Results of Rocket Observation of Electron Density at Syowa Station

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ロケットによる電子密度観測

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要旨: 昭和基地ロケット実験の電子密度分布の観測結果のうち，1971～72年にわたる 2 年間のデータについて概報する．この間，電子密度分布は高度 70～130 km の領域に関して，S-160JA 2 機，S-210JA 8 機，計 10 機のデータが得られた．

Abstract: The twelfth and thirteenth Japanese Antarctic Research Expeditions (JARE) carried out firings of two S-160JA rockets and twelve S-210JA rockets to observe the polar ionosphere and auroral phenomena at Syowa Station (69°00′ S, 39°35′ E; geomagnetic lat. 69.6° S, long. 77.1° E) in Antarctica. The electron density profiles of the ionosphere obtained by the two S-160JA rockets and eight S-210JA rockets experiments are given in this preliminary report.

1. Introduction

The existence of the ionosphere in the region between several ten km and over one thousand km plays an important role not only in the radio wave propagation but also in the field of the upper atmospheric physics. Many phenomena occurring in the upper atmosphere of the earth, especially in the ionosphere, have been gradually solved by systematic research on upper atmospheric physics in such fields as geomagnetism, atmospheric noise, cosmic rays, airglow, aurora, solar radio wave and so forth. Furthermore, ionospheric physics has made remarkable progress by direct sounding with rockets and satellites in addition to the usual indirect measurements. It is very important to obtain an exact knowledge of the physical state of the ionosphere not only for research in ionospheric physics itself but also in upper atmospheric physics.

The ionization and deionization processes and energy transfer mechanisms are quite complex in the lower part of the ionosphere; the lower ionosphere in the polar region has a close relation to auroral phenomena. In spite of the importance

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of the lower ionospheric observation for analyses of the above described problems, only a few experiments by means of ionosondes on the ground have been carried out up till now due to the difficulties caused by low electron density, comparatively high collision frequencies and inefficient antenna systems.

After the successful rocket flights of S-160JA-1 and -2 by the 11th JARE (HIRASAWA *et al.*, 1970), further rocket observations of the upper atmospheric disturbance during the appearance of auroras were carried out between 1971 and 1973 by the 12th, 13th and 14th JARE (MURAYAMA *et al.*, 1971).

2. Instrumentation

Table 1 shows the general specifications of the ionospheric sounding rockets including the rocket experiments made by the 11th and 14th JARE. In the last column, under the heading "Ionospheric probe", EP denotes electron current probe, LP denotes Langmuir probe and RFP denotes radio frequency probe.

Table 1. Ionospheric sounding rockets.

No.	JARE	Rocket	Date	Time (LT)	Launch angle (deg.)	Launch direction (deg.)	Max. alt. (km)	Hor. distance (km)	Time of flight (s)	Ionospheric probe
1	11th	S-160JA-1	1970. 2. 10	15h30m	75	240	86.9	88	270	EP
2		-2	2. 17	15 10	79	240	87.6	91	278	EP
3	12th	-3	1971. 4. 30	13 00	82	184	83.0	74	272	EP
4		S-210JA-5	9. 14	00 50	82	170	115	97	324	EP,LP,RFP
5		-6	12. 3	15 00	82	170	131	97	347	EP,LP,RFP
6	13th	-12	1972. 2. 11	15 00	82	135	107.5	120	318	EP,RFP
7		S-160JA-4	4. 17	02 42	82	135	86.0	79	274	EP
8		S-210JA-9	5. 14	02 13	82	135	129.3	117	340	EP,LP,RFP
9		-10	5. 16	02 02	82	315	115.4	61	327	EP,LP,RFP
10		-11	8. 7	04 45	82	315	125.9	134	337	EP,RFP
11		-8	8. 11	04 01	82	135	126.6	133	333	EP,LP,RFP
12		-7	12. 14	00 23	82	315	125.8	118	340	EP,RFP
13	14th	-16	1973. 2. 15	02 45	82	135	102.6	142	300	EP,LP,RFP
14		-17	4. 23	02 54	82	135	124.6	110	334	EP,LP,RFP
15		-19	7. 15	22 09	82	135	130.5	92	340	EP
16		-18	8. 23	03 53	82	315	130	128	343	EP,LP,RFP

Ionospheric plasma probes are classified into two categories, the electrostatic probe and the radio frequency probe. The well-known Langmuir probe method which has long been used to measure the electron density in plasma is the typical electrostatic probe method. The electron density is calculated from the current-voltage characteristic of the sounding electrode to which is applied the DC voltage from negative to positive. A cylindrical electrode was used in the rocket experiment. The probe electron current in the retarding potential region is expressed as follows,

$$I_e=2\pi rl N_e e\sqrt{\frac{kT_e}{2\pi m}} \exp\left(-\frac{eV}{kT_e}\right) \tag{1}$$

where r is the probe radius, l is the probe length, N_e is the electron density, T_e is the electron temperature, e is the electron charge, m is the electron mass, k is Boltzmann's constant and V is the probe voltage.

Taking the logarithm of I_e in eq. (1), we have

$$ln\, I_e=ln\ (\text{const.})-eV/(kT_e). \tag{2}$$

Then

$$T_e=\frac{e}{k}\cdot\frac{dV}{d\,(ln\, I_e)}\ . \tag{3}$$

Thus the electron temperature can be obtained from eq. (3). Inserting T_e into eq. (1), the electron density can be evaluated from the measured electron saturation current.

The probe electron current in the accelerating potential region can thus be expressed as follows,

$$I_e=2\pi\, rl\ N_e\sqrt{\frac{kT_e}{2\pi m}}\left(\frac{a}{r}\text{erf}\sqrt{\frac{r^2}{a^2-r^2}\cdot\frac{eV}{kT_e}}+\exp\left(\frac{eV}{kT_e}\right)\right)\left\{1-\text{erf}\sqrt{\frac{a^2}{a^2-r^2}\cdot\frac{eV}{kT_e}}\right\} \tag{4}$$

where a is the sheath radius,

$$\text{erf}\,(x)=\frac{2}{\sqrt{\pi}}\int_0^x \exp(-y^2)\,dy. \tag{5}$$

When

$$a/r\gg 1,\ eV/(kT_e)\gg 1, \frac{r}{a}\sqrt{\frac{eV}{kT_e}}\gg 1 \tag{6}$$

eq. (4) can be put in the simplified form (FINDLAY and BRACE, 1969).

$$I_e=2rl\,N_e e\sqrt{\frac{2eV}{m}} \tag{7}$$

That is, the electron current is proportional to the electron density. Thus the electron density profile can be measured continuously by using the probe biased with positive constant potential. This method is called the electron current probe method.

A plasma behaves as an electrical impedance against the radio frequency, the magnitude of the impedance changes with the frequency for the interaction between plasma and the electromagnetic field. Also, there are associated with plasmas certain characteristic frequencies such as the plasma frequency, the cyclotron frequency when a magnetic field exists, the frequency relating to the sheath around the probe inserted in plasma, that is, the space charge layer, and the hybrid frequency. The radio frequency probe method was employed for measurement of the plasma parameters using such characteristics of plasma. This method is subdivided into the following.

(i) Impedance measurement of plasma at a fixed frequency.

(ii) Measurement of the resonant frequency of the resonant or oscillation circuit on the assumption that plasma is an element of the circuit.

(iii) Measurement of phenomena occurring at a specific frequency such as the plasma frequency and the upper hybrid frequency.

(iv) Electromagnetic wave propagation method, topside sounding method and so forth.

In the above described radio frequency probe methods, the method which is to be adopted for plasma measurement depends on the individual case.

In these rocket experiments, the radio frequency probe method (iii) was used. There exist two electrodes, transmitting and receiving. Radio frequency voltage of some frequency range is applied to the transmitting electrode and the characteristic of the receiving signal is obtained from the other electrode. The following relation exists between the upper hybrid angular frequency, ω_{uh} the electron plasma angular frequency, ω_p, and the electron cyclotron angular frequency; ω_c

$$\omega_{uh}^2 = \omega_p^2 + \omega_c^2. \qquad (8)$$

Using eq. (8), the electron density can be calculated from the upper hybrid frequency which is obtained from the radio frequency characteristic curve of the receiving signal.

An outline describing the ionospheric probes of the individual rocket is presented in the following.

(a) S-160JA-3 and -4

The same type of instrument, the electron current probe, as was used in S-160JA-1 and -2 was installed on these rockets. A gold-plated nose tip of the rocket was used as the probing electrode.

(b) S-210JA-5 and -6

Both electrostatic probes and a radio frequency probe were installed on these rockets to measure precisely the electron density profile. Two parallel cylindrical electrodes were used. The diameter was 2 mm, the length 550 mm and the separation distance 60 mm. The sweep frequency range was between 0.2 MHz and 15 MHz and the measuring period was 0.5 s. A Langmuir probe and an electron current probe were used, and each electrode was cylindrical in shape, 2 mm in diameter and 200 mm in length.

(c) S-210JA-7

The sweep frequency range of the radio frequency probe was between 0.5 MHz and 7 MHz and the measuring period was 0.5 s. The electrodes were set in a 'V' shape, the angle of which is about 45°. Three electrodes, one vertical and two horizontal, were used as the electron current probe.

(d) S-210JA-8

The sweep frequency range of the radio frequency probe was between 0.5 MHz and 7 MHz and the measuring period was 0.125 s. The angle between the two electrodes was 90°. A Langmuir probe and an electron current probe were also used in this rocket. The sweep voltage waveform which was applied to the Langmuir probe was triangular in shape, with the voltage ranging between −8.2 V and +7.8 V, and with the period for the triangular waveform of 1 s.

(e) S-210JA-9 and -10

The sweep frequency range of the radio frequency probe was equal to that of JA-7. The measuring period was 0.125 s in the case of JA-9 and 0.5 s in the case of JA-10. The electrode system was identical with that of JA-8. The range of the sweep voltage applied to the Langmuir probe was between 0 V and 6 V. The vertical electrode was used as the electron current probe.

(f) S-210JA-11

The sweep frequency range of the radio frequency probe was between 0.5 MHz and 6 MHz. Two telemetry channels were used to analyse the detailed impedance characteristics.

(g) S-210JA-12

The sweep frequency range of the radio frequency probe was equal to that of JA-7 and the measuring period was 0.5 s. The electrode system was identical with that of JA-5.

(h) S-210JA-16, -17 and -18

The sweep frequency range of the radio frequency probe was between 0.5 MHz and 8 MHz, and the measuring period was 0.125 s. Two electrodes were set in a 'V' shape, the angle of which was about 30°. Both a Langmuir probe and an electron current probe were used in these rockets.

(i) S-210JA-19

Only an electron current probe was installed on this rocket for the limitation of the volume occupied by the instrument and of the telemetry channel.

3. Observational Results

Figure 1 shows the electron density profiles in the ascending and descending periods observed with the rocket S-160JA-3. The electron density in the case of JA-3 is higher than that of S-160JA-1 and -2 both during the ascent and descent.

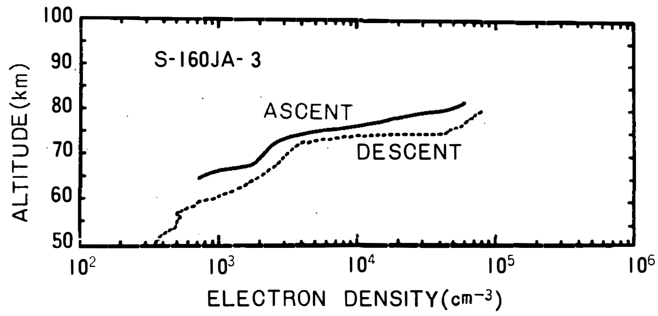

Fig. 1. S-160JA-3 rocket measurement of electron density.

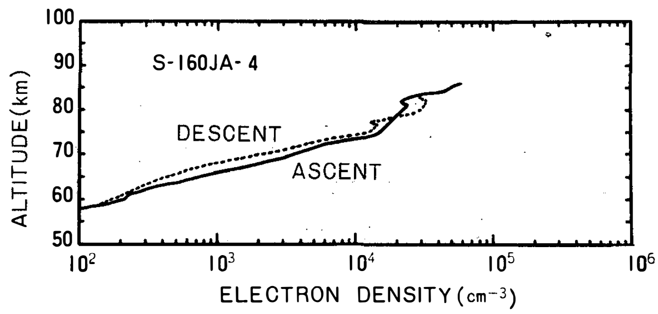

Fig. 2. S-160JA-4 rocket measurement of electron density.

Figure 2 shows the electron density profiles in the ascending and descending periods observed with the rocket S-160JA-4 which was fired in the nighttime. The cosmic noise absorption observed with the riometer at the frequency of 30 MHz was −1.2 dB, and the variation of the horizontal component of the geomagnetic field was −320 γ. The ionosphere was rather disturbed and the electron density of the ionosphere was high in the lower altitude region between 65 km and 80 km.

Figures 3 and 4 show the electron density profiles observed during the ascent

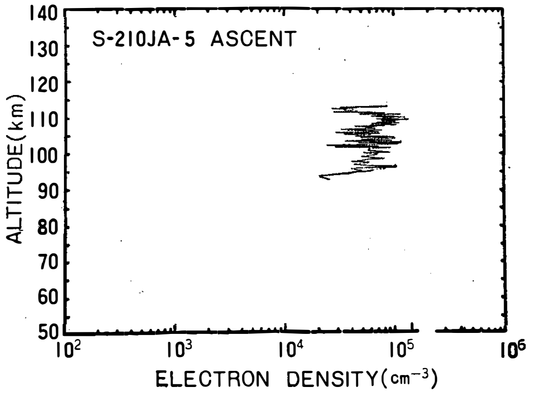

Fig. 3. S-210JA-5 rocket measurement of electron density.

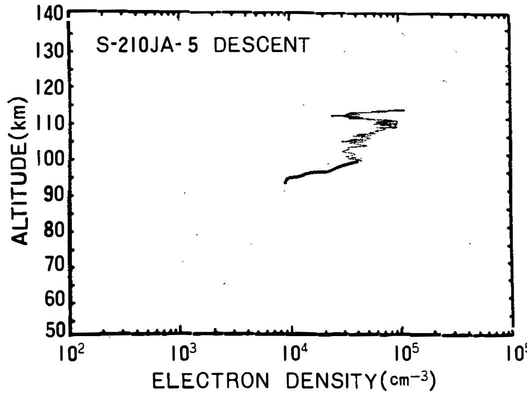

Fig. 4. S-210JA-5 rocket measurement of electron density.

and descent of the rocket S-210JA-5 which was fired in the nighttime. In the ascending period, the electron density increased with a steep gradient up to the altitude of about 95 km, then the gradient of the electron density became rather small above 95 km, while the electron density was about $1\times10^{5}cm^{-3}$ as shown in Fig. 3. In the descending period, the gradient of the electron density at 100 km changed. The gradient of the electron density above 100 km was larger than that during the ascent. That the electron density was low in the altitude region between 100 km and 105 km can be inferred from the measurements to arise from the effects of the rocket wake.

Figures 5 and 6 show the electron density profiles in the ascending and descending periods observed with the rocket S-210JA-6 which was fired in the daytime. The gradient of the electron density below about 88 km was comparatively large, the maximum electron density of $2\times10^{5}cm^{-3}$ appeared in the altitude region between about 95 km and 105 km, and the electron density decreased above 105 km. The ionosphere was slightly disturbed. The decreases of the electron density about 110 km in the ascent and around 125 km in the descent is inferred from the measurements to arise from the effects of the rocket wake.

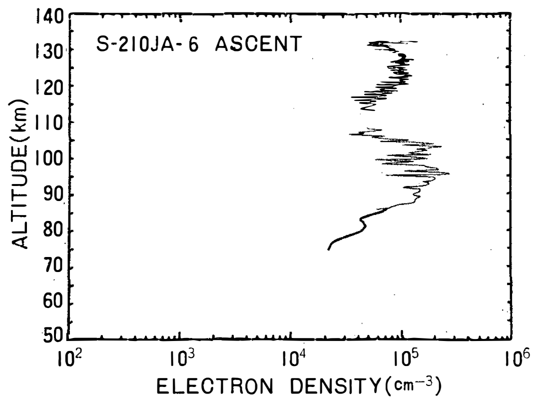

Fig. 5. S-210JA-6 rocket measurement of electron density.

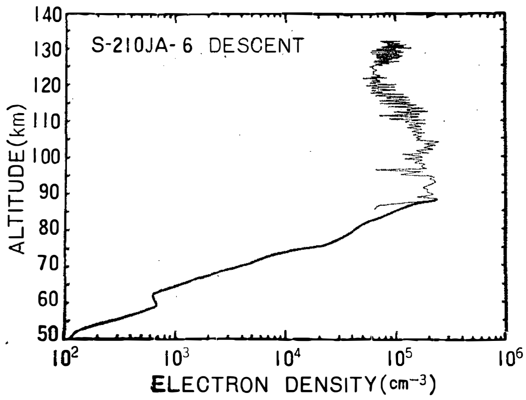

Fig. 6. S-210JA-6 rocket measurement of electron density.

Figures 7 and 8 show the electron density profiles observed along the trajectory of rocket S-210JA-7. The rocket was fired at a time when the solar elevation angle was a few degrees; therefore, the solar ultraviolet and X-rays contributed to the ionization of the upper atmosphere. The profiles of the electron density distribution in the ascent and descent are similar to each other. The electron density increased abruptly up to an altitude of about 95 km; the gradient of the electron density above 95 km was low and a maximum electron density of about $3-4\times10^{5}$ cm^{-3} appeared around 110 km. The electron density decreased above 110 km. It

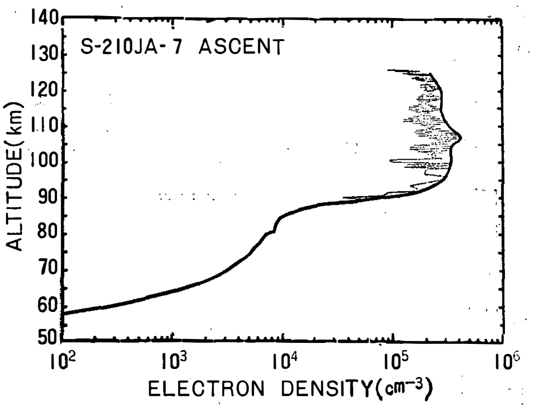

Fig. 7. S-210JA-7 rocket measurement of electron density.

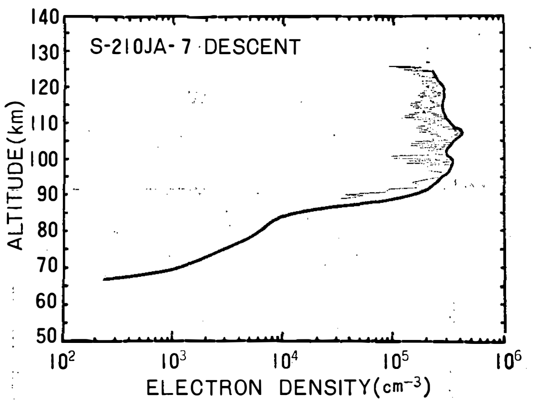

Fig. 8. S-210JA-7 rocket measurement of electron density.

is interesting that the gradient of the electron density at about 85 km changed. This fact may show that the ionization mechanism changes at this altitude.

In Figs. 9 and 10 are shown the electron density profiles observed in the ascending and descending periods with rocket S-210JA-8 which was fired during the period of the August event, 1973 (Radio Res. Labs., 1973). The magnitude of the ionospheric disturbance when the rocket JA-8 was fired was large similar to the case encountered during the flight of JA-11. The variation of the horizontal component of the geomagnetic field was -450γ and the cosmic noise absorption was -2.6 dB. The ionogram during the event shows the occurrence of a radio blackout. The electron density increased abruptly up to the altitude of 80 km in both the ascent and descent. The gradient of the electron density changed at 80 km, while the electron density increased gradually up to the altitude of about

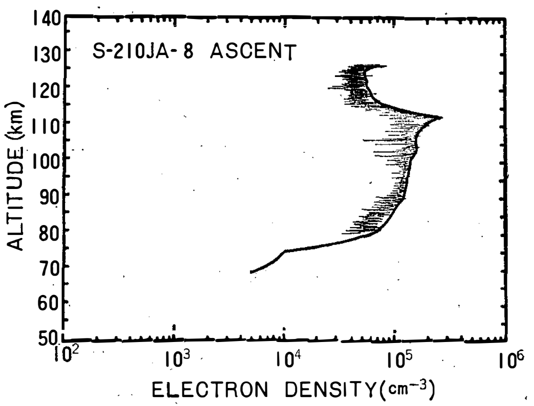

Fig. 9. S-210JA-8 rocket measurement of electron density.

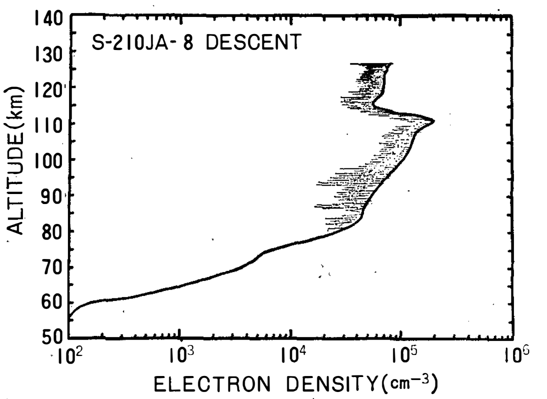

Fig. 10. S-210JA-8 rocket measurement of electron density.

112 km but decreased gradually above 112 km. The gradient of the electron density changed at about 75 km as in the case of the electron density profile of JA-7.

Figures 11 and 12 show the electron density profiles observed during the ascending and descending stages of the trajectory of rocket S-210JA-9. At the firing time,

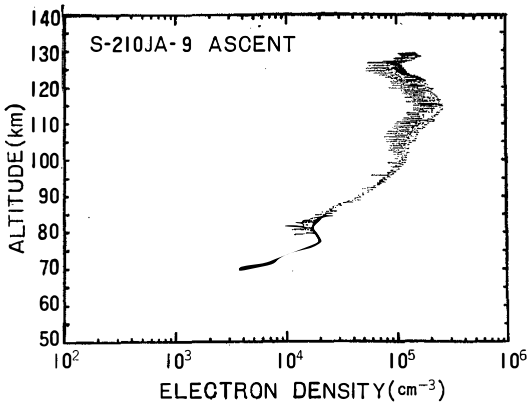

Fig. 11. S-210JA-9 rocket measurement of electron density.

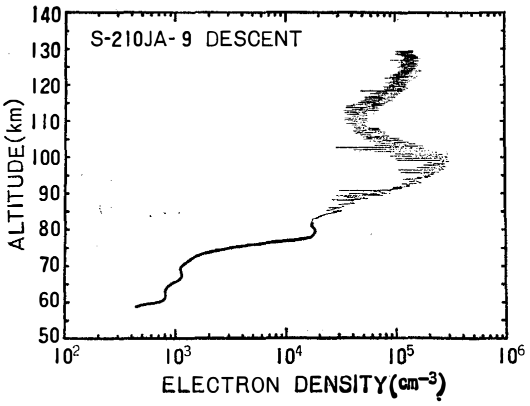

Fig. 12. S-210JA-9 rocket measurement of electron density.

the variation of the horizontal component of the geomagnetic field was -290γ and cosmic noise absorption was -1.3 dB. Although the ionogram shows an almost complete radio blackout, occasionally the Es layer appeared. The profiles of the electron density distribution in the ascent and descent are different from each other. That is, the electron density increased monotonically up to an altitude of about 115 km with a maximum electron density of about $2.5\times10^5\text{cm}^{-3}$ during the ascent. The electron density decreased above 115km. On the other hand, the electron density showed a maximum of about $3\times10^5\text{cm}^{-3}$ and had a minimum at 110 km during the descent. The difference between the profiles in the ascending and descending periods is not clear, but it is inferred that the location of the aurora or presence of the large rocket wake arising from the abnormal orientation of the rocket may have produced some unusual conditions.

Figures 13 and 14 show the electron density profiles observed during the ascent and descent of rocket S-210JA-10. At the firing time, the ionosphere was slightly disturbed; the ionogram shows the existence of spread *F*. The electron density increased abruptly up to the altitude of 102 km, while the electron density was about $8-10\times10^4\text{cm}^{-3}$ in both the ascending and descending periods.

Figures 15 and 16 show the electron density profiles observed during the ascending and descending trajectories of rocket S-210JA-11 which was fired during the period of the August 1972 event. The variation of the horizontal component of the geomagnetic field was $-600\,\gamma$ and the cosmic noise absorption was -4.8 dB. The ionogram shows the occurrence of radio blackout. During the ascent, the electron density

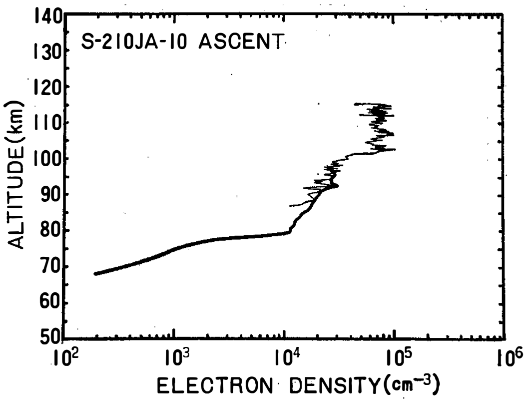

Fig. 13. S-210JA-10 rocket measurement of electron density.

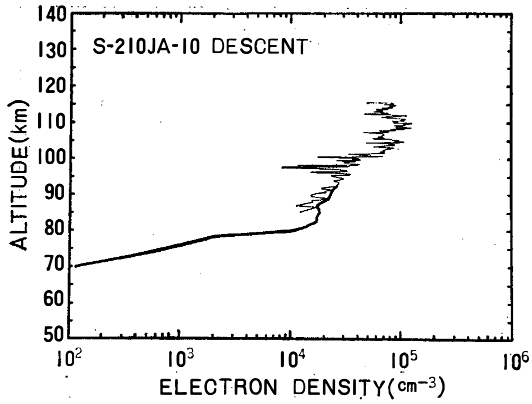

Fig. 14. S-210JA-10 rocket measurement of electron density.

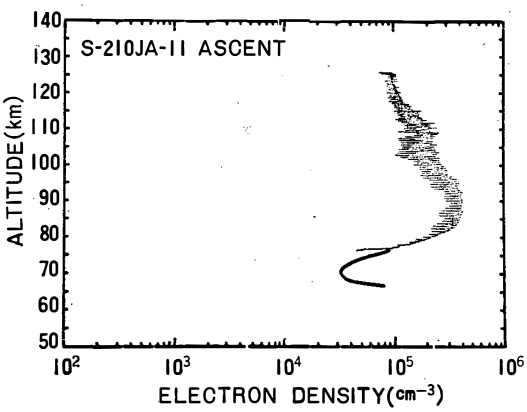

Fig. 15. S-210JA-11 rocket measurement of electron density.

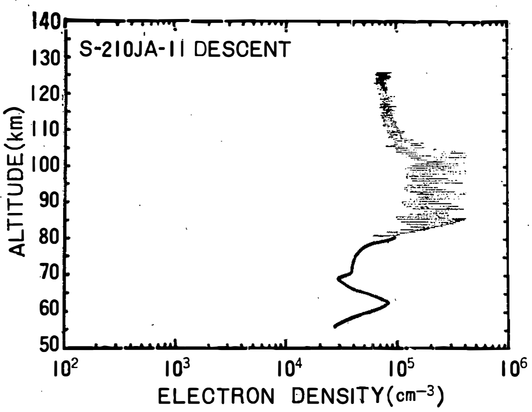

Fig. 16. S-210JA-11 rocket measurement of electron density.

increased rapidly up to the altitude of about 77 km, increased gradually above 77 km and reached a maximum of about $4-5\times10^5$cm^{-3} at about 90 km. The electron density decreased gradually above 90 km. During the descent, the electron density showed a maximum of $4-5\times10^5$cm^{-3} in the altitude region between 95 km and 105 km. The values of the measurements in this region with the radio frequency probe showed a saturation level of the upper limit of 6 MHz. The electron density decreased gradually above 105 km.

In Figs. 17 and 18 are shown the electron density profiles observed during the ascent and descent of rocket S-210JA-12 which was fired during quiet daytime ionospheric conditions. The profile shows the typical daytime ionospheric conditions. During the ascending stage, the electron density increased rapidly up to the altitude of about 88 km, and then remained approximately at a constant value of $1-2\times10^5$cm^{-3} above 88 km. During the descending period, the electron

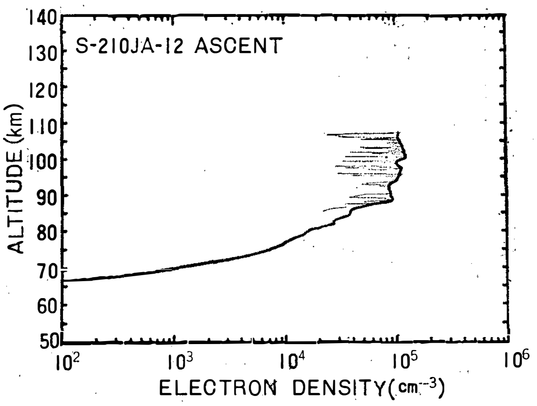

Fig. 17. S-210JA-12 rocket measurement of electron density.

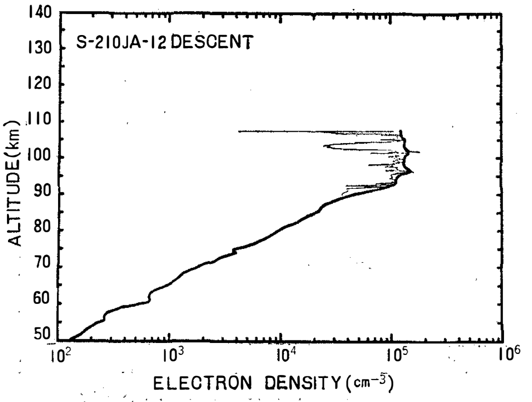

Fig. 18. S-210JA-12 rocket measurement of electron density.

density was nearly constant above 93 km but decreased rapidly with altitude below 93 km. The rapid decrease of more than one order in magnitude in the electron density measurement of the profile is assumed to be caused by the large rocket wake produced by the abnormal orientation of the rocket.

4. Summary and Discussions

In the previous section, the results of the electron density measurements with the rocket experiment of the 12th and 13th JARE are described.

The rockets S-160JA-3, S-210JA-6 and -12 were fired in the daytime, the rocket S-210JA-7 was fired at a low solar elevation angle and other rockets S-160JA-4, S-210JA-5, -8, -9, -10 and -11 were fired in the nighttime.

Comparing the results observed with S-210JA-6 and -12, the electron density above 88 km in the case of JA-6 is about twice that of JA-12. This reason is that JA-12 was fired during a quiet period and JA-6 was fired during a slightly disturbed period. The electron density in the *D* region between 75 km and 90 km in the case of JA-6 is larger than that in JA-12. In the case of S-160JA-3, the electron density at about 80 km is much higher than those of the former two cases.

Figure 19 shows the nighttime electron density profiles in the ascending period when aurora appeared. The rocket flight number is given in the figure. Increases of the electron density, especially in the *D* and *E* region between 75 km and 110 km are proportional to the magnitude of the disturbances such as the variation of the geomagnetic field and the cosmic noise absorption.

In the cases of S-210JA-7, -8 and -10, it is interesting that there exists a change of the gradient of the electron density in the *D* region. This may show that the ionization by the auroral X-rays in auroral zone disturbance contribute to the lower

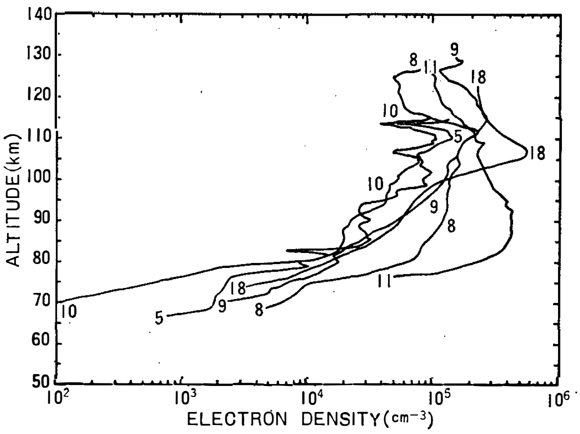

Fig. 19. Electron density profiles during auroral disturbances.

part of the D region (REES, 1964; KAMIYAMA, 1967).

It is shown that there appears a minimum value in the current measurement with the electron current probe in the altitude region between 40 km and 60 km. The current below that level is assumed to be carried by negative ions.

Lastly, the angle of the precession of the rocket axis becomes large after separation of the nosecone, and the aspect of the rocket during this stage becomes variable. Therefore, the effect of the rocket wake must be considered in the measurement of the electron density.

Acknowledgments

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