before the rocket firing and its rapid poleward movement with a speed of about 3 km/s. About 60–70 s after the launching, the S-310JA type rocket reached a height of about 100 km and the instruments on board began to observe the auroral phenomena. As clearly seen in the all-sky data taken at from 60 to 90 s after the firing, the rocket S-310JA-7 penetrated and passed through an intense breakup type aurora. In Fig. 5, the space-time diagrams along the geomagnetic meridian of OI 5577 Å electron aurora and $H\beta$ proton one are illustrated during the S-310JA-7 flight. The contours of the auroral luminosity are in units of 1 k$R$ for 5577 Å and 100 $R$ for $H\beta$ line. The trajectory of the rocket projected to the 100 km level along the geomagnetic

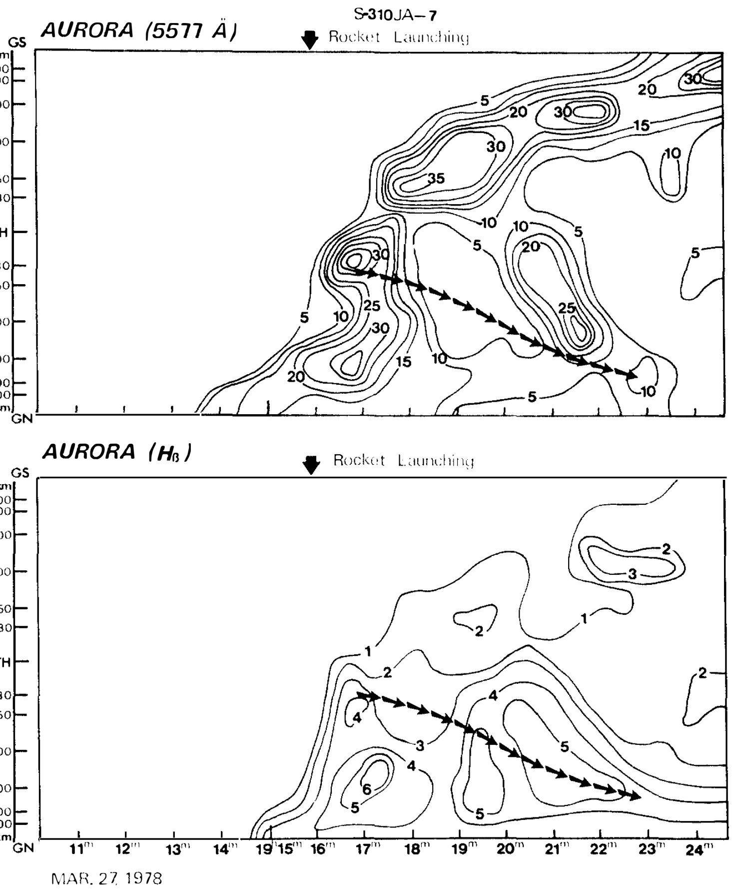


*Fig. 5. The meridian-time diagrams of IO 5577 Å and Hβ auroras during the S-310JA-7 rocket flight.*

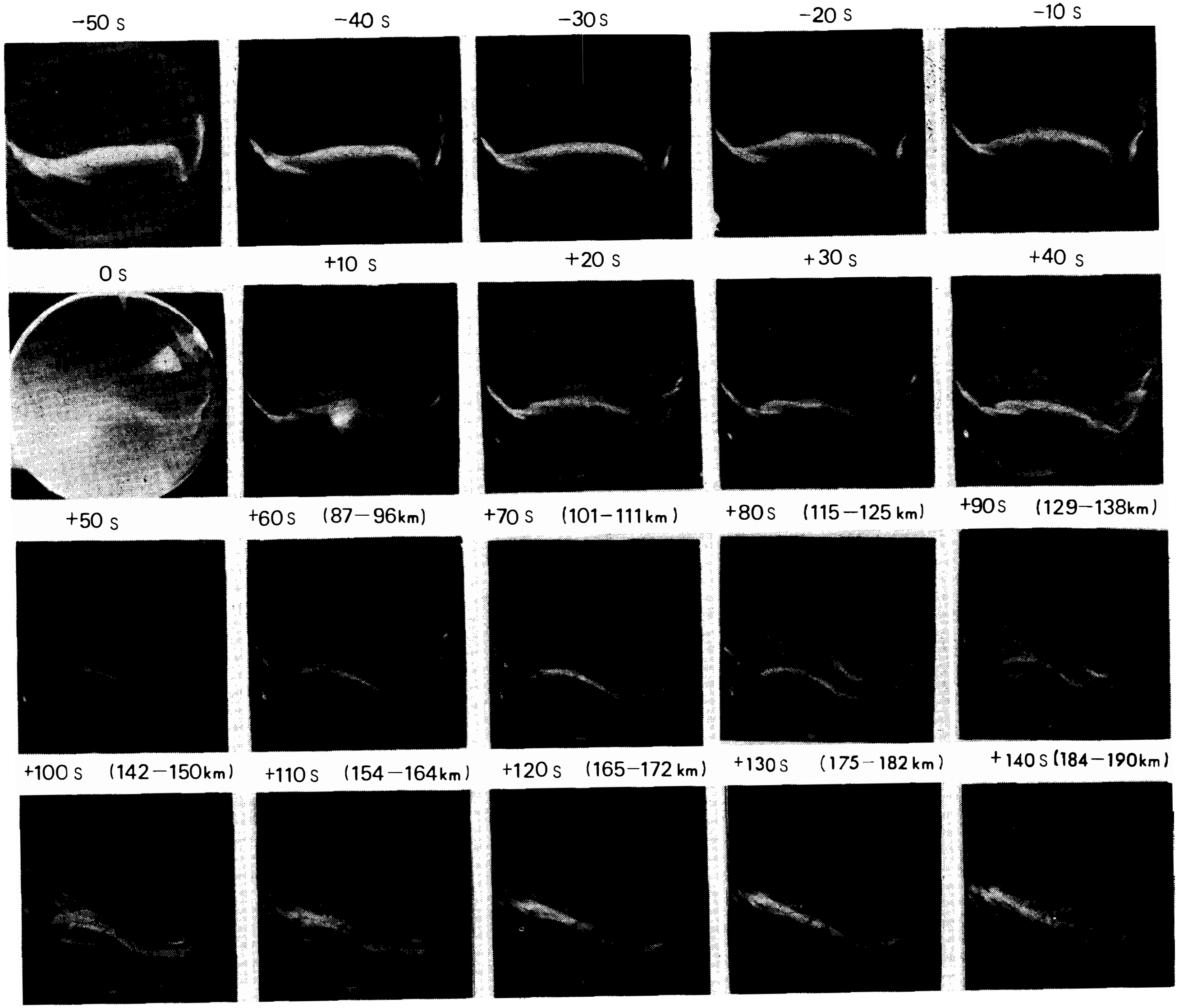


*Fig. 6. All-sky camera photographs taken at every 10 s during the S-310JA-5 rocket flight.*

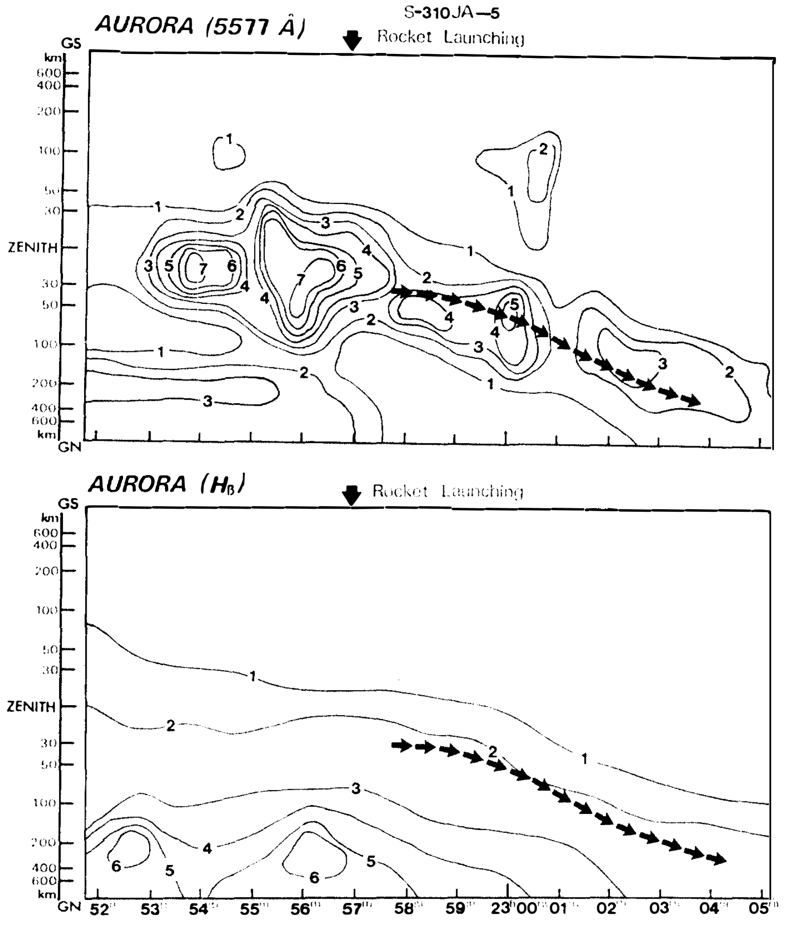


*Fig. 7. The meridian-time diagrams of OI 5577 Å and Hβ auroras during the S-310JA-5 rocket flight.*

field line is indicated by arrows in the diagrams. The auroral diagrams show that the S-310JA-7 rocket encountered an intense breakup type aurora with the luminosity (5577 Å) of about 30–40 k*R* at altitude of 100 km about 60–70 s after the launching, and then passed through the proton auroral region behind the poleward expanding auroral arc.

The S-310JA-5 rocket was launched equatorward at 22h56m00s (UT) on June 10, 1978, following the equatorward movement of an auroral arc before the onset of the auroral substorm as is clearly seen in the all-sky auroral photographs of Fig. 6 and in the auroral space-time diagrams of Fig. 7. This launching was very successful, the position of the rocket was continuously matching that of the aurora with luminosity of 2–5 k*R* throughout its flight.

In the rocket programs at Syowa Station, most of the rockets have been launched

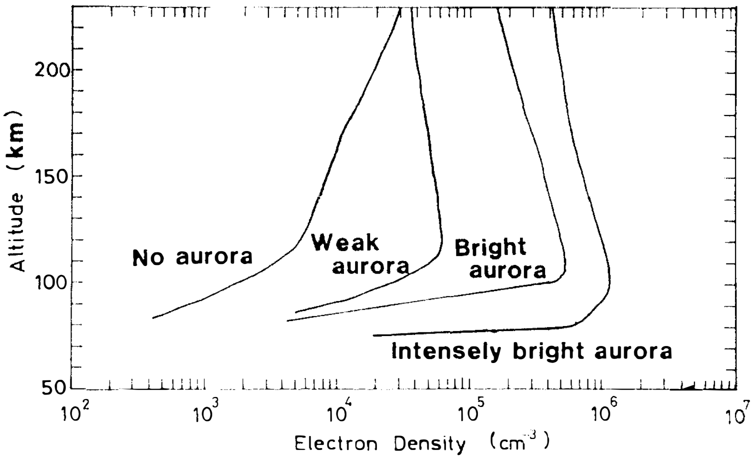


*Fig. 8. Schematic illustration of electron density profiles along the field line in intensely bright (~30 kR for OI 5577 Å) bright (~10 kR), weak (~5 kR) and no aurora.*

geomagnetically northward or southward. The auroral diagrams (shown in Figs. 5 and 7 for example) illustrate the space-time variations in the auroral luminosity along the geomagnetic meridian. The luminosity of aurora around a flying rocket can be estimated from the auroral diagram and the rocket trajectory projected on 100 km level along the geomagnetic field line (shown by arrows in Figs. 5 and 7 for example). Based on the available auroral diagrams at the times of 10 flights of S-210JA and 5 flights of S-310JA rockets and also on the observed electron density profiles shown in Figs. 1 and 2, the electron density profiles in auroras have been statistically estimated for various stages of auroral activity. In Fig. 8, the average electron density profiles along the field line are illustrated for the cases of the intensely bright (~30 k$R$ for OI 5577 Å), bright (~10 k$R$), weak (~5 k$R$) and no aurora.

## 3. Electric Fields within an Auroral Arc

A sounding rocket, S-310JA-7, was launched from Syowa Station at 19h15m50s (UT) on March 27, 1978 and passed through an intense aurora. The records of the geomagnetic $H$ component, 30 MHz CNA, VLF emission and auroral behavior at the time of the rocket flight are illustrated in Fig. 3. The electric field was measured by a double-probe type detector with two spherical probes 2.45 m apart from each other. Using the attitude data obtained by a geomagnetic aspect sensor and an auroral X-ray aspect sensor on board, the apparent $V \times B$ electric field induced by the rocket motion was subtracted from the observed electric field. Then the horizontal electric field was plotted in geomagnetic coordinates with an assumption that the electric field parallel to the geomagnetic field line is zero.

In Fig. 9, the horizontal variation of the electric field at the rocket altitude in the auroral ionosphere observed during the whole flight of S-310JA-7 is shown

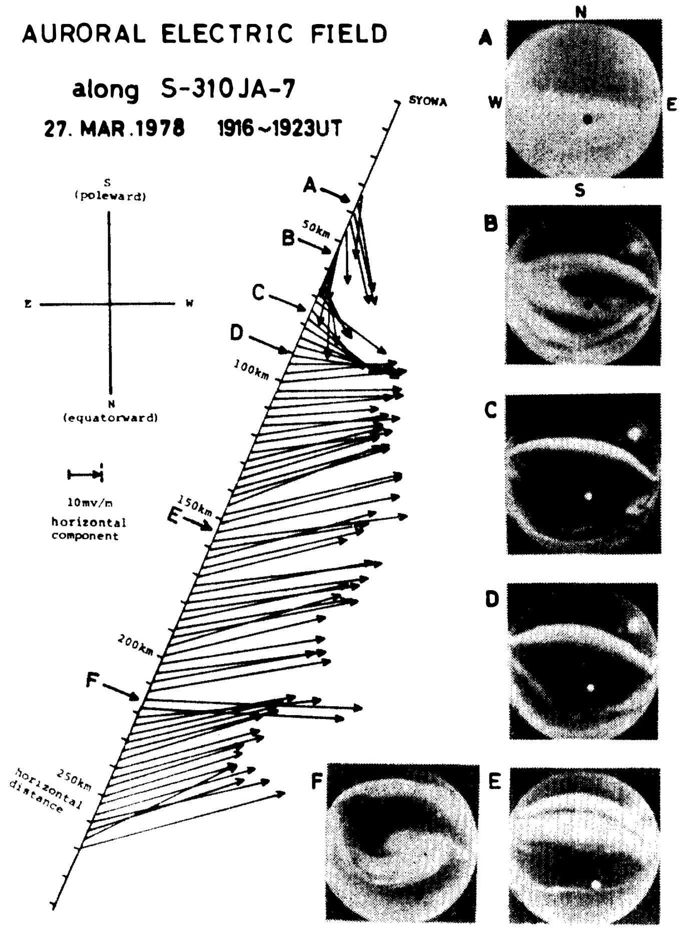


*Fig. 9. Electric field variation in the auroral ionosphere along the S-310JA-7 rocket trajectory.*

together with selected simultaneous all-sky photographs of aurora. The time of each all-sky photograph (A ~F) was indicated by an arrow pointing at the horizontal distance axis, while the position of the rocket projected on 100 km level along the geomagnetic field line is indicated by a circular spot in each photograph. This figure shows that the DC electric field is small and in the northward (equatorward) direction within the intense auroral arc (A, B and C), whereas it becomes large with the predominant westward direction in the space outside of the aurora (D, E and F). To more clearly show the relationship between the electric fields and the auroras, the observed electric fields in each case is indicated by a bar in each all-sky photograph of Fig. 10. The rocket altitude is shown at the bottom of each photograph and the intensity of electric field is presented by a bar-length from the rocket position (circle). The photographs in Figs. 9 and 10 show typical characteristics of an auroral arc motion at the time of an onset of a substorm. Namely, a bright arc moves rapidly poleward (southward) (A, B, C and D). Then

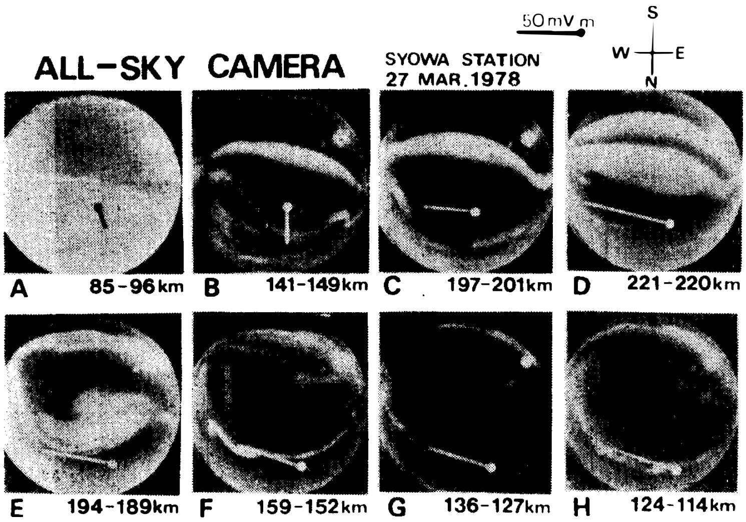


*Fig. 10. All-sky camera photographs with observed electric field directions, during the flight time of S-310JA-7 rocket.*

this arc separates into two arcs (D). The poleward arc moves farther poleward, while the other one moves equatorward forming a "holding structure" (E). The equator edge of this holding arc becomes a new arc and auroral curls traveling westward are seen along the arc (F, G and H). When the rocket encounters the poleward expanding arc, an equatorward electric field direction is dominant in the arc and in its vicinity. Comparison between the pictures A and B illustrates that the electric field is small in the arc. As the rocket moves equatorward away from the poleward expanding arc, a westward electric field is observed and the intensity of electric field becomes large. The result is quite similar to the electric field pattern at the equatorward side of an active arc at the onset of an auroral substorm as observed by the Stare auroral radar (NIELSEN and GREENWALD, 1978).

The rocket (S-310JA-7) also observed electric field fluctuations. Fig. 11 shows the power spectrum of the electric field AC component for frequencies up to 240 Hz. The rocket altitude and the flight time are given at the bottom and the top of each spectrum, respectively. In the middle of the figure, the all-sky photographs, in which DC electric fields are plotted, are shown, in order to illustrate the auroral activity. An enhancement of the frequency components below 10 Hz observed in every spectrum is attributable to rocket-generated disturbances in its wake. It is clearly seen that the electric field fluctuations are greatly enhanced over a wide frequency range in altitude of 105–120 km during the ascent. During this period (72–85 s in flight time), the rocket was located just within the intense auroral arc (*cf.* Fig. 5). It is suggested therefore that the electric field fluctuations of this type originate in the cross-field or the two stream instability caused by precipitating

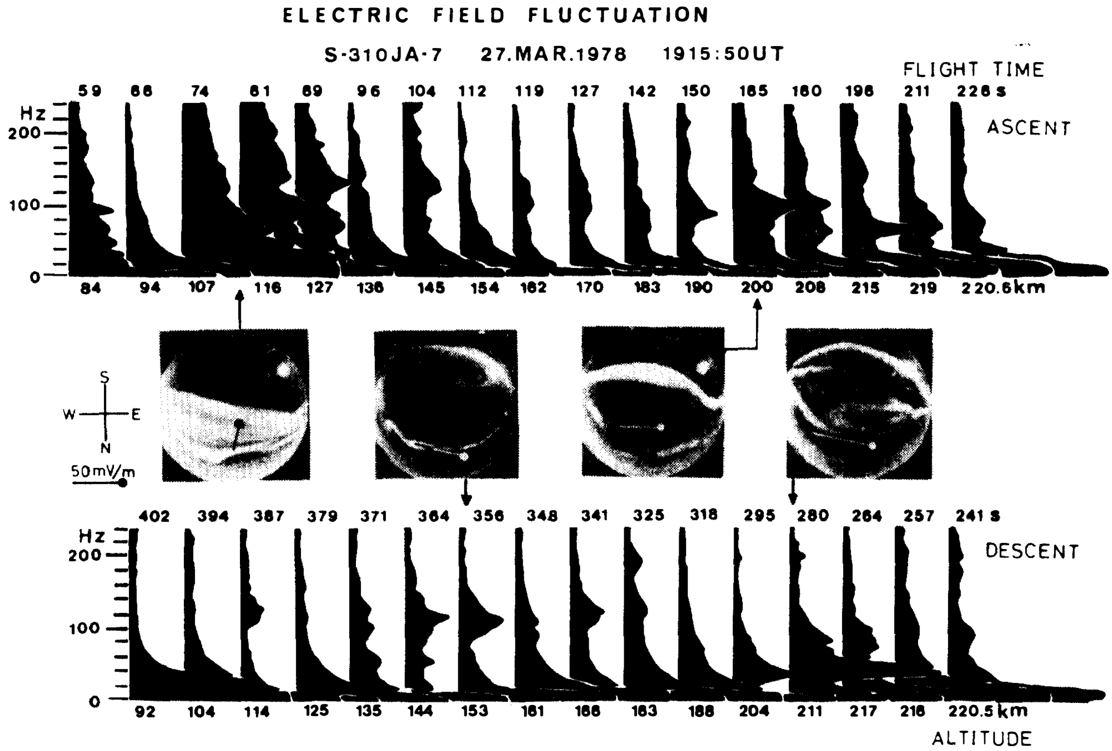


*Fig. 11. Power spectrums of electric field fluctuations observed on S-310JA-7.*

auroral electrons. The power spectrum of the electric field fluctuations observed in the altitude range of 180–220 km showed particularly large peaks at about 40 Hz, 60 Hz and 100 Hz. It seems likely that these frequencies correspond to $f_g(0^+)$ and $(n+2/l)f_g(0^+)$, where $f_g(0^+)$ denotes the gyrofrequency of $0^+$ which is about 40 Hz. Hence it seems likely that these fluctuations are electrostatic ion cyclotron waves generated by the field aligned currents.

## 4. VLF and HF Emissions in the Auroral Ionosphere

The S-310JA-5 rocket launched at 22h56m (UT) on June 10, 1978 penetrated into an auroral arc (see Fig. 7). By the VLF wideband receiver on board the rocket, relatively strong hiss emissions were observed by use of both loop and dipole antennas, in the altitude range of 150–200 km in the ascent period. In addition to the wide-band VLF spectra, the direction of the poynting vector of auroral hiss with respect to the geomagnetic field direction, and the direction and polarization of the propagation vector $\vec{k}$ with respect to the direction of the rocket axis, were measured at a frequency of 7 kHz. Based on these observed data, it was found that the polarization of the hiss wave was the right-handed (whistler) mode in the altitude range of 150–200 km and the wave was propagating downward. The angle between the $k$ vector and the local geomagnetic field direction was about 80° (KIMURA and HIRASAWA, 1979).

The S-310JA-6 rocket was launched at 21h56m (UT) on August 27, 1978 into an intense aurora of the corona type to observe the spectra of high frequency (HF) wave phenomena as well as those in the VLF range, for electron flux of energy less than 10 keV. In this rocket experiment, enhancement of a uniform noise band in the frequency range from 2 to 3.5 MHz was observed above an altitude of 100 km (type I HF-emission). It was found that at any altitude the frequency range of this type of noise band ranges from the local L (or Z) mode cutoff frequency up to the local upper hybrid resonance (UHK) frequency. In the frequency range from 0.4 to 0.8 MHz (around the half gyrofrequency), the noise intensity was also enhanced. These HF emissions can be considered as whistler mode emissions of natural origin (type II HF-emission). By comparing the time variation of the amplitudes of the type I and II emissions with that of the 40–60 keV electron flux of 75° pitch angle, it has been found that the type II emission correlates well with the electron flux, while the type I emission does not always do so. It may also be interesting to note that the occurrence period of intense VLF noise (4–8 kHz in frequency) coincides with the period when the type I and II emissions were enhanced. Especially the type II emission is closely related to the VLF emission of the electrostatic mode caused by beam-wave interaction (OYA *et al.*, 1980).

The S-210JA-20 and S-210JA-21 rockets were launched at 23h40m (UT) June 24, 1976 and at 00h23m (UT) July 26, 1976, respectively; a breakup aurora was being observed in the former case while a diffuse aurora was being observed in the latter case. In these experiments, VLF hiss was observed aboard the rockets simultaneously with weaker VLF emissions observed on the ground. It has been confirmed by examining the ratio of $E$ and $H$ fields observed on the rocket that this hiss was propagating in the whistler mode. The Poynting fluxes aboard in both experiments were almost the same being about $6\times10^{-14}$ W/m$^2$ Hz at frequencies of 6–8 kHz. The power flux of hiss on the ground around a frequency of 8 kHz was about $1.5\times10^{-15}$ W/m$^2$ Hz for the case of S-210JA-20 and was $2.5\times10^{-15}$ W/m$^2$ Hz for the case of S-210JA-21, implying that the absorption by the lower ionosphere amounted to 16 dB for the former case and 14 dB for the latter. A theoretically evaluated attenuation on the basis of the observed electron density profile is 14–24 dB, depending upon the incident wave normal direction. This theoretical estimate is in a good agreement with the observed values (KIMURA *et al.*, 1980).

Concerning the relationship of the hiss intensity with the flux of electrons of energy higher than 40 keV, the following results have been obtained. As shown in Fig. 12, the minimum level of the envelope signal level of the VLF wideband output observed aboard S-210JA-20 rocket (which especially corresponds to the electromagnetic wave component) is reasonably well correlated with the flux of 40–60 keV electrons. On the other hand, results of a similar experiment made

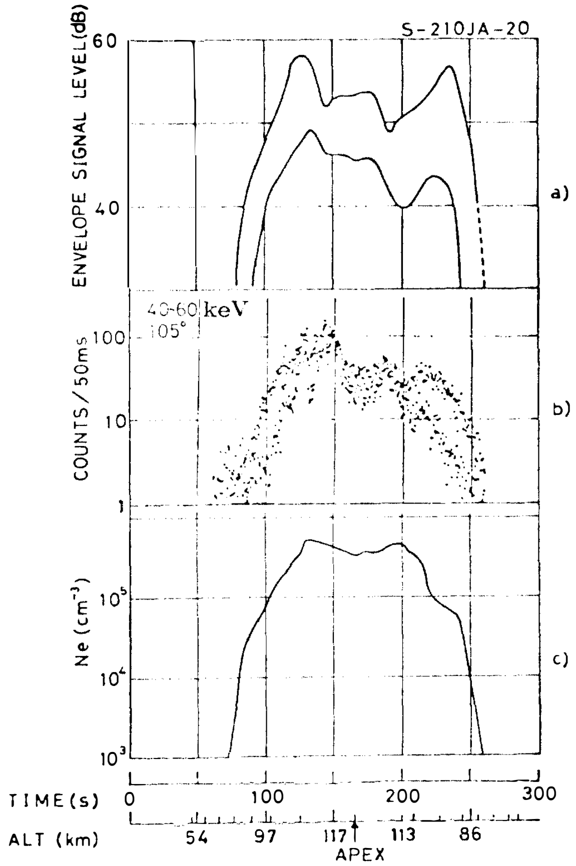


*Fig. 12. Intercomparison among a) VLF intensity, b) electron flux, and c) electron density observed by S-210JA-20 (after* KIMURA *et al., 1980).*

by S-210JA-21 show no clear correlation between these two parameters. These results may suggest that the source region of hiss emissions was located far above the rocket altitude. Sometimes the hiss propagation paths are very close to the trajectory of the causing electrons, but at other times they are not (KIMURA *et al.*, 1980).

## 5. Other Related Results

There are several other interesting phenomena observed by the sounding rocket experiments at Syowa Station. Some results will be very briefly summarized.

In Fig. 13, time variations of the precipitating electron fluxes of 4.45 and 1.14 keV are shown in comparison with two all-sky camera photographs of the most intense auroral displays during the observation period. From this figure, it may be clear that the intense auroral luminosity is well correlated with an intensified flux of 4.45 keV electrons, but not with that of 1.14 keV electrons (MATSUMOTO and KAYA, 1980).

The electron flux of energies of less than 10 keV is observed as quasi-periodic fluctuations with a period of the order of 0.1–0.3 s, as shown in Fig. 14. This kind of micro burst is often found in the auroral X-ray of energy much higher than 10 keV,

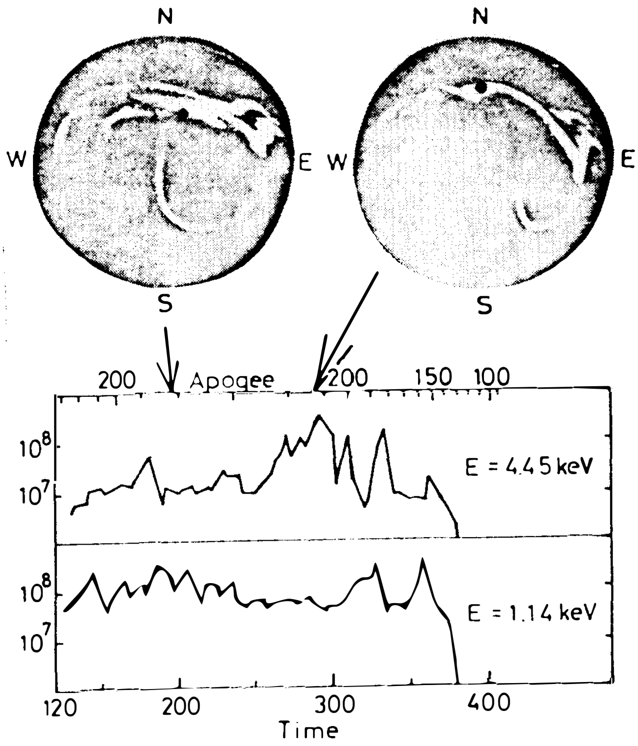


*Fig. 13. Electron fluxes observed by S-310JA-5 and the simultaneous all-sky photographs in which the position of the rocket is indicated by a black circle (after MATSUMOTO and KAYA, 1980).*

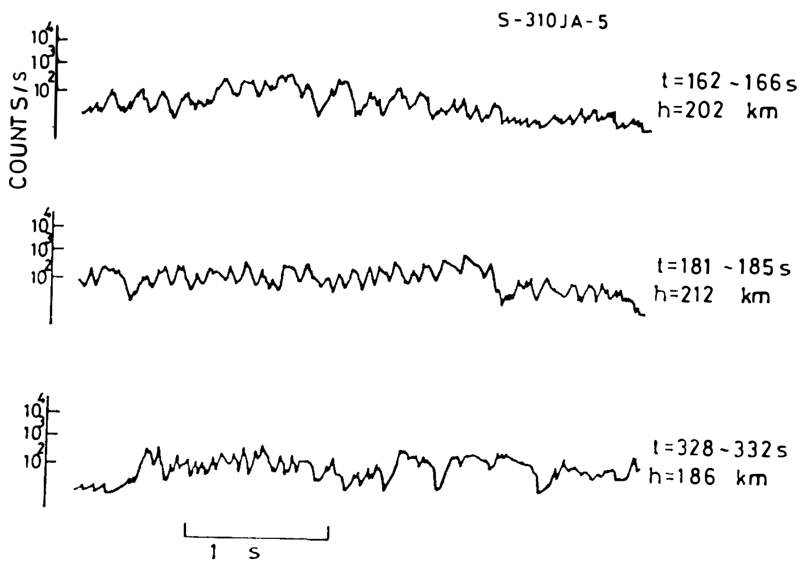


*Fig. 14. Microburst in electron flux observed by S-310JA-5 (after MATSUMOTO and KAYA, 1980).*

and is correlated with intensity fluctuation of VLF emissions (ROSENBERG *et al.*, 1971).

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**References**

FAIRFIELD, D. H. (1977): Electric and magnetic fields in the high-latitude magnetosphere. Rev. Geophys. Space Phys., **15**, 285–298.

HORWITS, J. L., DOUPNIK, J. R. and BANKS, P. M. (1978): Chatanika radar observations of auroral zone electric fields, conductivities, and currents. J. Geophys. Res., **83**, 1463–1481.

KIMURA, I. and HIRASAWA, T. (1979): Wave-particle interaction phenomena observed by Antarctic rocket. Japanese IMS Symposium. Institute of Aeronautical and Space Science, University of Tokyo, 112–121.

KIMURA, I., YAMAGISHI, H., MATSUO, T. and KAMADA, T. (1978): S-310JA-1 rocket observation of VLF emission spectra at Syowa Station in Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **9**, 51–68.

KIMURA, I., MATSUO, T. and DOI, T. (1979): Characteristics of a dipole and a loop antenna for plasma waves observed by the S-310JA-1 rocket. Nankyoku Shiryô (Antarct. Rec.), **64**, 42–49.

KIMURA, I., MATSUO, T., KAMADA, T. and NAGANO, I. (1980): Auroral hiss observed by Antarctic rockets, S-210JA-20 and 21. Nankyoku Shiryô (Antarct. Rec.), **69**, 17–36.

MATSUMOTO, H. and KAYA, N. (1980): S-310JA-5-gôki oyobi S-310JA-6-gôki ni yoru keV denshi no kansoku (Measurements of keV electron fluxes by the S-310JA-5 and -6 rocket). Dai-3-kai Kyokuiki ni okeru Denriken Jikiken Sôgô Kansoku Shinpojiumu (The Third Symposium on Coordinated Observations of the Ionosphere and the Magnetosphere in the Polar Regions, Programme and Abstracts), National Institute of Polar Research, 33.

MOSIER, S. R. and GURNETT, D. A. (1971): Theory of the Injun 5 very-low frequency Poynting flux measurements. J. Geophys. Res., **76**, 972–977.

NIELSEN, E. and GREENWALD, R. A. (1978): Variations in ionospheric currents and electric fields in association with absorption spikes during the substorm expansion phase. J. Geophys. Res., **83**, 5645–5654.

OGAWA, T., MORITA, M., FUKUNISHI, H., MATSUO, T. and YOSHINO, T. (1979): Nankyoku roketto S-210JA-24, 25-gôki ni yoru denrisô denba no kansoku (Measurements of ionospheric electric fields with Antarctic sounding rockets S-210JA-24 and 25). Nankyoku Shiryô (Antarct. Rec.), **63**, 252–275.

OGAWA, T., MORI, H. and MIYAZAKI, S. (1979): Roketto kansoku de erareta kyokuiki denrisô no denshi mitsudo·ondo purofairu (Rocket observations of electron density and temperature profiles in the auroral ionosphere). Nankyoku Shiryô (Antarct. Rec.), **65**, 15–27.

OYA, H., MIYAOKA, H. and MIYATAKE, S. (1980): Nankyoku roketto S-210JA-21-gôki ni yoru kôshûha purazuma hadô supekutoru no kansoku (Observation of HF plasma wave spectrum at ionospheric level using sounding rocket S-210JA-21 in Antarctica). Nankyoku Shiryô (Antarct. Rec.), **69**, 37–51.

ROSENBERT, T. J., HELLIWELL, R. A. and KATSUFRAKIS, J. P. (1971): Electron precipitation associated with discrete very-low-frequency emissions. J. Geophys. Res., **76**, 8445–8452.

TAKAHASHI, T. and OYA, H. (1979): Kyokuiki denrisô denshi mitsudo no keisoku (Measurements of electron number density in the polar ionosphere). Nankyoku Shiryô (Antarct. Rec.), **65**, 28–35.

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