OBSERVATIONS OF ELECTRON DENSITY IN THE POLAR IONOSPHERE USING THE SWEPT FREQUENCY IMPEDANCE PROBE

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Abstract: Results of the electron number density obtained by the swept frequency impedance probe onboard the rockets launched at Syowa Station (69°00′S, 39°35′E) in the IMS period from 1977 to 1979 indicate that the ionization level of the polar ionosphere corresponds well to the precipitating particle flux. In the active aurora, a distinct stepwise structure 2～3 km in width across the magnetic field line corresponding to the edge of the auroral arc has been observed. The small-scale ionospheric structures with characteristic length of several kilometers are frequently observed as one of the characteristics of the auroral ionosphere.

1. Introduction

Under the project of the IMS (International Magnetospheric Study) the 17th, 18th and 19th Japanese Antarctic Research Expeditions (JARE-17, -18 and -19) carried out sounding rocket experiments using the S-210JA's and S-310JA's rockets at Syowa Station (69°00′S, 39°35′E; geomagnetic latitude 69.6°S, and geomagnetic longitude 77.1°E). One of the main objectives of these experiments is a coordinated observation to investigate wave particle interactions in the polar ionosphere, especially in the active auroral ionosphere under the bombardment of particle precipitation. The rockets were equipped with various instruments to make observations on energetic particle detectors in various energy ranges, plasma wave detectors ranging from 1 kHz to 10 MHz, and plasma density and temperature. The other objective of the JARE rocket experiments in the IMS period is the studies on the composition of minor constituents such as NO and O_3 in the polar upper atmosphere. For both of the objectives, measurement of the electron density is a basic item. Among these experiments the swept frequency impedance probes (designed for the JARE rocket measurements of the electron number density by the impedance probe, NEI) are installed on six rockets in the S-310JA series and two rockets in the S-210JA series.

In the polar ionosphere, particularly in the auroral ionosphere, ionospheric parameters are highly variable in time and space. The spatial variations in the polar ionosphere are distributed in a wide range of the characteristic scale length from several tens of kilometers corresponding to the arc structures to a few meters or less. After a review by FEJER and KELLEY (1980) it is pointed out that the probable sources of these irregularities are categorized as; (1) production by particle precipitation, (2) generation by electrostatic turbulence and (3) plasma instabilities. For the complex natures of these physical processes in the auroral ionosphere, it is important to measure accurately the ionospheric parameters such as electron number density and electron and ion temperatures, by the *in situ* technique.

One of the aims of the *in situ* measurement of the electron number density by the NEI equipments is the accumulation of the data of the electron density profiles of the polar ionosphere with their small-scale structures under various conditions of the precipitating particles. In addition to this basic objective, NEI can provide the elementary plasma parameter of electron density, for the analysis and the investigation of the results obtained by plasma wave detectors such as PWH (plasma wave detector in high frequency range) and PWL (plasma wave detector in VLF range). For the problems of minor constituents, the measurement of the electron number density gives a key parameter to analyze the photo-chemical processes under the bombardment of particle precipitation.

The purpose of the present paper is to give the results of the electron number density distribution obtained with the five sounding rockets in JARE-18 and -19, namely S-310JA-3, S-310JA-5, S-310JA-6, S-210JA-30, and S-210JA-31. The results are discussed from various aspects in comparison with the simultaneous ground-based observations and observations with other instruments onboard the sounding rockets. For the case of S-310JA-3 a brief description of the density profile is given in the previous report (TAKAHASHI and OYA, 1979). A good correspondence is found between the vertical sounding data and the density profiles obtained by the NEI onboard the rocket.

2. Observations

2.1. Instrumentation

The swept frequency impedance probe has been developed since 1964 by using Japanese sounding rockets (OYA, 1969). The admittance of a probe immersed in a magnetized plasma shows a minimum value at the upper hybrid resonance frequency F_{UHR} (OYA, 1966). When the stray capacity adherent to the probe circuits is eliminated by means of a special bridge circuit, we can detect the upper hybrid resonance frequency with high accuracy, by sweeping the frequency applied to the probe. Then, from the value of F_{UHR} the electron density N_e can be obtained for a given electron cyclotron frequency F_c, as

$$N_e = \frac{m\varepsilon_0 4\pi^2}{e^2}(F_{\mathrm{UHR}}^2 - F_c^2),$$

where m, e, and ε_0 are the electron mass, the electron charge and the dielectric constant of vacuum in the rationalized unit system, respectively. The impedance values of the probe reflect the RF characteristics of the ambient plasma as a function of frequency of the applied signal; the impedance value contains various information on the ionospheric plasma. For example, the capacitance of the probe in the low frequency region ($f < F_c$) gives the sheath capacitance around the probe, which is related to the Debye length; and then the measured sheath capacitance can give information on the electron temperature when we have information on the electron density.

The NEI system is a swept frequency impedance probe of standard type in which the amplitude of the signal from the capacitance bridge is telemetered with the reference frequency marker. The block diagram of the NEI system is shown in Fig. 1. A signal with sawtooth voltage is applied to VCO to operate as a swept frequency oscillator. The signal from VCO is converted, through a balanced mixer, to a signal with the frequency ranging from 100 kHz to 10 MHz. The output signal from the bridge circuit in the total swept frequency range is converted to a fixed intermediate frequency (IF) signal of 50 kHz through the mixer where the local swept signal is fed. The intermediate signal is then amplified in the IF stage with a bandwidth of 1 kHz.

For the NEI system onboard the S-210JA series, an additional mode of measurement that was designed to measure the impedance at a constant frequency is appropriated to obtain a high spatial or temporal resolution of the plasma parameters.

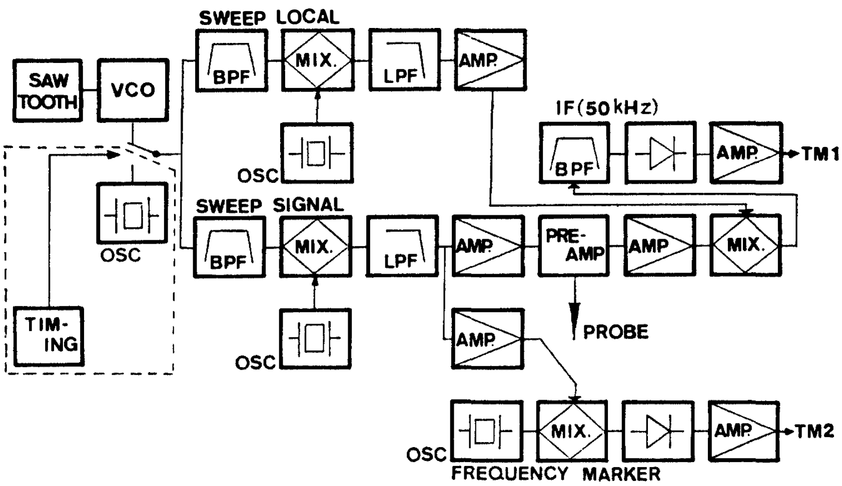

Fig. 1. A block diagram of the NEI system used for the JARE rocket experiments of the IMS project. The part enclosed by a broken line is added to the instruments onboard the rockets S-210JA's to measure the impedance at a constant frequency of 200 kHz with a high time resolution.

Table 1. Main parameters of the NEI onboard JARE sounding rockets.

	S-310JA-3	S-310JA-5	S-310JA-6	S-210JA-30/31
Probe (m whip)	1.2	1.2	1.2	1.2
Sweet frequency (MHz)	0.2~11	0.2~13	0.2~12	0 ~ 7
Fixed frequency (kHz)	—	—	—	200
Seep time (s)	0.5	0.25	0.3	0.25
Fixed time (s)	—	—	—	0.75
TM responce (Hz)	25	59	81	450

The fix frequency used is set at 200 kHz, which is sufficiently low in value and can afford information about the sheath capacitance of the probe. This mode of observation can detect small fluctuations of the ionospheric plasma up to the upper limit of telemeter response, *i.e.* 450 Hz for this case. The main parameters of the NEI system are listed in Table 1 for the five rocket experiments.

The accuracy of the NEI system is 3% for typical ionospheric electron density of 5×10^4 electrons/cm^3.

2.2. *Flights*

The flight sequence of the JARE rockets experiments is given in Table 2, with the abbreviations of instruments as follows: PWH, for the plasma wave detector in the high frequency range (100 kHz~10 MHz); PWN, for the detector of the high frequency plasma wave (1~8 MHz) and electron flux by the Faraday cup; PWL, for

Table 2. JARE sounding rocket experiments with the NEI observation.

	S-310JA-3	S-310JA-5	S-310JA-6	S-210JA-30	S-210JA-31
Date	1977.7.26	1978.6.11	1978.8.28	1978.1.28	1978.2.6
Local time (45 EMT)	18 : 35	01 : 57	00 : 56	23 : 10	21 : 55
Launch elevation (deg.)	80	80	80	82	82
Launch azimuth direction (deg.)	315	315	315	22	39
Maximum altitude (km)	221.5	224.8	237.0	125.2	116.0
Horizontal distance (km)	313.0	277.9	250.3	96.0	148.6
Flight time (s)	456	458	465	340	322
Scientific instruments	PWN,PWL MGF,ESH TEL,NEI	PWL-PFX PWL-ELF DPL,ESM TEL,NEI	PWL-PFX PWH ESM,ESH TEL,NEI	NNP-O_3 NNP-NO NEI	Same as S-210JA-30

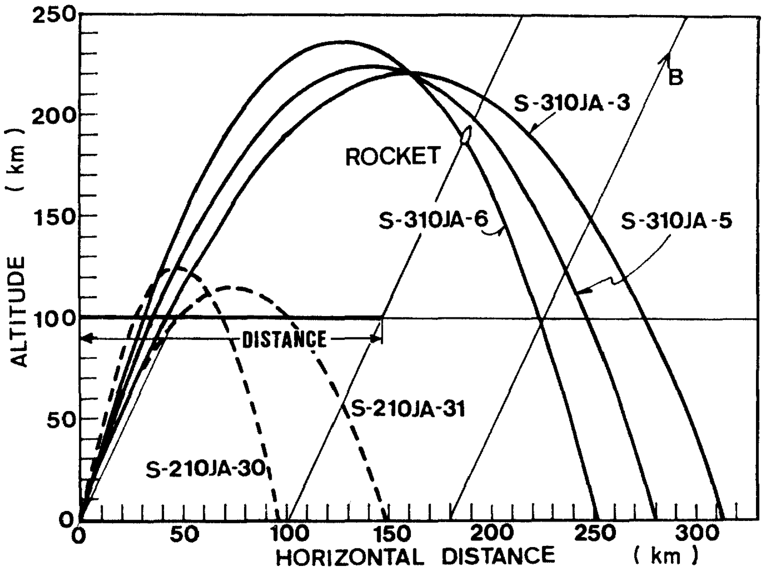

Fig. 2. Trajectories of the five sounding rockets with the NEI measurements. For comparison the inclination of the geomagnetic field line is indicated in the figure. To discuss the interrelation between the electron number density around the rocket and the auroral luminosity, the position of the rocket is represented by the distance from the zenith to the foot of the field line at the altitude of the maximum luminosity (100 km).

the plasma wave detector in the VLF range (1～8 kHz); PWL-PFX, for the detector in the ELF range (300 Hz～3 kHz); DPL, for the electron number density measurement with Doppler shift of VLF signal from NWC; ESM, for the electron energy spectra in the energy range from 1 keV to 10 keV; ESH, for the electron energy spectra in the energy range larger than 30 keV; TEL, for the electron temperature detector; NNP-O_3, for the number density of O_3; NNP-NO, for the number density of NO; and MGF, for the magnetic field vector measurement to deduce the current system.

The trajectories of the five sounding rocket flights with the NEI measurements in JARE-18 and -19 are shown in Fig. 2. Three S-310JA rockets were launched in the azimuth direction that coincides with the geomagnetic field. In the figure the geomagnetic field line inclination is shown in reference to the trajectories of S-310JA's.

3. Electron Density Profiles

3.1. Result of S-310JA-3

The sounding rocket S-310JA-3 in JARE-18 was launched in a very quiet condition of the geomagnetic activity. The records of *H*-, *D*- and *Z*-components of the geomagnetic field and the cosmic noise absorption at Syowa Station are shown in Fig. 3. A very quiet geomagnetic activity is evident from both of the records. The

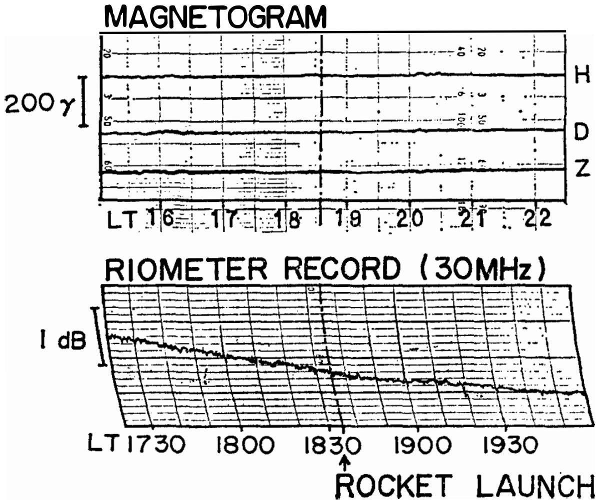

Fig. 3. Ground-based data of the magnetometer and the riometer around the time of the flight of the S-310JA-3 rocket.

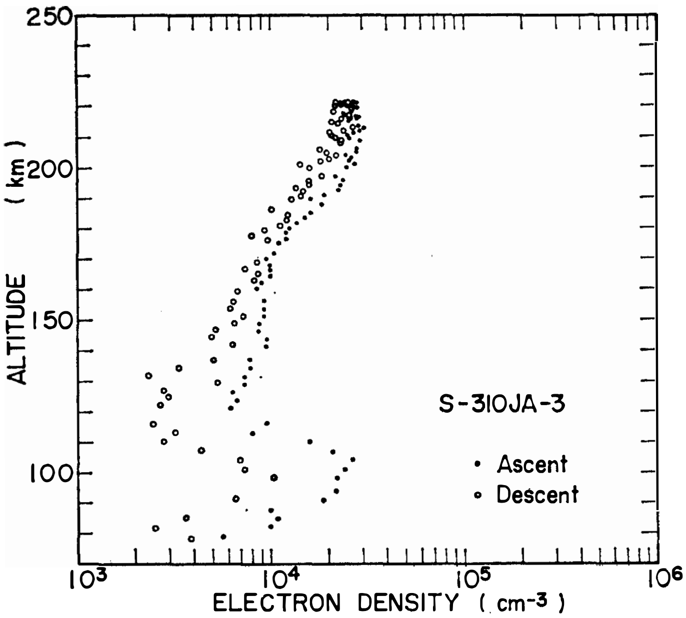

Fig. 4. Electron density profiles observed during the ascending period (solid circle) and the descending period (open circle) of the S-310JA-3 rocket flight.

arrow in the figure indicates the time of the launch. Fig. 4 shows the electron density profiles observed during the ascending (solid circles) and descending (open circles) periods of the S-310JA-3 flight. The characteristics of the profiles are summarized as follows:

1) The profiles in the upleg and the downleg are similar in their structures, and show a well-developed layer at an altitude near 100 km. The peak density of this layer is 2.6×10^4 electrons cm^{-3} for the ascent, and 1.04×10^4 electrons cm^{-3} for the descent.

2) The number density shows a minimum value at the altitude of 120 km, then increases monotonously to the height of apogee. Near the apex, the number density seems nearly constant with altitude.

3) The electron density profile shows a tendency to have smaller values in the downleg than in the upleg. This may be due to the latitudinal variation rather than to the temporal variation.

4) Near the apex in the upleg and throughout the whole trajectory in the downleg, the observed density shows considerable fluctuation due to the probe's traverse across the wake of the rocket body. Thus, the profile of the ambient electron density is given by an envelop of the observational points.

3.2. *Results of S-310JA-5 and S-310JA-6*

The sounding rockets S-310JA-5 and -6 are launched in similar conditions of

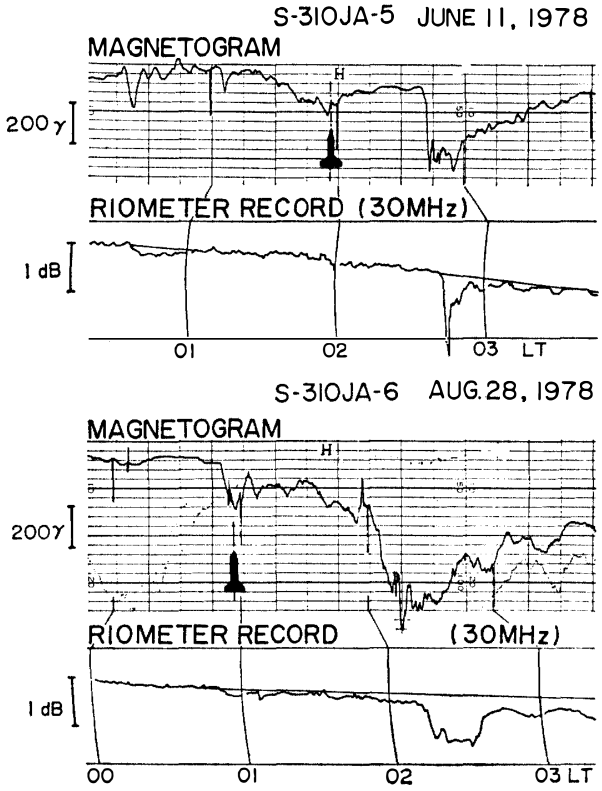

Fig. 5. Ground-based data of the horizontal component of the geomagnetic field around the time of the flight of the rockets S-310JA-5 and -6. The time of the launch is indicated with the symbol for the both cases.

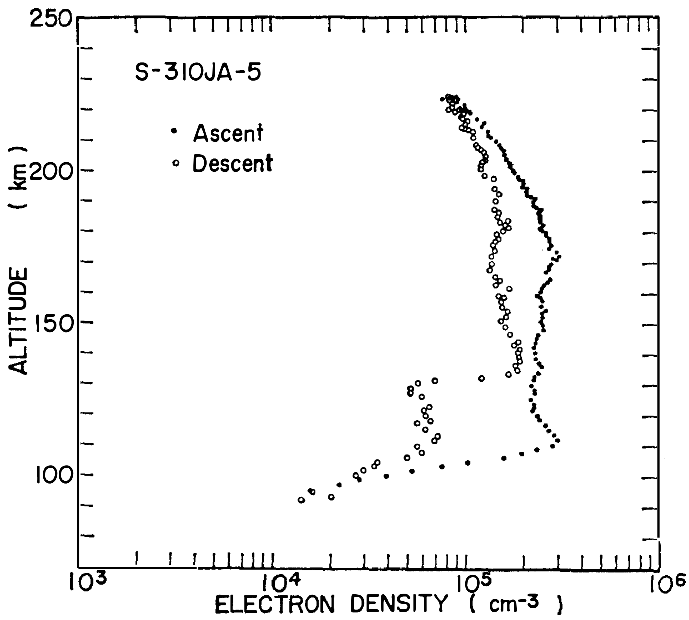

Fig. 6. Electron density profiles observed during the ascending period (solid circle) and the descending period (open circle) of the S-310JA-5 rocket flight.

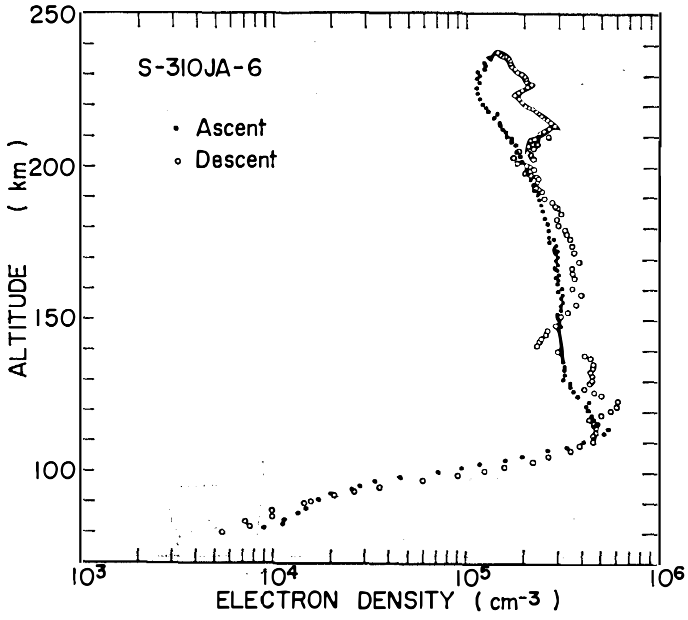

Fig. 7. Electron density profiles observed during the ascending period (solid circle) and the descending period (open circle) of the S-310JA-6 rocket flight.

geomagnetic activity, and both of the rockets passed through the auroral arc in their downlegs. Fig. 5 shows the records of the *H*-component of the geomagnetic field for the time of launch of the two rockets. In both cases the rockets were launched near local midnight when the magnetometer shows small negative bay disturbances as indicated by arrows in the figure. The large negative bay disturbances follow about one hour after the launch. The profiles of the electron number density are shown in Figs. 6 and 7. In both cases the ionization level is considerably larger than the case of a very quiet condition of the auroral activity in the evening, as observed by the S-310JA-3 rocket. The characteristics of the ionospheric profiles obtained by the S-310JA-5 and -6 rockets are as follows.

1) The general feature of the electron density profile shows a peak value near the altitude around 113 km, the density decreases monotonously to the region of nearly constant density from 130 km to 180 km, then the profiles decrease monotonously towards the altitude up to the apex. Overlapping the general features irregular structures are observed in the profiles. The maximum density at the altitude of 113 km in the upleg of the S-310JA-6 rocket flight indicates the value of 5.5×10^5 cm^{-3}.

2) Near the altitude of 130 km in the downleg of the S-310JA-5 rocket flight, a large gradient of the electron density is observed. The electron density decreases sharply from 1.85×10^5 cm^{-3} to 5.7×10^4 cm^{-3} within a horizontal distance range of 3 km across the field line. As will be discussed later, this evidence may correspond to an ionization wall which is created near the auroral arc edge along the geomagnetic field line.

3) In the downleg of S-310JA-5 a wave-like structure with amplitude of about 20% is observed in an altitude range from 110 km to 175 km. The wave length is about 15 km across the field line.

4) Irregular structures are remarkable in the downleg of the S-310JA-6 flight. In the altitude range from 215 km to 195 km relatively small scale irregularities with characteristic wave length of about 1～3 km are observed.

5) In the downleg of the S-310JA-6 flight, following the gradual decrease of the electron density in the altitude range from 160 km to 140 km, an abrupt density increase was observed. The electron number density increases from 2.4×10^5 cm^{-3} to 4.5×10^5 cm^{-3} within a range of 2 km across the field line. This also may correspond to the rocket's traverse of the ionization wall of the auroral arc edge.

6) The ionization level in the downleg from 140 km to 110 km shows a remarkable fluctuation with amplitude of about 50%. This fluctuation may correspond to the auroral arc structure.

7) Below the ionization peak, the electron density decreases with altitude rapidly for both cases of the observation. The density value at 90 km is about 1.5×10^4 cm^{-3} in these profiles. It is interesting that the ionization level at the 90 km altitude shows a similar value to that obtained in the quiet conditions.

3.3. Results of S-210JA-30 and S-210JA-31

Two rockets of the S-210JA series were launched in a twilight condition at local time of premidnight in Antarctica as shown in Table 2. The geomagnetic conditions during the periods of the two rocket flights are relatively quiet in both cases. The electron density profiles obtained by S-210JA-30 are shown in Fig. 8. Due to the large deviation of the rocket axial angle with respect to the ram direction, the observed electron density was largely disturbed by the effects of the wake of the rocket body. In the figure the shaded area indicates depletion of the observed number density due to the traverse across the wake. The electron density profile shows large depletion near the apex in ascent and descent. The attitude of the rocket in both cases of the depletion is in a similar condition so that the crossing of the wake due to the precession motion may deplete the observed density. Thus the observed profiles of the ionosphere obtained with S-210JA-30 are rather modified, on account of the unpreferable attitude of the rocket with a large precession motion. Using the en-

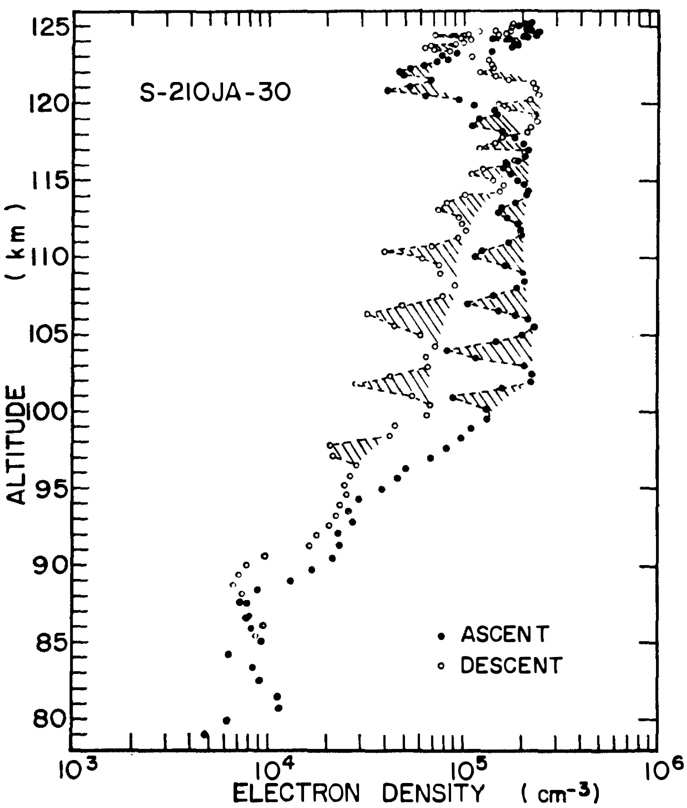

Fig. 8. Electron density profiles observed during the ascending period (solid circle) and the descending period (open circle) of the S-210JA-30 rocket flight. The shaded areas in the figure indicate the depletion of the observed density due to the traverse across the wake synclonized with the spin motion of the rocket.

velope of the periodically fluctuating profile, characteristic points of the ionospheric electron density profile can be summarized as follows. The profile in the ascent shows a peak density of 2.3×10^5 cm^{-3} near the altitude of 102 km, and the density keeps a nearly constant level above the peak to the altitude of the apex. In the descent the profile shows a monotonous decrease with altitude. Below the altitude of the peak electron density both in the ascent and descent cases, the density distribution shows a rather rapid decrease with altitude. And the profiles show a ledge of the electron density enhanced about 10^4 cm^{-3} in the altitude range from 80 km to 90 km. In Fig. 9, the electron density profiles obtained by S-210JA-31 are shown.

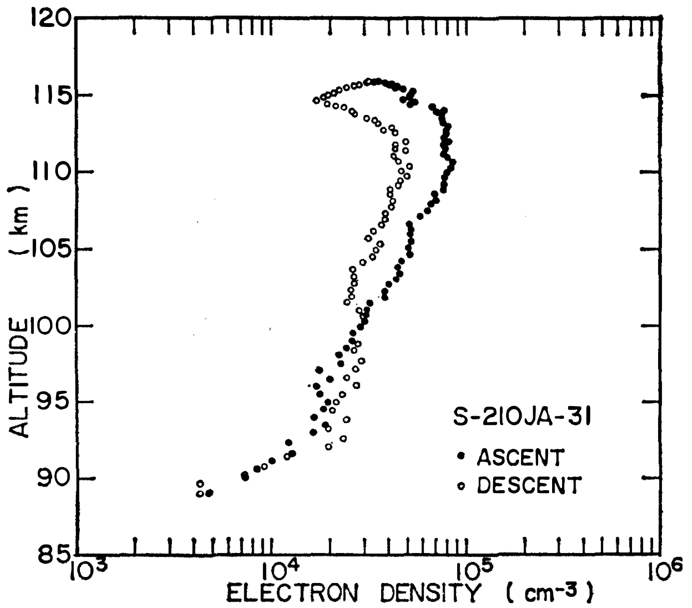

Fig. 9. Electron density profiles observed during the ascending period (solid circle) and the descending period (open circle) of the S-210JA-31 rocket flight.

The observed profile shows the peak density of 8.4×10^4 cm^{-3} in the ascent. The peak density decreases to 4.1×10^4 cm^{-3} in the descent. The density shows a deep depletion near the altitude of 115 km, which is attributed to the attitude of the rocket due to the precession motion as in the case of S-210JA-30. Compared with the data of S-210JA-30 the ionization level is rather small. It is interesting that the ionization ledge below the altitude of 90 km, as observed by S-210JA-30, is not found. Although the two experiments were carried out in a similar condition of the solar zenith angle, the density profiles are remarkably different. The higher density level near the peak and the ledge structure below 90 km in the case of S-210JA-30 may indicate the existence of an ionization agency containing higher energetic particles with several tens of keV.

The NEI instruments, onboard S-210JA-30 and -31, have an observation mode of the measurement with a constant frequency of 200 kHz. Since the frequency is sufficiently lower than the electron cyclotron frequency, the effective capacitance at 200 kHz reflects the value of Debye's length,

$$\lambda_D = \sqrt{\frac{\epsilon_0 k T_e}{n_e e^2}}.$$

In Fig. 10, a relation between the electron number density and the observed value of the effective sheath capacitance is given; in the figure the effective sheath capacitance is expressed as output levels of the fixed frequency mode observation. From the values in the figure we can estimate, for example, that the difference of the output of 0.1 V corresponds to the electron number density of 13% around 3.0×10^4 cm^{-3}. In the case of S-210JA-31, enhancements of the fluctuation of the output level in the fixed frequency mode are observed. Fig. 11 gives examples of these fluctuations. The fluctuations may correspond to the variation of the electron density fluctuations in the ionosphere. Several different types of fluctuations are identified in these variations of the data; the fluctuations observed by the S-210JA-31 rocket are categorized as follows:

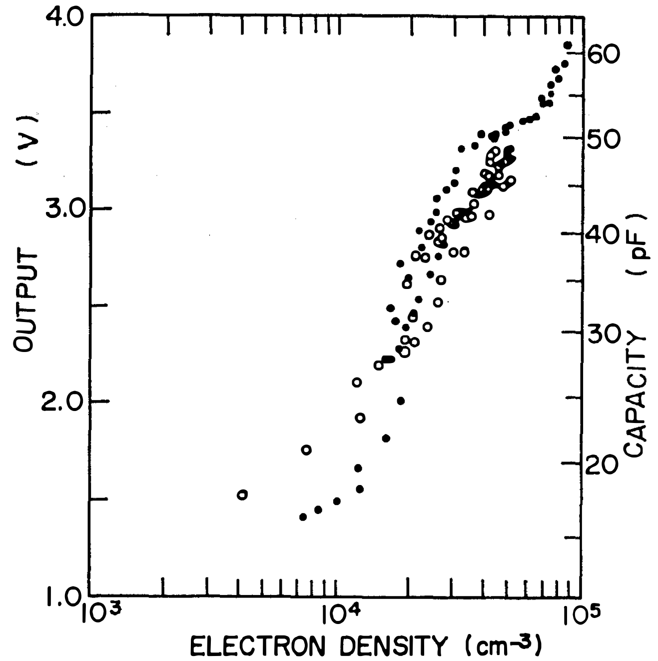

Fig. 10. Relation between the output level of the fixed frequency mode and the electron number density deduced from the upper hybrid resonance frequency. Data are represented distinctly for the ascending period (solid circle) and the descending period (open circle) of the S-210JA-31 rocket flight.

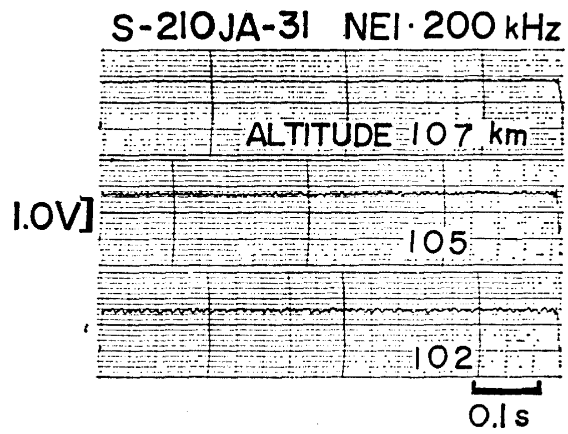

Fig. 11. Some examples of the output level of the fixed frequency observation showing fluctuations of the plasma parameter. The data are given for the ascending path of S-210JA-31.

1) Sinusoidal fluctuation of about 1 Hz observed in the altitude range from 110 km to 115 km.

2) Irregular fluctuations ranging from 1 Hz to 10 Hz, observed in the altitude range from 100 km to 90 km, in the descent path.

3) Enhanced fluctuations ranging from 30 Hz to 200 Hz observed in the altitude range from 95 km to 105 km.

4. Comparison with the Particle Precipitations

Several characteristics of the polar ionosphere are clarified by the *in situ* observations with the NEI system onboard the JARE sounding rockets. The profiles indicate the variations of the ionization level corresponding to the auroral activity, and the ionization structure of the auroral arc with various types of irregular fluctuations of the electron density, reflecting the various aspects of the polar ionosphere concerning the formation and the dynamics. The S-310JA-5 result of the electron density is compared (see Fig. 12) with the data obtained by ESM (MATSUMOTO *et al.*, 1980) for the energy of 2.73 keV and the pitch angle less than about 30°, and is compared with the auroral luminosity obtained by a meridional scanning photometer (HIRASAWA, 1980) during the flight. The auroral luminosity is given by contours in unit of 1 kilo-Rayleigh for OI 5577 Å line, for the north half meridian. The particles of the energy and the pitch angle as shown in the figure are the representative portion of the precipitating particles for the discrete aurora. In the figure the position of the rocket is indicated by arrows in the photometer map projected along the magnetic field line to the 100 km level. As shown in the figure the rocket path is almost along the discrete auroral arc which is moving northward during the rocket flight. It seems from the figure that the general tendency of the ionization level corresponds to the precipitating particle flux which is stronger in the ascending period of the flight. The similar tendency is also seen in the auroral luminosity along the rocket

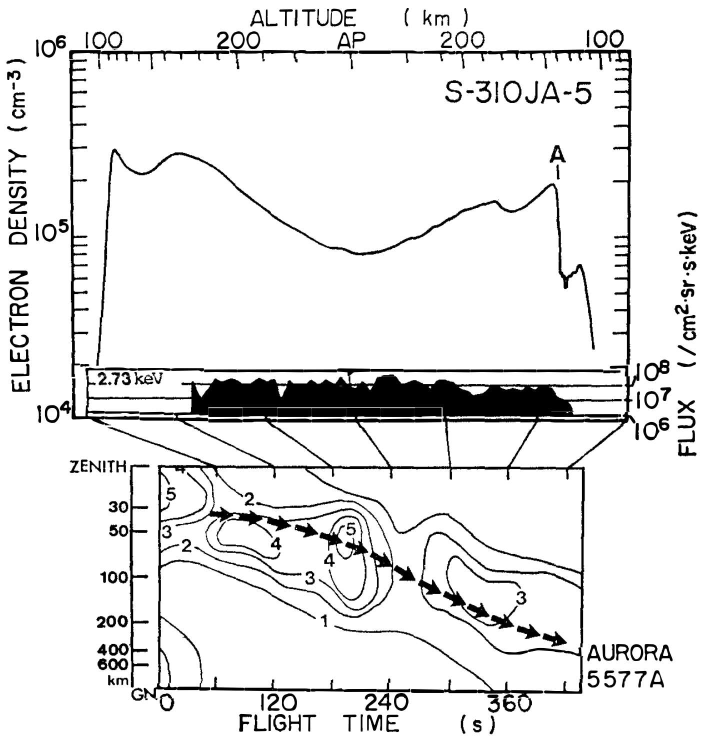

Fig. 12. Electron density variations during the flight of S-310JA-5. Figure indicates the spatial variations, relations to the results of the ESM and the meridional scanning photometer for the auroral OI 5577 Å line. The auroral luminosity is given by contours in unit of 1 kilo-Rayleigh.

path. The small-scale fluctuations are observed in both of the electron number density and the energetic particles. The correlation between these fluctuations is not necessarily good. The most remarkable feature of the density profile is a rapid decrease of the electron number density near the altitude of 130 km (denoted as A in the figure). As the attitude of the rocket at the time showed trivial variation, such a stepwise variation of the observed electron density should be attributed to the ambient electron density variation. The drastic decrease of the energetic particle flux is also observed at this altitude. Although the spatial resolution of the auroral photometer map is not enough to identify the correspondence of the auroral luminosity variation to the rapid decrease of the electron number density, it is supported by the all-sky photographs that the rocket trajectory crosses the edge of the auroral arc at the time of the rapid decrease of the observed electron density. It is concluded that the structure corresponds to the wall-like structure of ionization produced at the edge of the discrete auroral arc.

For the case of S-310JA-6, the same type of comparison is given in Fig. 13. In this case the data of the energetic particles are shown for the energy of 2.3 keV and

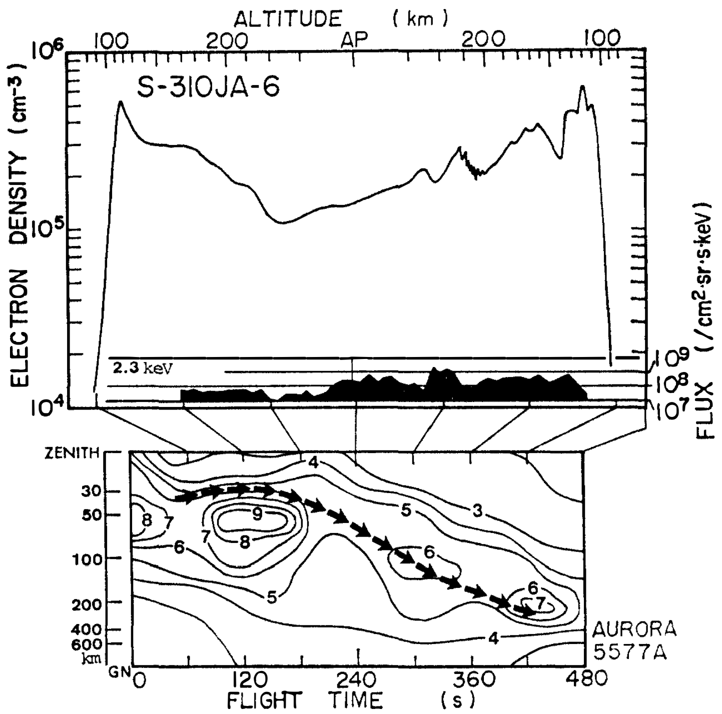

Fig. 13. Same as Fig. 12 for the case of S-310JA-6.

the pitch angle less than about 30°. In this case also the general tendencies of the three parameters show a good agreement.

5. Summary

The results of the electron number density distribution obtained by the five sounding rockets in JARE-18 and -19 are given. Several characteristics of the auroral ionosphere are clarified by these experiments. The ionization level and the altitude profiles of the polar ionosphere correspond well to the geomagnetic activity.

Various types of small-scale structures are recognized in the observed profiles of the ionosphere. These are summarized as follows:

1) A distinct stepwise structure 2~3 km in width across the magnetic field line, which may correspond to the wall-like structure of ionization at the edge of the discrete auroral arc.

2) Large fluctuations about 10 km in scale length near the ionization peak, which may correspond to the auroral arc structure.

3) A wave-like structure about 15 km in scale length observed in the lower F-layer.

4) Irregular structures several km in scale length observed at the altitudes of the E-layer and the lower F-layer.

The structures represented in 3) and 4) do not necessarily correspond to the observed fluctuations of the precipitating particle fluxes. It is suggested that the ionospheric plasma process such as electrostatic turbulence or plasma instabilities may contribute to the formation of these fluctuations.

With the impedance measurement in constant frequency, fluctuating components of the ionospheric plasma are obtained for the data of S-210JA-31, namely:

1) A sinusoidal fluctuation of about 1 Hz observed in the altitude range from 110 km to 115 km.

2) Irregular fluctuations ranging from 1 Hz to 10 Hz, observed in the altitude range from 90 km to 100 km.

3) Enhanced fluctuations ranging from 30 Hz to 200 Hz observed in the altitude range from 95 km to 105 km.

The fluctuations represented in 3) are similar to the fluctuations in the *E*-layer obtained by the Langmuir probe in the previous JARE experiments (OGAWA *et al.*, 1976; MORI *et al.*, 1979). It is interesting that the fluctuating components are less distinct in the case of S-210JA-30, although the ionization level is higher than S-210JA-31.

As described above the characteristics of the polar ionosphere show a very complicated nature. Observational evidences such as the relationship between the ionization level and the particle fluxes, the remarkable difference of the height profiles of the electron density in quiet and disturbed conditions, and the spatial correspondence of the auroral pattern and ionospheric structures should be investigated more precisely in future study.

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