

Electron temperature in nighttime sporadic E layer at mid-latitude

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Abstract. Electron temperature in the sporadic E layer was measured with a glass-sealed Langmuir probe at a mid-latitude station in Japan in the framework of the SEEK (Sporadic E Experiment over Kyushu)-2 campaign which was conducted in August 2002. Important findings are two fold: (1) electron temperature and electron density vary in the opposite sense in the height range of 100–108 km, and electron temperature in the E_s layer is lower than that of ambient plasma, (2) electron temperature in these height ranges is higher than the possible range of neutral temperature.

These findings strongly suggest that the heat source that elevates electron temperature much higher than possible neutral temperature exists at around 100 km, and/or that the physical parameter values, which are used in the present theory to calculate electron temperature, are not proper.

Keywords. Ionosphere (Ionospheric irregularities; Mid-latitude ionosphere)

1 Introduction

To measure electron temperature (T_e) inside sporadic E (E_s) is a difficult task because sounding rockets go through thin layer(s) where electron density changes very fast. To obtain T_e in the nighttime E_s , together with that outside E_s from Langmuir probe, is especially difficult or almost impossible when the electron density (N_e) is not high enough and the amplifier of the instrument does not have enough gain with the sufficient frequency response. In addition, the v-i characteristic curve of the Langmuir probe is distorted by the spinning of the rocket and/or by the irregular electron density structure if the probe sweep bias is not fast enough. To obtain an accurate v-i characteristic curve in the rapidly changing media, a well-designed instrument is needed, as well as careful laboratory experiments.

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For these reasons, only few T_e data exist so far. Schutz and Smith (1976) reported T_e of 520 K inside the E_s layers at the heights of 108.5 km and 114.5 km. T_e outside was 550 K at 106.5 km and 111.5 km, which means that T_e inside E_s was about 30 K lower than the ambient plasma. This result was obtained by simply averaging 29 points of T_e values, which were measured in the height range of 105 km–125 km. No detailed analysis of the rocket attitude was conducted. Szuszczewicz and Holmes (1977) reported T_e inside E_s in the height range of 105–107 km, both for up leg and down leg. In the up leg, N_e starts increasing at the height of 106.0 km, and takes a peak at the height of 106.71 km, and then decreases. T_e at the peak N_e was 345 K, and T_e at the height of 107.5 km was 380 K. For the down leg, the height of N_e maximum was 106.2 km. Below the N_e maximum that is found at the height of 105.7 km, T_e was 345 K and above the maximum N_e at the height of 106.5 km, T_e was 500 K. Thus, T_e inside E_s is 140 K lower than outside E_s . Two other papers reported on T_e inside E_s . Aubry et al. (1966) showed two E_s events. One case is that T_e inside E_s was 1/2 that of the ambient. Another case is that T_e is two times higher than the ambient. Andreyeva et al. (1971) reported two cases; one case shows T_e inside E_s equal to that of outside E_s , and the other case indicates T_e inside E_s is 10% lower than that of the ambient.

Gleeson and Axford (1967) conducted theoretical discussion by taking the heating due to the internal gravity wave into account. T_e in the midst of E_s , which was located at the height of 115 km, was calculated to be about 90 K lower than that of the ambient.

As described above, T_e data inside E_s is still very scarce and no clear conclusion on T_e inside E_s has been drawn, in spite of the long history of sounding rocket experiments. We report the measurement of T_e , which was obtained with one of the sounding rockets during the SEEK2 rocket campaign to study QP (Quasi Periodic) echoes associated with the sporadic E layer (Yamamoto et al., 2005).

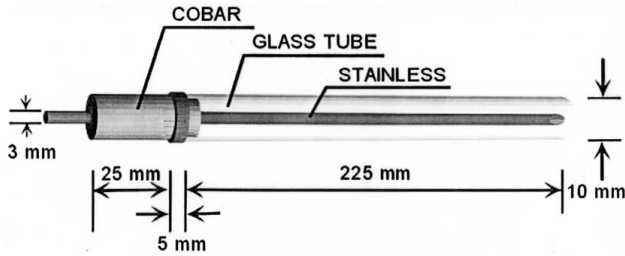


Fig. 1. Diagram of glass-sealed Langmuir probe sensor “support rod”, which is mentioned in Fig. 2a, and made of COVAR (25 mm in length, and 10 mm outer diameter).

2 Instrumentation

Special attention should be paid to be electrode and the electronics, in order to obtain an accurate value from the Langmuir probe measurement, although the principle itself of the measurement is very simple. The contamination of the electrode surface is most serious problem (Oyama, 1976). To avoid the effect of the electrode contamination, a glass-sealed Langmuir probe, which consists of a cylindrical stainless electrode and a glass tube, was used (Oyama and Hirao, 1976). A cylindrical stainlesssteel electrode of 3 mm in diameter and 22.5 cm long was installed in the glass tube with an inner diameter of 9 mm and outer diameter of 10 mm (see Fig. 1). The glass tube was connected to the turbo-molecular pump, and the tube was evacuated inside. During the evacuation, under the pressure of less than 1×10^{-7} Torr, the system, including electrode and the glass tube, was baked. It is essential to heat the electrode higher than 100°C , because the main contaminant is water. It is highly recommended that the temperature of the electrode and glass tube should be $160\text{--}200^\circ\text{C}$. After the evacuation, 2–3 days later, the end of the glass tube was cut from the vacuum system and the cylinder electrode was sealed in the glass tube. Without these procedures, it is impossible to remove the electrode contaminants, which usually cover the surface of the electrode.

Probe voltage in a triangular shape was swept from 0 V to 2.5 V and then from 2.5 V to 0 V within 0.25 s, which provided one *v-i* characteristic curve every 0.125 s. The use of the triangular wave allows us to check the hysteresis of the *v-i* curve (Oyama, 1976). The hysteresis appears when the electrode is contaminated. The small hysteresis of the *v-i* curve is also produced in the measurement system itself. It originates from the stray capacitance of the cable, connecting the electronics and the electrode. The amplifier itself causes the second hysteresis, if the frequency response is limited to a low frequency. The hysteresis should be eliminated, in order to obtain an accurate T_e . To remove the hysteresis associated with the stray capacitance, the sweep voltage is applied to the outer shielding cable. This finally leads to no accumulation of the electronic charge between the center wire and the outer shielding cable. In order to remove the amplifier hys-

teresis, the amplifier needs enough of a frequency response. One should note that it is impossible to obtain an accurate electron temperature without special attention regarding the electrode and the electronics.

3 Rocket experiment

The S-310-31 rocket was launched at 23:24 JST on 3 August 2002, to study the QP echo associated with sporadic E from the Kagoshima Space Center ($131^\circ 05' \text{E}$, $31^\circ 15' \text{N}$ in geographic coordination). The second rocket, S-310-32, was launched 15 min after the first rocket. Adjusted solar radio flux and the K_p index (sum) were 172.7 and 22, respectively.

A glass-sealed Langmuir probe, which was described above, was installed in the rocket S-310-31. The location of the glass-sealed Langmuir probe is illustrated in Fig. 2. The nose cone was opened 60 s after the launch at the height of 70 km. Two seconds after opening the nose cone, the root of the glass tube was destroyed by a guillotine actuated by the first squib (shown in Fig. 2 as wire cut 1); one second after the destruction of the glass tube, the second squib (shown in Fig. 2 as wire cut 2) was activated to cut the wire, which fastened the glass tube along the rocket spin axis, and the Langmuir electrode was ejected perpendicularly to the rocket spin. Simultaneously, the glass tube was removed by a centrifugal force of the rocket spin.

The spin rate of the rocket was reduced from an initial spin rate of 2.2 Hz to 0.7 Hz by a yo-yo despinner 55 s after the launch at the height of 55 s. Accordingly, one *v-i* characteristic curve was obtained during about 30 degrees of rocket spin. A current amplifier picked up the probe current and the voltage-converted current was amplified with three amplifiers. Output voltage of 5 V corresponds to 1 microampere for a low gain amplifier, 0.1 microamperes for a middle gain amplifier, and 0.01 microamperes for a high gain amplifier, respectively. The output voltages of the three amplifiers have an offset voltage of 0.5 V, in order to measure the ion current, which means that zero current corresponds to 0.5 V. A circuit was calibrated every 30 s by connecting 40 mega ohm resistance to the input of the amplifier right after disconnecting the wire to the electrode. An 8-bit A/D converter converted the output voltage with the sampling frequency of 3200 Hz. During 78–108 s (height: 90–120 km) after the launch, the output voltage from the middle gain amplifier was converted by 12 bits, with a sampling frequency of 6400 Hz and stored in the memory. The data, which is thus stored in the memory, was transmitted to the ground 193 s after the launch when the rocket reached approx. the apogee. The retrieval of the data was completed at 313 s after the launch.

The *v-i* characteristic curves thus obtained are analyzed by taking the attitude and spin phase into account. By examining each *v-i* characteristic curve carefully, one set of T_e and N_e was calculated. T_e was calculated from the semi-log plotting of the electron current, which is obtained by subtracting

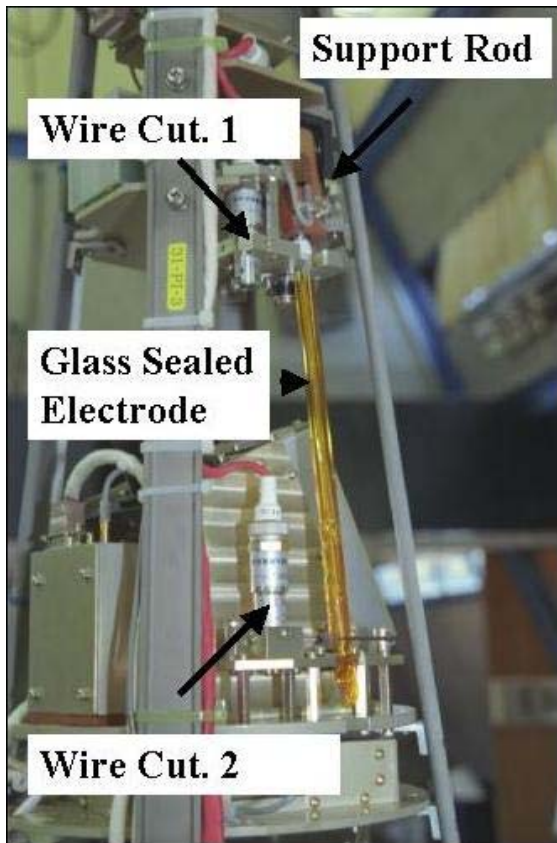


Fig. 2a. Location of glass-sealed Langmuir Probe (indicated as glass-sealed electrode in the figure), and two wire cutters. Glass tube of glass-sealed Langmuir probe is covered with adhesive tape, so that the pieces of the glass cylinder do not scatter when the glass tube is broken by the first squib (indicated as a wire cut 1 in the figure) at the end of the support rod, which is shown in Fig. 1. The second squib (indicated as wire cut 2 in the figure) releases the wire, which holds the glass-sealed Langmuir probe along the rocket axis.

ion current from the curve. N_e was calculated in 3 ways. One is calculated by taking the electron current, i , at the inflexion point of the semi-log plotted i - v curve by the following equation, although argument exists on the inflection point to be defined as space potential:

$$N_e = i / \{S \cdot e \cdot (kT_e / 2\pi \cdot M_e)^{1/2}\},$$

where S is surface area of the cylindrical electrode, e is the electron charge, M_e is the mass of electron, and k is the Boltzmann constant. Another value of electron density is obtained by normalizing the ion current at f_oE_s of the ionogram observed at the nearest ionosonde station located at Yamagawa. One more electron density was measured with a spherical Langmuir probe of a fixed bias, which gives better high resolution than the other two methods. The value is normalized by ionosonde data. Among the three N_e values, the last one has the smallest spin modulation because

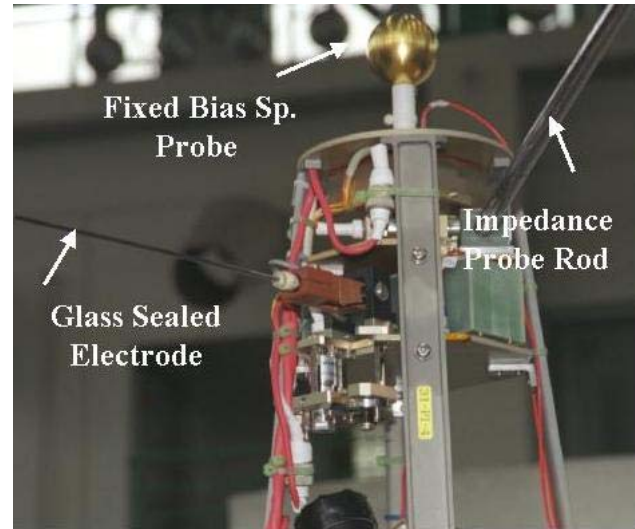


Fig. 2b. Deployed glass-sealed Langmuir probe, which is perpendicular to the rocket spin axis near the top of the payload section. A fixed biased spherical electrode to measure the height profiles of the relative electron density and an impedance probe to measure the absolute electron density are also shown.

the sensor was located at the center of the payload top. The value from the cylindrical probe, which was deployed radial to the spin axis, is influenced strongly by the angle between the electrode and the direction of the geomagnetic field. The data were processed with respect to the spin phase and the moving direction of the rocket.

The ion current, electron current and T_e that are modulated by the spinning of the rocket are shown in Fig. 3a, b, and c, respectively. In the figures, zero of the spin phase defines the position of the cylinder electrode, which points to the moving direction of the rocket. On the left side of Fig. 3a, a height profile of the ion current is provided in the height range of 138.3–143.9 km. Superposed to the rocket spin effect on the ion current, a small noise associated with the S/N of the amplifier appears. The right figure shows the variation of the ion current with respect to the rocket spin, where the ion current is normalized. The ion current shows the maximum at the moving direction, while the current shows the minimum in the midst of the rocket wake. Figure 3b indicates the same as Fig. 3a, but for the electron current. At the left, the electron current is plotted versus height in the height range of 134.2–140.71 km. Data in the right figure shows two minima with respect to the spin. The electron current becomes minimum when the angle between the electrode and geomagnetic field becomes minimum. This happens two times per one spin. Figure 3c shows the variation of T_e in the height range of 110.6–120.9 km. T_e does not indicate any spin angle dependence, as T_e is calculated from the slope of the semi-log plotted electron current near the floating potential. The effect of the geomagnetic field upon the electron collection is

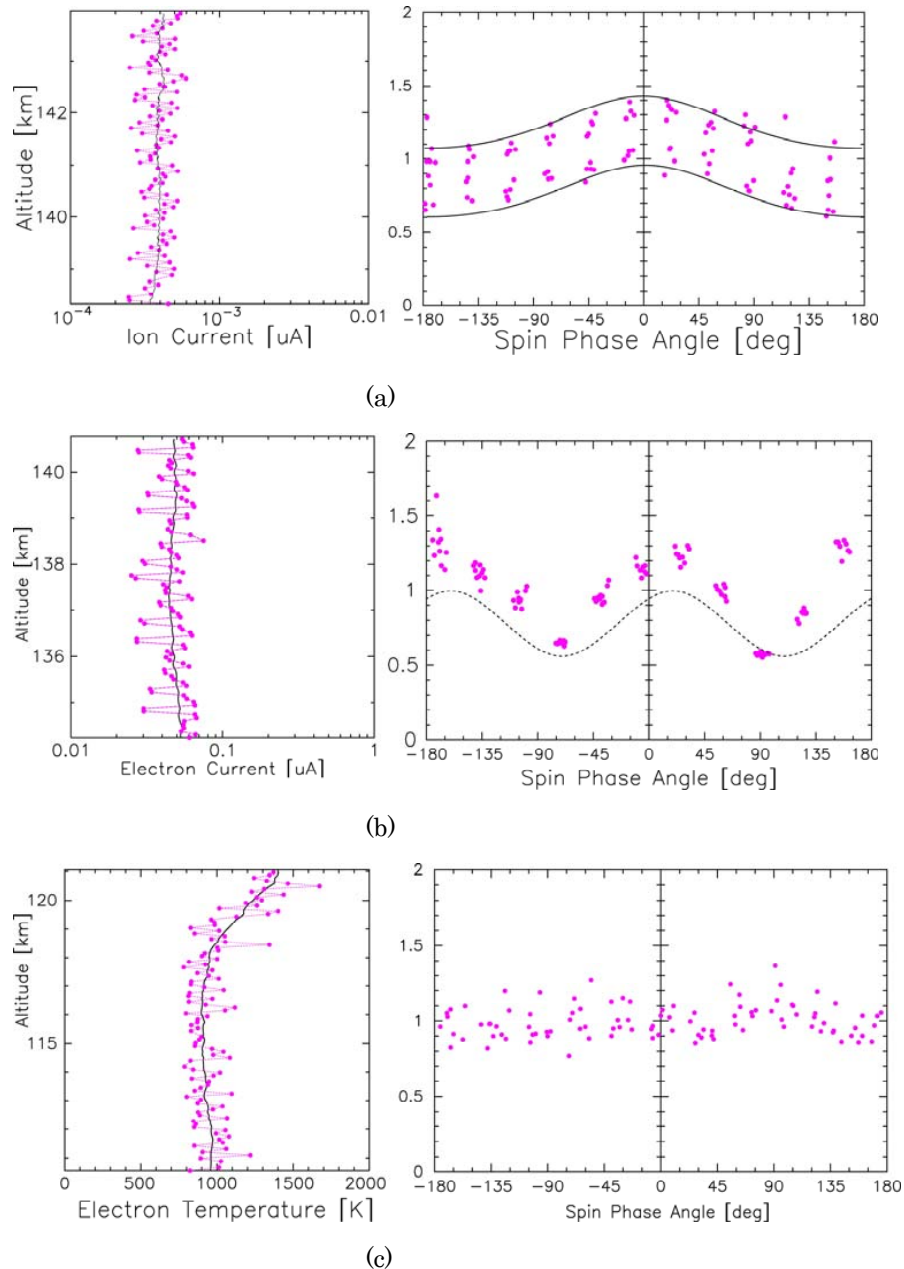


Fig. 3. (a) Variation of ion current in the height range of 138.3–143.9 km, (b) variation of electron current in the height range of 134.2–140.7 km and (c) variation of electron temperature in the height range of 110.5–120.9 km, versus height (left), and spin phase (right). Ion and electron current, and electron temperature are normalized.

more pronounced near the space potential, and therefore, the effect of the geomagnetic field does not reach the floating potential region. Figure 3c shows that the ambiguity of the T_e measurement is roughly less than 100 K.

4 Data obtained and discussion

The ion current of the v-i characteristic curves at the probe voltage of 0 V is illustrated in Fig. 4, as the effect of the geomagnetic field upon the ion current collection is smaller than the case for the electron current, due to larger gyro radius of ion, as shown in Fig. 3b. The voltage where the probe current is zero (floating potential) varied between 1 V and 1.5 V with respect to the rocket body, except inside E_s . Therefore, 0 V

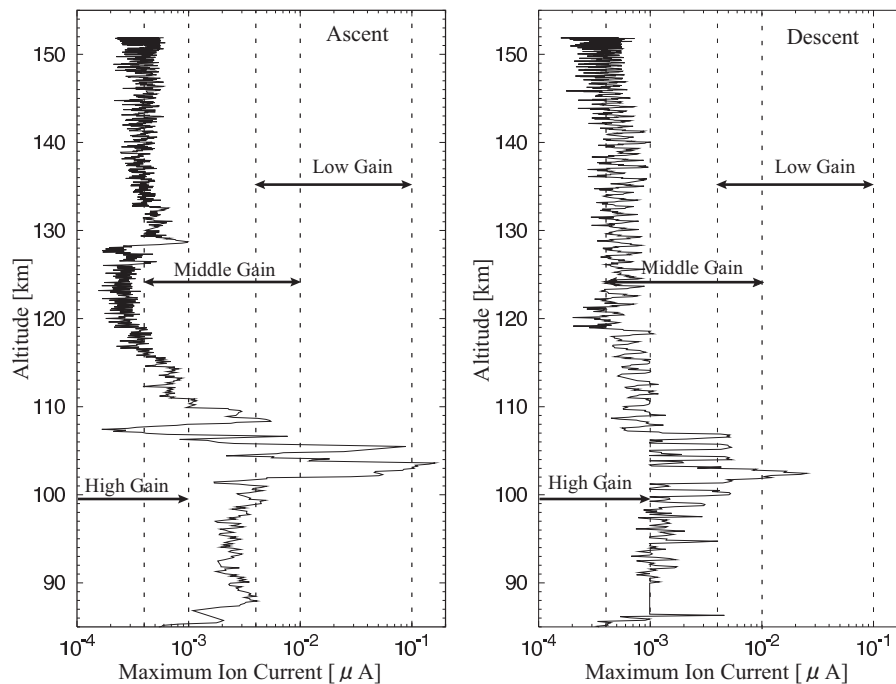


Fig. 4. Height profile of the ion current from the v - i characteristic curve for the up leg (left) and the down leg (right) of the rocket trajectory. Three amplifiers of different gains (low, middle, and high) provide the height profile of the ion current. The rocket spinning causes fine scale fluctuation in the current. The large structure, which appears in the 100–112 km and 127–130 km during up leg, shows the real structure of the ionosphere, although down leg profile is highly modulated by rocket spin, a small reduction in the current, which exists at the height of 118–122 km and the peak of the ion current at the height of 100–106 km, seems to be real.

of the sweep voltage is well in the ion saturation regime of the v - i characteristic curves.

In the height region between 100–110 km, the E_s layer was found. The first maximum of $1.5 \times 10^{-1} \mu\text{A}$ was located at the height of 103.5 km. At the height of 105.5 km the second maximum of $9 \times 10^{-2} \mu\text{A}$ was found. Finally, at the height of 107 km, a thin layer of $8 \times 10^{-8} \mu\text{A}$ was found. After the rocket went through the E_s layer between 100–110 km, the ion current gradually reduced, reaching its minimum at 123 km and again gradually turned to increase. At the height of 128 km the current dropped from $4 \times 10^{-4} \mu\text{A}$ to $1.8 \times 10^{-4} \mu\text{A}$ and suddenly jumped to $10^{-3} \mu\text{A}$ at the height of 129 km and then dropped to $4 \times 10^{-4} \mu\text{A}$. This peculiar behavior might be the key observation to study the formation mechanism of the E_s layer, as we will discuss in a separate paper. A small peak is seen at the height of 142 km. This small peak can be seen more clearly in the electron current (which is not shown here) of the v - i characteristic curve. Similar structures, which exist at the heights of 100, 110, 123 and 142 km during the up leg, are also recognized at 98–108, 120 and 141 km during the down leg.

In Fig. 5, the height range of 100–110 km is expanded, where T_e is plotted together with N_e . T_e was calculated from the semi-log plot of the electron current, that is measured with a cylindrical Langmuir probe. The accuracy of T_e , as

a worst case, might be about 50–100 K, taking into account all possible factors, such as spin effects, the ambiguity of curve fitting, and the frequency response of the instrument. Although the results, which have been reported earlier, also mentioned the same accuracy, the quality of our data is incomparably excellent.

The electron current, which was measured with a fixed biased spherical Langmuir probe, at the probe voltage of 4.5 V, was normalized by the upper hybrid resonance of the gyroplasma probe (Oya, 1969) at the maximum density height of 103.5 km. The impedance probe gives reliable absolute values for N_e higher than 10^3 els/cc. One can see that even small variations in T_e are well anti-correlated with N_e , in spite of the fact that two parameters are measured by different electrodes and calculated independently.

The first and second peaks of N_e at the heights of 103.5 km and 105.3 km are 10^5 els/cc and 9×10^4 els/cc, respectively. Just below the first peak, N_e is 4×10^3 els/cc at the height of 101.5 km. N_e between the two density peaks, at the height of 104.5 km, is 3×10^3 els/cc. T_e is 1000 K and 300 K at the heights of 101.5 km and 102 km, respectively. Above the first N_e peak, T_e is 500 K. Between the first and second N_e peaks, T_e is 1000 K.

Figure 6a, b and c provides raw v - i characteristic curves and semi-log plotted electron currents to show the accuracy

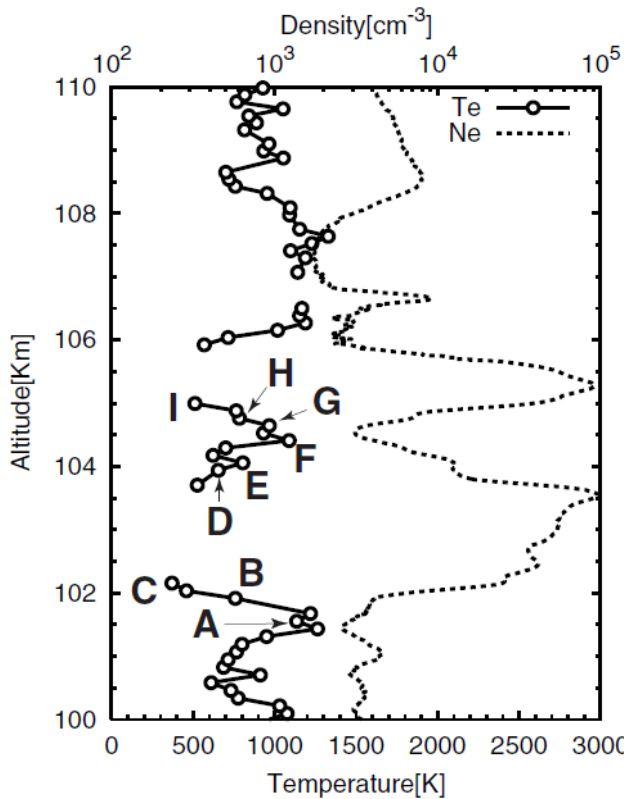


Fig. 5. T_e (solid line with white circles) and N_e (dashed line) in the height range of 100–110 km. The heights indicated by A, B, C, D, E, F, G, and I show the heights where v - i characteristic curves and semi-log plotted curves of electron current, shown in Fig. 4, were measured. N_e and T_e below the height of 100 km are not shown here, in order to show the better fine height profile by reducing the height range.

and reliability of the T_e measurements, which are shown in Fig. 5. In Fig. 6a, v - i characteristic curves in the height range of 101.5–102.2 km are shown in the left part of the figure and the electron current is plotted in a logarithmic scale versus probe voltage in the right part of the figure. Comparison between the v - i current characteristic curves (left) and the semi-log plotted electron current characteristic shows that the electron temperature is calculated only from the very beginning of the rising part of the current-voltage characteristic curve near the floating potential. The high gain of the DC amplifier (output voltage of 5 V for 0.01 microamperes) has a resolution of 3.9×10^{-5} microampere. The middle gain (output voltage of 5 V for 0.1 microampere) has a resolution of 2.5×10^{-5} microampere during 78–108 s; the semi-log plotting of the small electron current is possible, as shown in the right figure. Our observation shows that the high gain output with an 8-bit A/D converter is still acceptable.

The rocket goes into the E_s layer with the order of the curves A, B, and then C. The change in the slope is clearly seen for the semi-log plotted curves. T_e reduces as the N_e in-

creases from A to C. We could not obtain the full v - i curve at point C, because the rocket potential went down to negative to the extent that the probe bias could not cover the voltage range sufficiently to obtain the full v - i curve. Above the height marked C, the rocket potential further became negative and therefore the v - i curve showed only an ion saturation region and T_e was not available.

In Fig. 6b, three similar curves in the height range of 103.7 km to 104.4 km, where N_e decreases from the maximum to the minimum are shown. The slope of the semi-log plotted electron curve reduces from curves D to F. T_e of curve F shows the highest among the three curves, which shows that T_e increases as N_e decreases.

Figure 6c shows the height range from 104.4 km to 105 km, where N_e starts to increase from its minimum value toward the peak value. Although T_e does not decrease on the order of the increase in N_e (compare the slope of the semi-log plotted curve, G and H), T_e is surely lower at higher N_e . Above the height I, the rocket potential again becomes negative far below the probe sweep voltage, and the v - i curve was not available.

The mechanism of the abnormal increase in the negative potential of the rocket is not clear at this moment. However, one possible explanation could be related to the collection of the electrons/ions of the sounding rocket with the existence of strong horizontal neutral wind. In fact, the rocket S-310-32 observed a strong neutral. As the turbulent shadow is formed in opposition to the wind direction, ions have difficulty to be collected by the rocket surface, which faces in the opposite direction to the wind, due to the larger collision frequency between the ions and neutrals. Electrons can directly hit the rocket body along the magnetic field, because at the place where the electric field is radial to the rocket axis, electron does not experience an $\mathbf{E} \times \mathbf{B}$ drift around the rocket (Rohde et al., 1993). As ions are collected only by the surface area which faces the neutral wind, the rocket will become more negative in the strong neutral wind region. The amount of the collection of the electron by a rocket body might depend on the angle between the geomagnetic field and the axis of the sounding rocket. The spin motion of the rocket is independent of the ion and electron corrections, as long as the surface condition is the same with respect to the wind direction.

Although we need complicated computer work to calculate the potential of the rocket body, especially in the presence of strong neutral wind, the speculation above should be pursued quantitatively in the near future.

5 Concluding remarks

This manuscript reports the T_e inside E_s layer, which is measured with a glass-sealed Langmuir probe. We believe that the T_e , which was obtained by the careful analysis of the rocket attitude and the rocket spin, is one of the most reliable

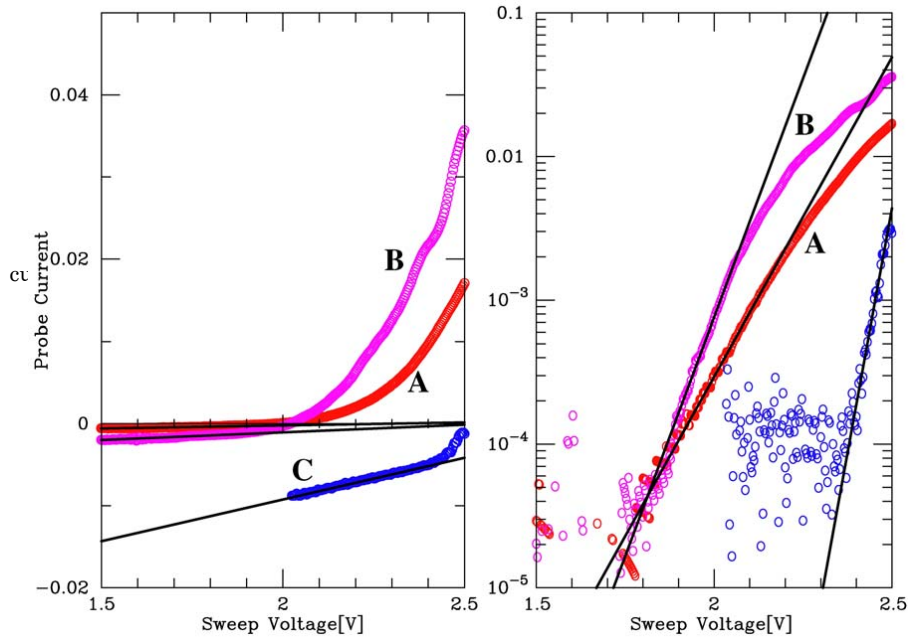


Fig. 6a. Three v-i characteristic curves (left) and semi-log plotted electron currents (right) obtained at 3 heights denoted as A, B, and C, which are marked in Fig. 5.

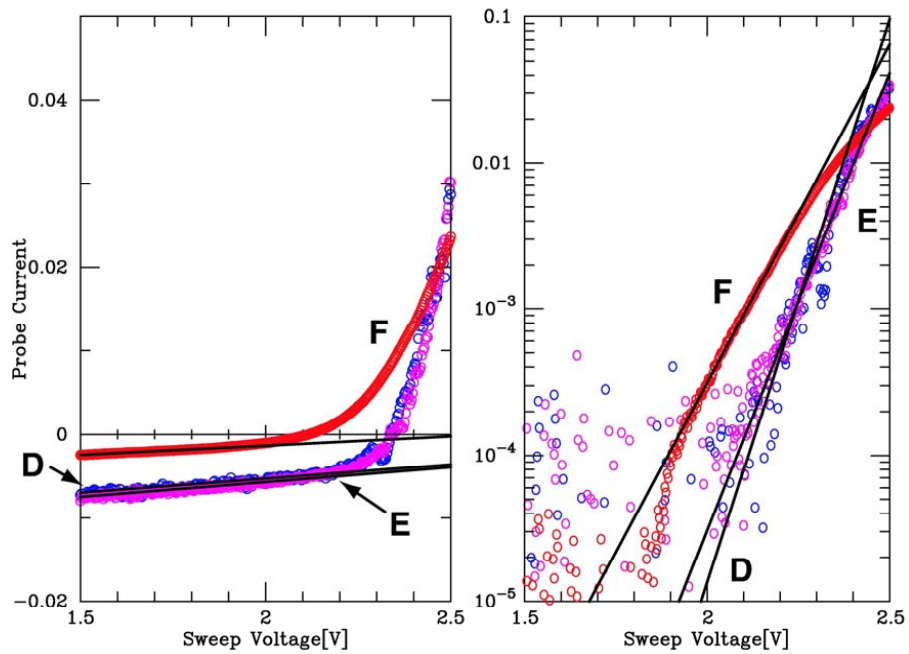


Fig. 6b. Same as Fig. 6c but for E, F, and D, which are marked in Fig. 5.

data measured so far. From this measurement, two important findings are made. Those are:

1. Electron density varies in antiphase with T_e ; when electron density is high, electron temperature is low. This feature was observed most clearly inside E_s , that is, T_e

is lower than that of outside E_s . In the highest electron density region (102.1 km–103.6 km), T_e seems to be close to T_n . It is noted that this feature was seen in all altitude ranges in the nighttime ionosphere where no direct solar EUV exists.

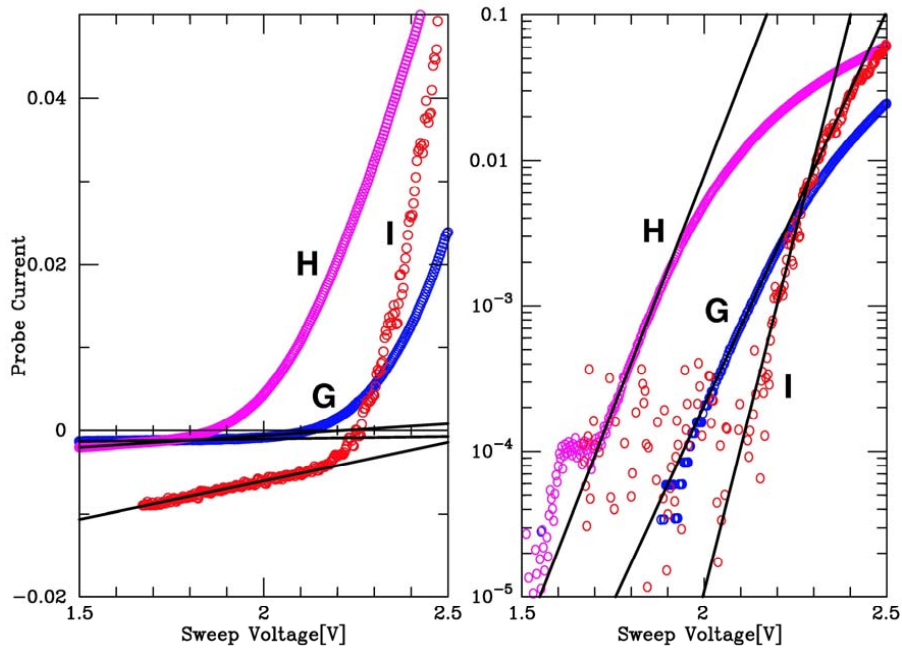


Fig. 6c. Same as Fig. 6a but for H, G, and I, which are marked in Fig. 5.

- T_e in the height range of 100–110 km is, on average, 800 K, which is still much higher than the possible range of neutral temperature (about 250 K) in this height region.

We now strongly believe that some heat source is still missing (Oyama and Hirao, 1980), that can elevate electron temperature higher than neutral temperature (Oyama, 2000; Rohde et al., 1993), or that the current theory on T_e uses incorrect parameter values, such as suggested by Jain et al. (1981) on the electron temperature in the equatorial electrojet. Further neutral density, which we usually take from MSIS, might differ from the real one (Kurihara and Oyama, 2005). The heating of electrons by a vibrationally excited nitrogen molecule is still one of the strong candidates (Oyama, 2000; Kurihara et al., 2003).

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