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Detailed Structure of Electron Temperature and Density inside the Sporadic E Layer

Yumika SAKAMOTO, Takumi ABE and Wataru MIYAKE

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Detailed Structure of Electron Temperature and Density inside the Sporadic E Layer

Yumika SAKAMOTO[*1], Takumi ABE[*2], Wataru MIYAKE[*1]

ABSTRACT

Unusual current-voltage characteristics were found by the Fast Langmuir Probe measurement inside sporadic E (Es) layer during S-520-29 sounding rocket flight. The characteristics are caused by a significant gradient of electron density inside the Es layer. We employ a new analysis method for accurate estimation of the electron temperature and density. It also allows us to obtain the temperature and density in a shorter time interval than the voltage sweep period. Our new observation and analysis method provide us with first detailed structure of electron density and temperature inside the Es layer with an unprecedented spatial resolution. The maximum electron density and the minimum electron temperature observed inside Es layer are estimated to be 9.7×10^5 cm^{-3} and 550 K, respectively, at an altitude of 98 km. The total thickness of the layer is about 1 km. Furthermore, the detailed trend of the electron temperature from its boundary toward the center of Es layer was revealed so clearly owing to the new method. Electron temperature in the surrounding region of the Es layer is found to be quite high, suggesting significant heating at the altitude range. The observed reduction of electron temperature in the Es layer embedded in an elevated temperature region is interpreted in terms of dependence of heat sources and cooling processes on the thermal electron density.

Keywords: Ionosphere, Sporadic E layer, Electron density, Electron temperature, Sounding rocket, Energy budget

1. INTRODUCTION

Sporadic E (Es) layers in the lower ionosphere have been studied for a long time, and wind-shear theory is generally accepted as its generation mechanism (e.g., Whitehead, 1989). This theory explains an accumulation process of the electron concentration, but hardly gives information on thermal energy budget inside the layer. Although the electron temperature is one of the most important parameters for discussing the thermal energy budget in the ionosphere, there were few data of reliable electron temperature in Es layers in the past.

Measurements of the electron density and temperature in the ionosphere have been made by a probe on the sounding rocket for more than 50 years. In general, it is not easy to measure the electron temperarure accrately on the sounding rocket because of various practical problems such as the surface contamination (Oyama et al., 1980) and the rocket wake. Among them, a contamination of the probe surface is a serious problem which has to be considered (Hirao and Oyama, 1972). In order to avoid undesirable effect of the contaminated layer on the measurement, Oyama and Hirao (1976) developed a way to keep the probe surface clean by sealing the cylindrical electrode with a glass tube until starting the measurement, which is called the glass-sealed cylindrical probe. Data from this type of probe on Japanese sounding rocket are used in the present study.

Electron temperatures inside the sporadic E (Es) layer were measured by Langmuir probe on the sounding rocket in the past. However, only the limited electron temepration data were available for discussing thermal structure of the Es layer. Although an increase of electron temparature in the Es layer was suggetsed in a few papers (Aubry et al., 1966; Szuszczewicz and Holmes, 1977; Yoshimura et al., 1999), other observations found rather decrease of electron temperature. Schutz and Smith (1976) estimated electron temperature structure in the Es layer from observations by four Nike Apache rocket flights, and obtained a result that all of the four Es layers had lower electron temperature than the circumference. Oyama et al. (2008a) evaluated Langmuir probe data with careful attention to the rocket attitude. They also concluded that the electron temperature in the Es layer decreased by several hundred K compared to the neighboring temperature.

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[*] Received August 23, 2018
[*1] Department of Aeronautics and Astronautics, Tokai University
[*2] Department of Solar System Sciences, Institute of Space and Astronautical Science

Barjatya et al. (2013) showed anticorrelation between the electron density and temperature within and around the double Es layers. Moreover, electron temperature was observed to increase dramatically above or below the Es layer.

One of the problems on measuring electron density and temperature inside Es layers comes from thin vertical width of Es layers (around 1 km). Because of low time resolution, the early observations had only one or a few data points in the Es layers and no detailed discussion on energetics were available. Low time (i.e., spatial) resolution leads to poor accuracy because of a large gradient of thermal electron density. There has been few observations with a high time resolution enough for discussing the detailed energetics in Es layers.

The sounding rocket S-520-29 was launched from Uchinoura Space Center of Japan Aerospace Exploration Agency (JAXA) at 19:10 JST on August 17, 2014. The main purpose of this experiment is to reveal spatial density structure of the Es layer in the lower ionosphere by conducting three complementary measurements of optical imager, medium frequency radio receiver and *in-situ* probes. FLP (Fast Langmuir Probe) was installed as one of the probes for direct measurements, which has been developed for fast measurement of thermal electron density and temeprature in the ionosphere. The sounding rocket reached an altitude of 243 km. The FLP onboard the rocket started measuring after the nosecone opened at 55 seconds after the launch, and observed a sporadic E layer at around 98 km altitude during the rocket's upleg. We present an analysis result on this Es layer during the upleg where no effect of rocket wake provides us with a high time resolution measurement.

In the present paper, we are focusing on the detailed structure of electron temperature and density inside Es layer from Fast Langmuir Probe measurement on board the sounding rocket S-520-29. We introduce a new analysis method to enable accurate estimation of the electron temperature and density, which successfully leads us to obtain a first clear structure of electron temperature and density variation inside the Es layer. We further discuss a physical implication of the observed depletion of electron temperature for energy budget inside the Es layer.

2. MEASUREMENT

The FLP onboard the sounding rocket S-520-29 consists of a cylindrical stainless probe with a length of 200.0 mm and a diameter of 3.0 mm, and was installed on the payload zone. The contamination on the probe surface causes hysteresis in I-V characteristics and disturbs the accurate measurement [Abe and Oyama, 2013].

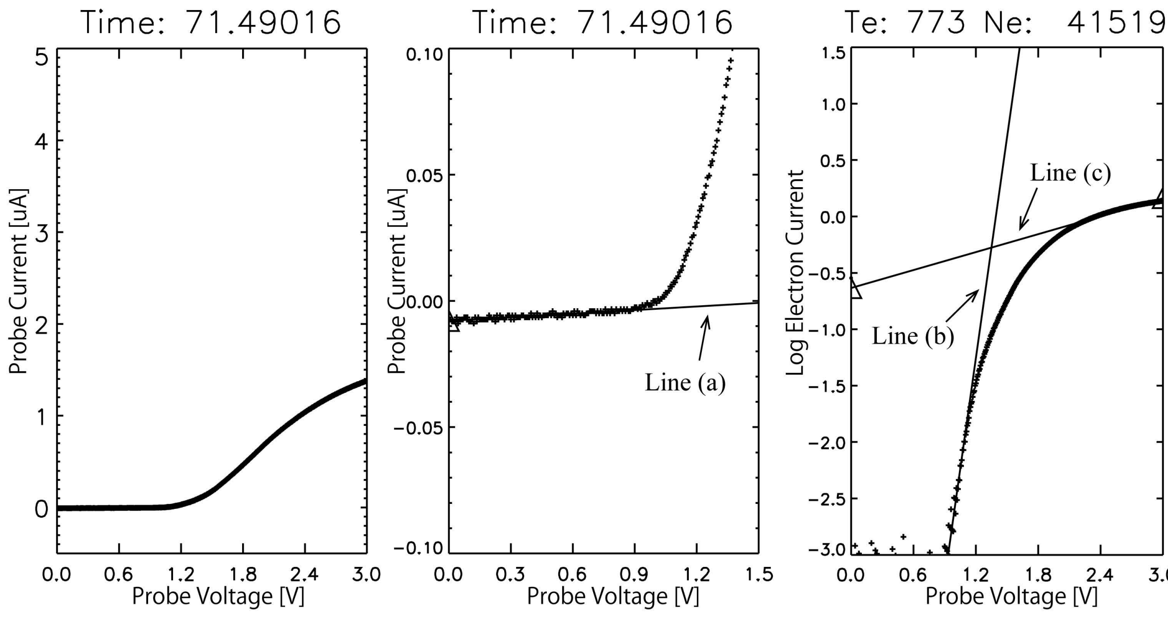

Fig. 1. An example of fitting procedure for obtaining electron density and temperature. Three panels represent current-voltage curve of the probe. Line(a): linear fitting to the ion current region, (b): linear fitting to the electron retarding region, and (c): linear fitting to the electron saturation region.

In order to perform a Langmuir probe measurement with a clean electrode on a sounding rocket, a glass-sealed cylindrical probe was prepared. Before the rocket launch, this glass tube with the probe was connected to a vacuum chamber evacuated by a pumping system, and baked at a high temperature for a long time. Subsequently, the glass tube is sealed. The probe was installed on the sounding rocket and the glass tube was broken at 59 second after the launch, and deployed to the direction perpendicular to the rocket axis to avoid a possible influence of the rocket wake. At the same time, the glass tube was removed by a centrifugal force of the rocket spin.

The probe is directly biased by a triangular voltage with amplitude of 3.0 V with respect to the rocket potential and a period of 125 msec in order to provide the incident current - voltage relationship. A current incident on the probe was sampled with a rate of 6400 Hz, and amplified by two different gains (low and high) so that it can work in a wide range of the plasma density. The current gain is adjusted to become the full scale with 3.0 μA and 90.0 μA for High Gain and Low Gain, respectively. In order to measure the ion current as well as the electron current, the amplifier has an offset voltage of +0.5 V; a positive (> 0.5 V) voltage means the electron current while a negative one does the ion current. The calibration signal is obtained by switching the input from the probe to the resistance once every 30 seconds. The electron temperature and number density can be derived from a relationship between the incident current versus the probe voltage.

Electron density and electron temperature can be derived from the I-V characteristics obtained from the FLP. Figure 1(a), (b) and (c) show an example of I-V curves of the probe, linear fitting to the ion current region, and a linear fitting to the electron retarding and saturation current regions on a logarithmic scale, respectively. The data here were taken above the Es layer mentioned later, where electron density and temperature were rather stable. The electron temperature is calculated from the gradient of linear fitting to the electron retarding current region (Figure 1 (c)), while the electron density is calculated from its cross point with another linear

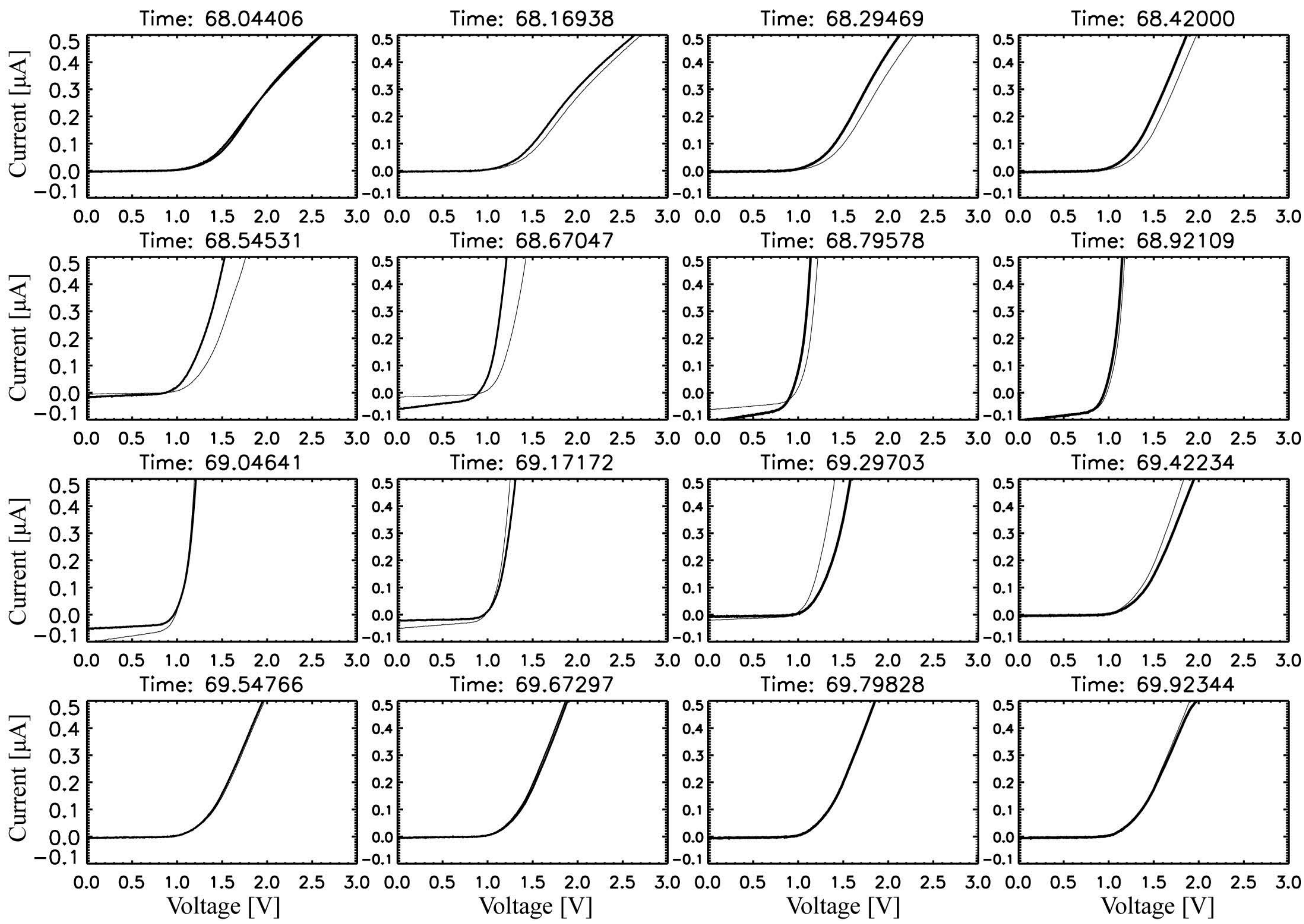

Fig. 2. Current-voltage characteristics inside Es layer during the upleg of the rocket flight. Thin line in Figure 2 represents the probe current during the sweep up from 0.0 to 3.0 V, while thick line indicates the current during the sweep down.

fitting to the saturation current region (Figure 1(c)). The electron temperature and density was estimated to be 773 K and 4.15×10^4 cm^{-3} for this example, respectively. Details of the conventional procedure deducing electron density and temperature are described elsewhere (e.g., Abe and Oyama, 2013).

3. NEW ANALYSIS METHOD USING SPLINE INTERPOLATION

3.1. Current-voltage curves inside the Es layer

The I-V curves obtaind at 68.044-69.923 second after the launch are shown in Figure 2. As already explained, a triangular voltage with an amplitude of 3.0 V and a period of 125 msec was applied to the FLP probe. Thin line in Figure 2 represents the probe current during the sweep up from 0.0 to 3.0 V, while thick line indicates the current during the sweep down. When electron density increases towards a peak of the electron density of the Es layer (68.169～68.921 second from the launch), the probe currents shown by a thin line during the sweep up are obviously smaller than the current by a thick line during the sweep down. However, this relationship became opposite from 69.046～69.422 second when the rocket was above the density peak in the Es layer.

In general, a difference between the sweep up and the down in the current is likely caused by a hysteresis effect related to the contamination on the probe surface. However, this is not the case because a pattern of the relationship is opposite between above and below the Es density peak. Instead, it is suggested that the difference in current is caused by the electron density variation during the sweep period. When the rocket approached the Es layer peak during the upleg, the current in the sweep down should be larger than that in the swep up. Similarly, the current in the sweep up should be larger than the sweep down when the rocket passed away from the peak. This reltionship is consistent with the the actual current variation during the sweep. Therefore, it is interpreted that such a change in the probe current is due to a rapid change of electron density in the Es layer.

This also suggests that the electron parameters were not constant even during a half period of the voltage sweep (62.5 msec) and that we cannot derive accurate electron parameters even with fast sweeping capability of the FLP. The conventional linear fitting to the retarding and saturation regions in Figure 2 does not work properly, since electron density may possibly change drastically even for a sweep up or down intervals. The

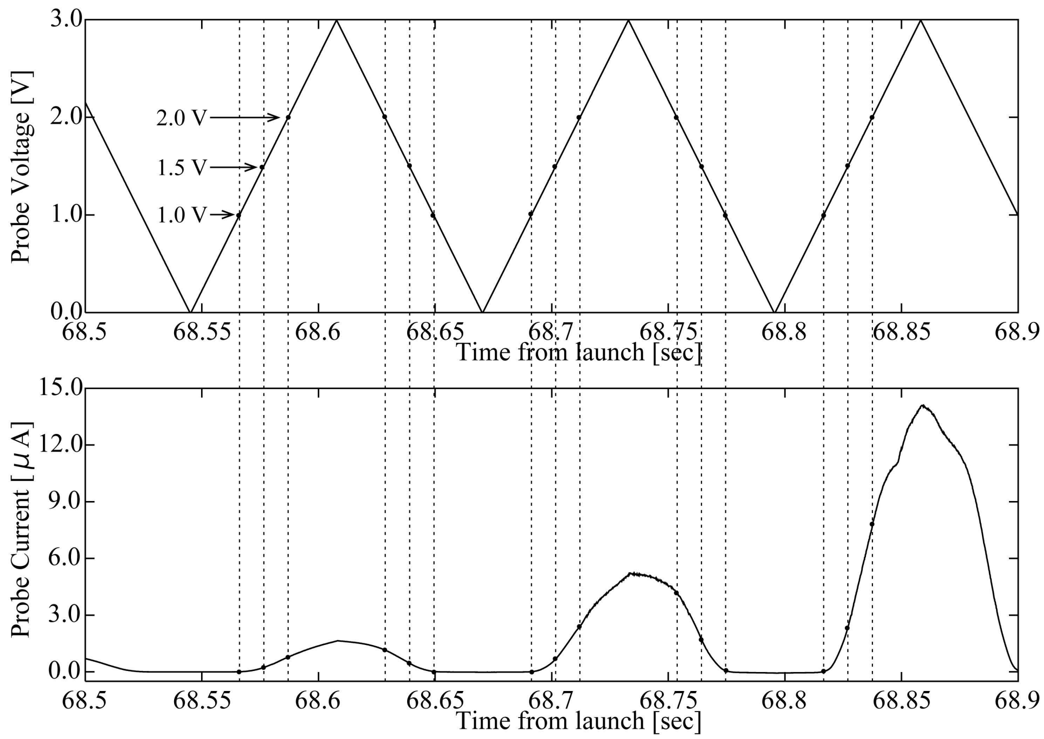

Fig. 3. Time variation of probe voltage (upper panel) and probe current (lower panel) when the rocket approached the center of the Es layer.

estimated electron density and temperature are largely affected and contain errors by a steep gradient of the electron density inside Es layers. Therefore, it is necessary to introduce an effective new method of analysis for such data.

3.2. New analysis method

In several current-voltage characteristics obtained by the FLP during this experiment, it was noted that a significant difference between the sweep up and the sweep down in the current-voltage characteristics was found, and this is likely related to the steep gradient of the electron density inside the Es layer. The same problem might possibly affect previous measurements of electron density and temperature in Es layers, which prevented us from revealing detailed structure and from discussing energetics in Es layers. In order to proceed our understanding further, we need to overcome the difficulty and to obtain accurate electron denisty and temperature in Es layers. We propose here a new analysis method which enables accurate estimation of the electron temperature and density, even when these parameters are rapidly changing.

Procedure of the method is as follows. First, we pick up the probe current in each voltage step from 0.0 to 3.0 V. In Figure 3, we show time sequence of probe voltage (upper panel) and probe current (lower) at three distict voltage steps; 1.0, 1.5 and 2.0 V, during 0.5 sec. Current values for the three voltage steps are shown as an example. The current value for a voltage step is increased as the rocket approached the center of the Es layer. Time variation of the probe current at each voltage step is then plotted by symbols in Figure 4. A fitted curve can be drawn by using 4-th order spline function for the current variation at each voltage step.

Finally, we can summarize the fitted curves of the current at any voltage between 0 and 3 V as shown in Figure 5. We can estimate the interpolated value of the probe current at each voltage step for any time from the fitted curves, which, in turn, means that we construct the instantaneous I-V curves for any time we want. Once accurate I-V curves are obtained, then we can apply the same method as described in the previous section for estimating electron temperature and density. Consequently, accurate electron temperature and density are deduced with a time resolution even higher than the voltage sweep period.

3.3. Electron density and temperature around the Es layser

The method was applied to the FLP data from 68 to 73 second (after the launch) where the Es layer was observed. Then, electron density and electron temperature were calculated from the relation of current and

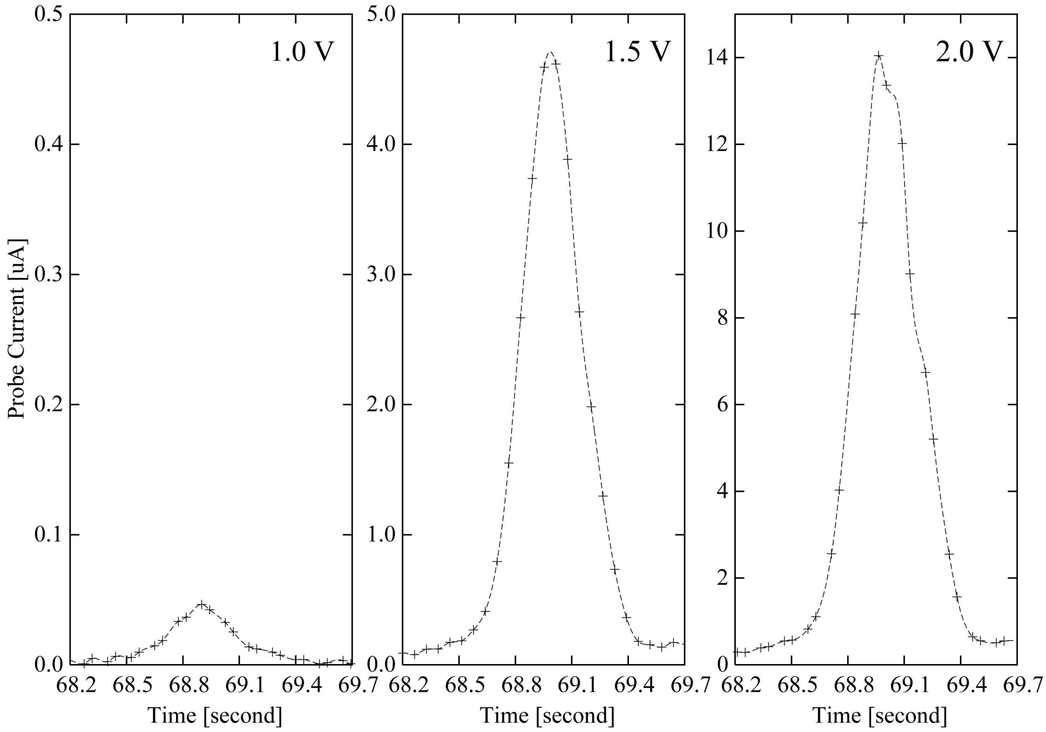

Fig. 4. Current variation at the three voltage steps (symbols) with interpolated curves.

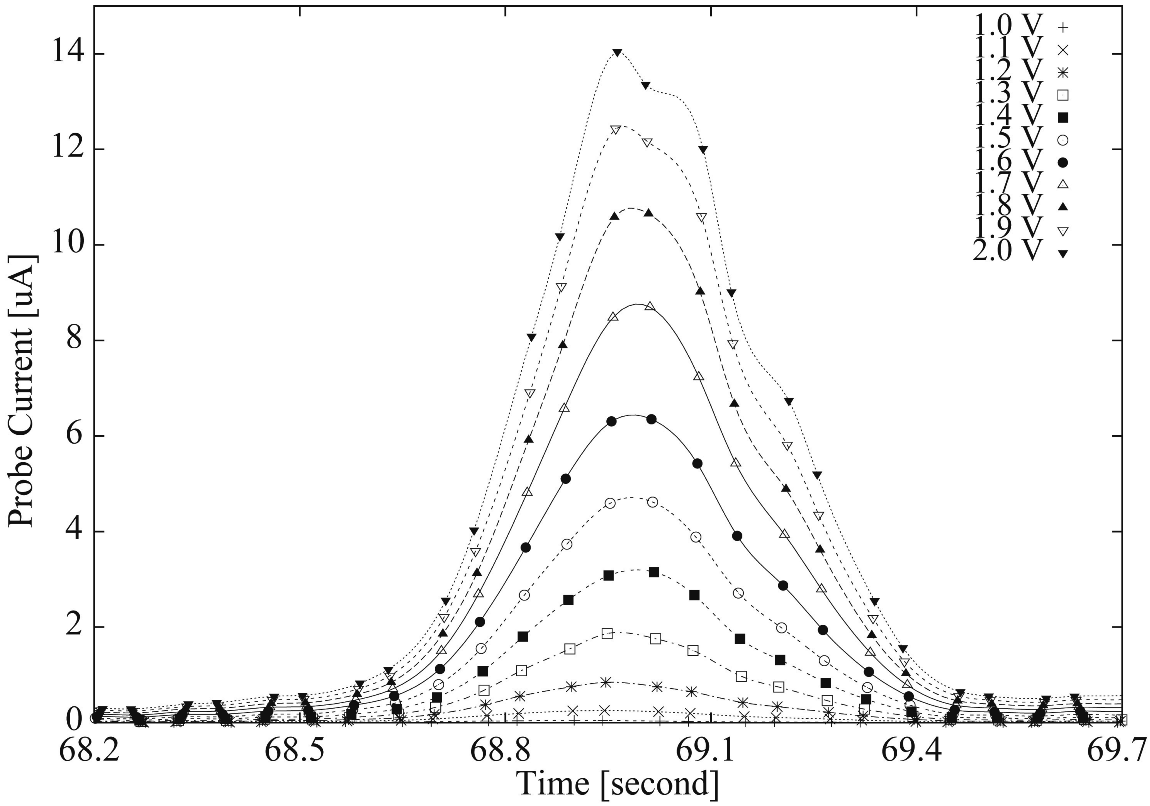

Fig. 5. Interpolated time variation of probe current at each voltage step for the time interval of the Es layer passage.

voltage in any time. Fig. 6 shows altitude profile of electron density and electron temperature by using the new method described above. A corrected I-V curve was made for every 10 msec, less than 64.5 msec, half of the sweep period. Each symbol in the figure represents 13-point running mean of the electron density and temperature.

The total thickness of the layer is estimated to be about 1 km. Furthermore, the detailed trend of the electron temperatures from its boundaries toward the center of Es layer was revealed so clearly owing to the new method. The maximum electron density of this Es layer is 9.7×10^5 cm^{-3}, and the minimum electron temperature is 550 K at an altitude of 98 km. If we employ the conventional fitting directly to the I-V curves in Figure 2, the maximum density and minimum temperature are estimated to be 1.15×10^6 cm^{-3} and 503 K, respectively. Deviation from those by the new method is obvious and the conventional method is not sufficient to discuss accurate energetics inside Es layers.

Although the detailed structure of the Es layer in Figure 6 is quite unprecidented, large-scale anti-correlation between electron temperature and density should be first noted. The overall anti-correlation is found not only in the Es layer but also between the upper and lower regions just outside of the Es layer. The temperature is about 900-1000 K at altitude of 96-97 km, whereas it is around 800 K at altitude of 99-100 km. On the other hand, the density is higher in the higher altitude region. Although the estimation accuracy for temperature is generally lower for low density region below 97 km, the difference between upper and lower regions surrounding the Es layer should be pointed out.

Another feature worth to note is that the derived electron temperature in the surrounding region is quite high. The MSIS model gives temperature of neutrals less than 500 K at the altitude range. The minimum electron temperature in the Es layer (i.e., 530 K) may be close to the neutral temperature, but difference in temperature between electrons and neutrals is quite significant at most of the region. The contamination of probe surface is known to cause higher temperature estimation (e. g., Hirao and Oyama, 1972). Our measurement, however, was carefully conducted to maintain the clean surface as described in the previous section.

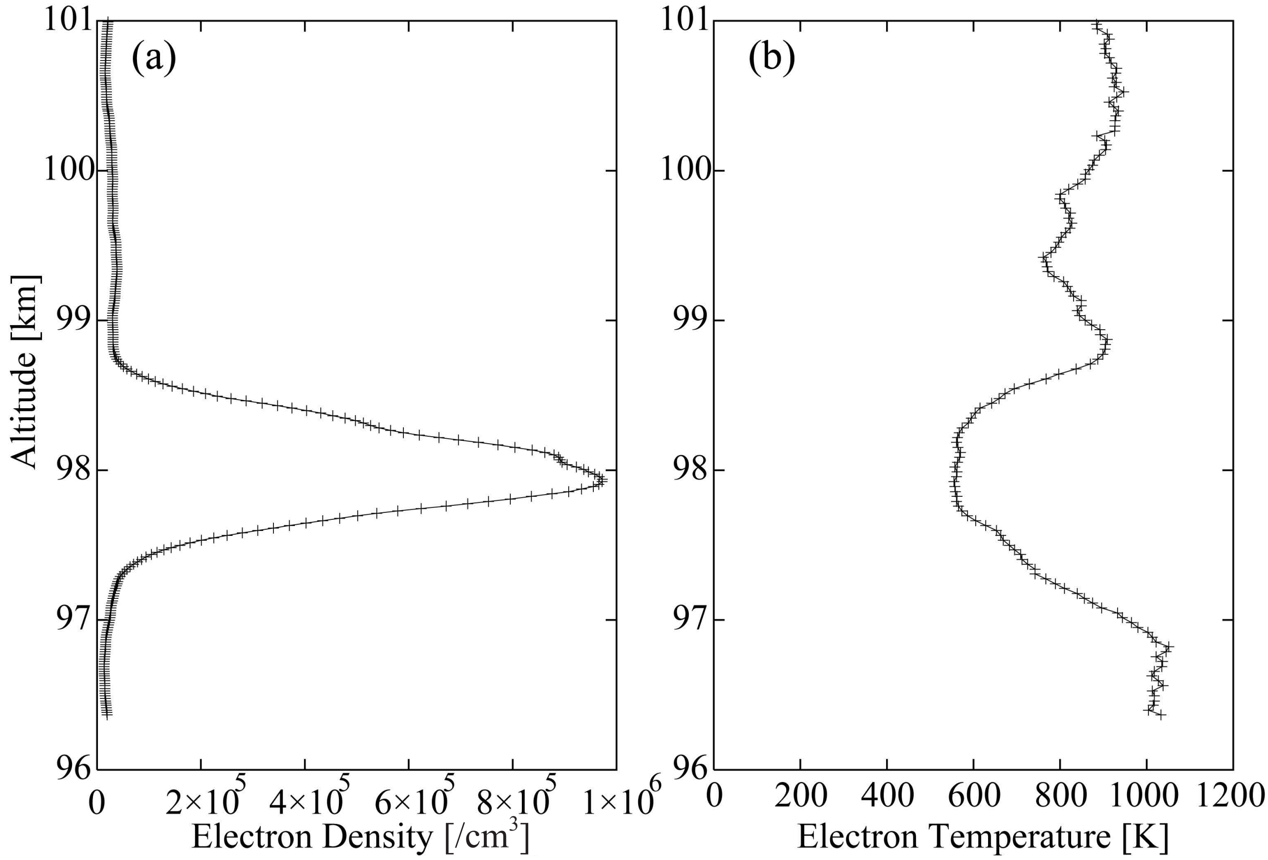

Fig. 6. Altitude profiles of electron density (a) and electron temperature (b) around the Es layer derived by the new analysis method.

4. DISCUSSION

We observed large depletion of electron temperature inside the Es layer, which is consistent to the recent and more reliable observations (i.e., Oyama et al., 2008a; Barjatya et al., 2013). Apart from decrease of electron temperature inside the Es layer, another consistent point with the previous measurements is high electron temperature around the Es layer. In general, high electron temperature in the E region has been sometimes observed (e.g., Oyama et al., 1980), and some possible heat sources are proposed. For example, Oyama (2000) mentioned a possibility that vibrationally excited nitrogen molecules give the energy to the ambient thermal electrons and electrons are heated. Oyama et al. (2008b) found that energy density of thermal electrons increases in the height range of 100-110 km and heat source is confined to the height region where Es layers appear. The heat source which raises ambient electron temperature higher than neutral temperature, however, is still not identified.

Barjatya et al., (2013) reported elevated electron temperature around twin Es layers and proposed frictional heating from parallel electric currents generated by F region nighttime dynamo as the possible heat source. Anti-correlation between electron density and temperature around the Es layers requires a heating mechanism in which ambient electron density acts only as a thermal capacitor. We should rule out any heating propotional to electron density, such as Joule heating in perpendicular electric field, which could lead high temperature in the high density Es layers.

By neglecting chemical reactions and viscous heating of electron gas, Sakamoto (2017) numerically solved electron energy equation for thermal equibrium (Schunk and Nagy, 1978)

$$\frac{\partial}{\partial z}\left(K^e \frac{\partial T_e}{\partial z}\right) + \sum Q_e - \sum L_e = 0 \quad (1)$$

where K^e is the electron thermal conductivity and $\sum Q_e$ and $\sum L_e$ are the sum of all the heating and cooling rates, and investigated effects of given density variation to vertical profile of electron temperature. The heat sources considered are photoelectron heating and Joule heating. The cooling mechanisms are of various interactions with ions and neutrals. The numerical calculation confirmed that the electron temperature tends to decrease in an Es layer, but expected amplitude of temparature variation was much smaller than the observation.

Sakamoto (2017) discussed dependence of heating and cooling rates on electron density in the Es layer. Most of the heating and cooling rates are almost proportional to the electron density. When the density is large, then the cooling rates can be large but the heating can be also large. This cancellation results in the small difference in electron temperature. In contrast, the electron cooling rate is almost propotional to the square of plasma density for the case of electron-ion interaction (Schunk and Nagy, 1978). If this process is dominant in the Es layer, the lower electron temperature may be explained by incremental of cooling rate larger than thermal capacitance which is proportional to the electron density. Furthermore, by assuming heating rates proportional to square root of electron density (i.e., less dependence on electron density), they successfully obtain a decrease of electron temperature by hundreds of K. The discussion on the heat source is basically on the same line of Barjatya et al., (2013) in which heating independent of ambient thermal electron density is considered.

Large-scale decrease of electron temperature at Es layer surrounded by high temperature region is probably explained by introducing heat source almost independent of themal electron density and cooling by electron-ion interaction more depending on electron density. However, detailed structure of electron density and temperature inside the Es layer suggets more processes involed. Our observation shows a steep peak of electron density whereas electron temperatute has a broad bottom (Figure 6), where simple anti-correlation is not exactly maintained. Our new result with a high spatial resolution raises more questions and shows that we need further study to understand the small-scale structure and processes acting inside Es layers.

5. SUMMARY

We found unusual current-voltage characteristics in the FLP measurement inside Es layer during S-520-29 sounding rocket flight. It can be understood that such characteristics are caused by a significant gradient of the electron density inside the sporadic E layer. We suggest a new analysis method to enable us to estimate accurately the electron temperature and density in such a case, even when electron density is rapidly changed. It becomes possible to obtain the temperature and density in a shorter time interval than the voltage sweep period by adopting a new method of interpolation for obtained current-voltage relationship.

We found Es layer embedded in a high electron temperature region. The maximum electron density and the minimum electron temperature observed inside Es layer are estimed to be 9.7×10^5 cm^{-3} and 550 K, respectively, at an altitude of 98 km. The total thickness of the layer is about 1 km. Furthermore, the detailed trend of the electron temperature from its boundary toward the center of Es layer was revealed owing to the interpolation.

Low electron temperature inside the Es layer is consistent with the recent observations, and physical implication of the low temperature is discussed in terms of heat sources and cooling processes. We conclude that any heat sources less dependent on electron density and cooling by electron-ion interaction more dependent on electron density can be the candidate processes which explain the lower electron temperature in the Es layer, though we should also point out that more processes are involved to create fine structures inside Es layers, which are open for future studies.

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