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ABSTRACT

This paper describes the phenomenon of the midlatitude red arc of September 29, 1967, through observations of the properties of the ionospheric plasma. The ion and electron temperatures, ion composition and density, and suprathermal electron flux during this period are measured by retarding potential analyzers near 900 km from OGO IV and near 2000 km from Explorer 31. These parameters show the following changes in the region L=2.3 to L=3.0 during the red arc period as compared to their values during normal periods: (1) Electron and ion temperatures increase to above 4000 °K from a normal value of 2000 °K at 900 km, while at 2000 km electron temperature increases to above 5000 °K from a normal value of 2500 °K; (2) at 900 km the ratio of $O^+/(H^+ + He^+)$ changes from 1 to 5 while the total density remains approximately the same; (3) at 2000 km the ion density decreases by a factor of 10 with the composition remaining all H^+; (4) there is no significant increase in the flux of 5-10 ev electrons. The relative importance of electric field heating, magnetospheric conduction and the changes in the neutral composition in the lower atmosphere are examined in the light of these observations. It is concluded that the SARARC is caused by a combination of thermal conduction of energy from the magnetosphere and changes in the neutral composition in the lower atmosphere.

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INTRODUCTION

Recent measurements of electron temperatures in the region of sub auroral red arcs (SARARC) have given direct support to the concept that the arc is produced primarily by the thermal excitation of atomic oxygen (Norton and Findlay, 1969). The understanding of the mechanism for exciting the SARARC is therefore related to the understanding of the mechanism for heating the ambient plasma. A number of mechanisms have been proposed in recent years for heating the electron gas. These are (1) a d.c. electric field (Megill, Rees and Droppleman; 1963), (2) a precipitating flux of low energy electrons (Dalgarno, 1964), and (3) the thermal conduction of energy from the magnetosphere in the ionosphere along the geomagnetic field lines (Cole, 1965). Walker and Rees (1968) have investigated the relative merits of the three processes in raising electron temperature to the point of exciting the red arc. They concluded that all of them satisfied the necessary criteria as far as their ability to heat the ambient plasma was concerned. However, the physical constraints imposed by each one of them on the ionospheric plasma were different. For example, an electric field of the order of 0.1~0.2 v/m orthogonal to the earth's magnetic field would produce the observed luminosity of the arc but this would also raise the ion temperature to about 5000° K in the altitude range of 200 km. The low energy electron or suprathermal electron hypothesis requires a flux of more than 10^9 electrons cm^{-2} sec^{-1} with energies of about 15 ev. The thermal conduction hypothesis, on the other hand, requires the electron temperature above 1000 km to be at least 5000° K with a positive gradient of about 2.5° K/km. It is obvious, therefore, that the choice of any particular hypothesis would be easy if the relevant ionospheric parameters could be measured during the SARARC condition. The purpose of this paper is to present the result of such measurements during the SARARC period of Sept. 28-29, 1967 and discuss the merits of the three hypothesis outlined here in the light of these observations.

Discussion of the Observational Data

The SARARC of Sept. 28-29 was observed photometrically from ground based airglow observatories (Hoch, Marovich and Clark, 1968; Ichakawa and Kim, 1969) and by photometers aboard the OGO 4 satellite (Reed and Blamont, 1968). The photometers observed the arc in both hemispheres in the region L=2 to L=3. OGO 4 also had aboard it a planar trap capable of measuring electron and ion temperature and the integrated flux of the suprathermal electrons (E > 5 ev) and thus afforded an excellent opportunity of making simultaneous measurements of both the airglow intensity and the ionospheric parameters. In addition, Explorer 31, which also had aboard it a planar trap, passed over the arc region and provided information about the ionospheric parameters.

The design of the traps and the orbital characteristics of the two satellites have been described elsewhere (Chandra, Troy, Donley and Bourdeau, 1970; Donley 1969) and will not be repeated here. The traps on the two satellites were similar and therefore the data obtained from them were compatible. However, their orbital characteristics were different and therefore they provided measurements in the different altitude regions of the arc. This turned out to be of considerable advantage because it was possible for the first time to obtain an estimate of the temperature gradients in the arc region - information most vitally needed to test the validity of the thermal conduction hypothesis.

Figure 1 shows the belt of the arc as mapped by the groundbased airglow observatories on the night of September 28-29, 1967. Also shown are the positions of OGO 4 and Explorer 31 for which the data from the plasma traps were available in the arc region on the same night. On one pass the Explorer 31 data was taken in the southern hemisphere; the data region is shown in its conjugate northern hemisphere position in Figure 1.

The variations in electron and ion temperatures with L parameters as obtained from OGO 4 are shown in Figure 2. The upper part of the figure shows the temperature variations for the night of Sept. 29 when the SARARC occurred. For comparing the characteristics of these variations with a non arc and magnetically quiet night, we have plotted the electron and ion temperature for the night of Sept. 23, 1967 in the lower part of Figure 2. To facilitate the comparison between the various passes, we have indicated at the top of the figure their date, the universal time,(U.T.), the altitude in kilometers, the longitude and the local time. Thus all the measurements correspond to approximately the same local time (about midnight) even though the satellite was in different geographical locations at the time of these measurements. The inference from this figure is quite obvious, i.e., compared to a non arc night both the electron and ion temperatures in the region between L=2.5 - 3 have risen dramatically from a value of about 2000° K to about 4000° K. In both the cases the electron and ion temperatures are not different significantly from each other and for all practical purposes, a thermodynamic equilibrium within the plasma is maintained. The electron and ion temperatures from Explorer 31 are shown in Figure 3. Following the pattern of Figure 2, the temperature for the arc night is plotted in the upper part and for the non arc (magnetically quiet) nights in the lower part. The inference of this plot is very similar to that obtained from Figure 2, i.e., compared to a non arc night the plasma temperatures have risen from about 2500° K to about 5000-6000° K in the arc region. This figure also suggests an indication of the positive temperature gradient. The temperature in the arc region corresponding to the pass of 14:57 UT is about 1000° K higher than the one corresponding to 09:21 UT. Since both the measurements approximately correspond to the same local time and their altitudes are respectively 3000 km and 2100 km, it is reasonable to infer a temperature gradient of about 1° K/km. The evidence for a positive temperature gradient is much stronger when these measurements are compared with those of Figure 2 which also correspond to about the same local time. The temperature at about 900 km inferred from Figure 2 is about 4000° K. Comparing this with the measurements of Explorer 31, we again infer a temperature gradient of about 1°K/km.

Since the groundbased observations placed the maximum intensity of the arc at an altitude of 400 km (Hoch, Marovich, and Clark, 1968) it is interesting to project the positions of our satellite arc measurements (made at 900 - 3000 km altitude) down along the field lines to the lower altitude. These projections are shown in Figure 1, alongside the actual positions. Notice that the projected high temperature positions from two of the satellite observations fall within the groundbased observation region. If this same region were extrapolated or extended to the west, it might well contain the projected high temperature positions from the other two satellite observations. Therefore, our data indicates the existence of a rather narrow, field-aligned high temperature region, with a positive temperature gradient of 1° K/km and with its base in the region of maximum observed 6300 Å intensity.

Even though the knowledge of ion composition has not been considered to be important from the point of view of producing an arc by thermal excitation,we shall argue later that this fills a significant gap in our understanding of the physical processes responsible for exciting the SARARC. Another important parameter which we must measure is the flux of the suprathermal electrons to estimate its contribution in exciting an arc. Figure 4 shows such measurements as obtained from OGO 4. The upper and the middle part of the figure show the ion composition for the arc and the non arc night and the lower part shows the corresponding changes in the flux of the suprathermal electrons. These measurements clearly indicate that in the region between L = 2 to L = 3, the major constituent during the arc condition is O^+, followed by H^+ and He^+. In the non arc condition the situation is reversed. The major constituents are H^+ and He^+ with O^+ as a minor constituent. With the increasing value of L, O^+ increases with a corresponding decrease in H^+ and He^+. Finally, in the auroral region and beyond (L > 3) O^+ becomes a dominant constituent. In spite of the changes in the relative concentrations of O^+, He^+ and H^+ in the arc and the non arc condition the total electron density in the 900 km region substantially remains the same in the two conditions. Also there is no change in the flux of the suprathermal electrons in the two cases as seen from the lower most part of Figure 4.

Figure 5 shows the variation in electron density and the flux of suprathermal electrons in the altitude range of 2000 km as measured from Explorer 31. The only ionic constituent which could be measured in this altitude range is H^+ and its variation is therefore analogous to electron density variations. The density variations for the arc (Sept. 29 passes) and the non arc (Sept. 20 and 23 passes) are shown in the upper part of the figure and the corresponding changes in the flux of the suprathermal electrons are shown in the lower part of the figure. The figure clearly shows that the electron density in the arc condition has decreased considerably, sometimes as much as a factor of ten. There is no indication that the flux of the suprathermal electrons has changed in the two conditions except in the auroral region.

Concluding Remarks

On the basis of the observational data on electron temperature and the flux of suprathermal electrons presented in this paper, it is clear that we will have to accept the thermal conduction hypothesis proposed by Cole (1965) as the mechanism for heating the ambient plasma during the SARARC condition. In the absence of any significant increase in the flux of suprathermal electrons, we have to rule out the soft electron hypothesis from consideration. An electric field can heat the ambient plasma to the temperature required to produce the observed emission in 6300 Å line. However, it can not produce the positive temperature gradient as we infer from these measurements. There is an additional difficulty in accepting the electric field hypothesis - the problem of maintaining such a large d.c. field over a long period of time. An electric field of the order of 0.1 - 0.2 v/m which is needed for maintaining the SARARC should also produce a vertical drift of the order of 1 ~ 2 km/sec in this region. A drift of this magnitude will simply blow the ionosphere out of existence in a few hours.

If thermal conduction is really the mechanism for exciting SARARC, we may ask why this phenomenon is so rare! Why is every storm not accompanied by a SARARC? Roble, Hays and Nagy (1970) have provided some clue to this question. From the theoretical study of the SARARC event of Sept. 28-29, 1967 they concluded that in order to increase electron temperature to over 5000° K in the altitude range of 2000 km, the thermal energy flowing into the ionosphere should be of the order of 10^{10} ev cm^{-2} sec^{-1}. They noted, however, that this is not a sufficient condition for exciting an arc unless a sufficiently high temperature can also be maintained in the altitude range of 400 km. This is the region where most of the emission takes place through collisional excitation of atomic oxygen. In order to maintain a higher temperature, it is necessary to reduce the ion density in this region to prevent the heat loss through coulomb collision. Roble et al. (1970) noted from their theoretical calculations that there were two distinct regions, one at 50.5° and another at 52.5° invariant latitude, where the heat flux was sufficiently high to give rise to the arc condition. However, the arc was produced only at 52.5° latitude where the electron density was sufficiently low. Thus the understanding of the SARARC not only depends upon the understanding of the mechanism for heating the electron gas but also on the understanding of the mechanism which produces the depression in electron density in the arc region.

But does the depression take place at all the latitudes in the arc region? Density measurements from Alouette I and II (Norton and Findlay, 1969) for the arc of Sept. 28 - 29 indicate that this is not the case. The depression in electron density takes place only near the height of the F_2-maximum and in the altitude range of 2000 km. In the altitude range of 1000 km there was no significant change. From the measurements of ion composition reported in this paper we find ourselves to be in substantial agreement with this conclusion. At 900 km, in the altitude range of OGO 4, we only see a change in ion composition, indicating a transition from the light ions (H, He^+) to the heavy ions (O^+). There is no appreciable change in the total electron density. In the altitude region of 2000 km Explorer 31 measures considerable reduction in the ion density in agreement with Alouette II measurements.

The changes in ion composition during the arc of Sept. 28 - 29 are characteristic of the storm time changes usually observed in these latitudes. By solving a system of basic ionospheric and atmospheric equations, Chandra and Herman (1969) and Chandra and Stubbe (1970) showed that the ion composition changes observed during geomagnetic storms result primarily from the changes in the neutral composition in the lower atmosphere or more specifically from the decreases in $[O]/[N_2]$. It was shown in these papers that a decrease in $[O]/[N_2]$ not only produces a depression in electron density, but also an increase in electron, ion and neutral gas temperatures. The relative changes in these parameters compared to an undisturbed ionosphere depended exclusively on the extent of variation in $[O]/[N_2]$ at the lower boundary. Such changes could not be affected by the thermal conduction process. By increasing the heat flux in 1000 - 1500 km, one can only increase the electron temperature and increase the transition height. It has a negligible effect on the electron density distribution near the F_2-peak. The ion composition in the altitude range up to 400 km can be affected only by the changes in $[O]/[N_2]$ in the lower atmosphere. No specific explanation has been given for the change in neutral composition but it is reasonable to believe that the change in circulation pattern in the lower atmosphere caused by the Joule dissipation of the ionospheric current may provide the necessary mechanism. It should be noted here that the hypothesis for the Joule dissipation was also advanced by Cole (1962).

From the foregoing discussion we should like to conclude that the occurence of SARARC events, even though uncommon, does not signify a new physical mechanism. It can be explained within the framework of the two processes,i.e.,the thermal conduction and the Joule dissipation which provide the principal mechanisms for transferring energy from the magnetosphere to the ionosphere during geomagnetic storms. The decrease in electron density combined with the heat flow from above may sometimes give rise to an excessive temperature for electrons causing the thermal excitation of atomic oxygen which is responsible for production of the SARARC.

Figure Captions

Figure 1. Position of the 29 September 1967 red arc, as observed optically from the ground (Hoch, Marovich, and Clark, 1968) and by planar traps on the satellites Explorer 31 and OGO 4. Also shown are the satellite trajectories, including the measured high temperature regions, projected down the field lines to an altitude of 400 km.

Figure 2. Ion and electron temperatures from OGO 4 for two passes through the red arc region on 29 September 1967 (upper curves), and for one pass through the same latitudes during a magnetically quiet period six days earlier (lower curves).

Figure 3. Ion and electron temperatures from Explorer 31 for two passes through the red arc region on 29 September 1967 (upper curves), and electron temperatures for two passes through the same latitudes on earlier days (lower curves).

Figure 4. Positive ion composition and densities from OGO 4 for one pass through the red arc region on 29 September 1967 (upper curves) and through the same latitudes during a magnetically quiet period six days earlier (middle curves). The lower curves show the suprathermal electron fluxes for the same two days.

Figure 5. Electron densities from Explorer 31 for two passes through the red arc region on 29 September 1967 and for two passes through the same latitudes on previous days (upper curves). The lower curves show the suprathermal electron flux for the same four passes.

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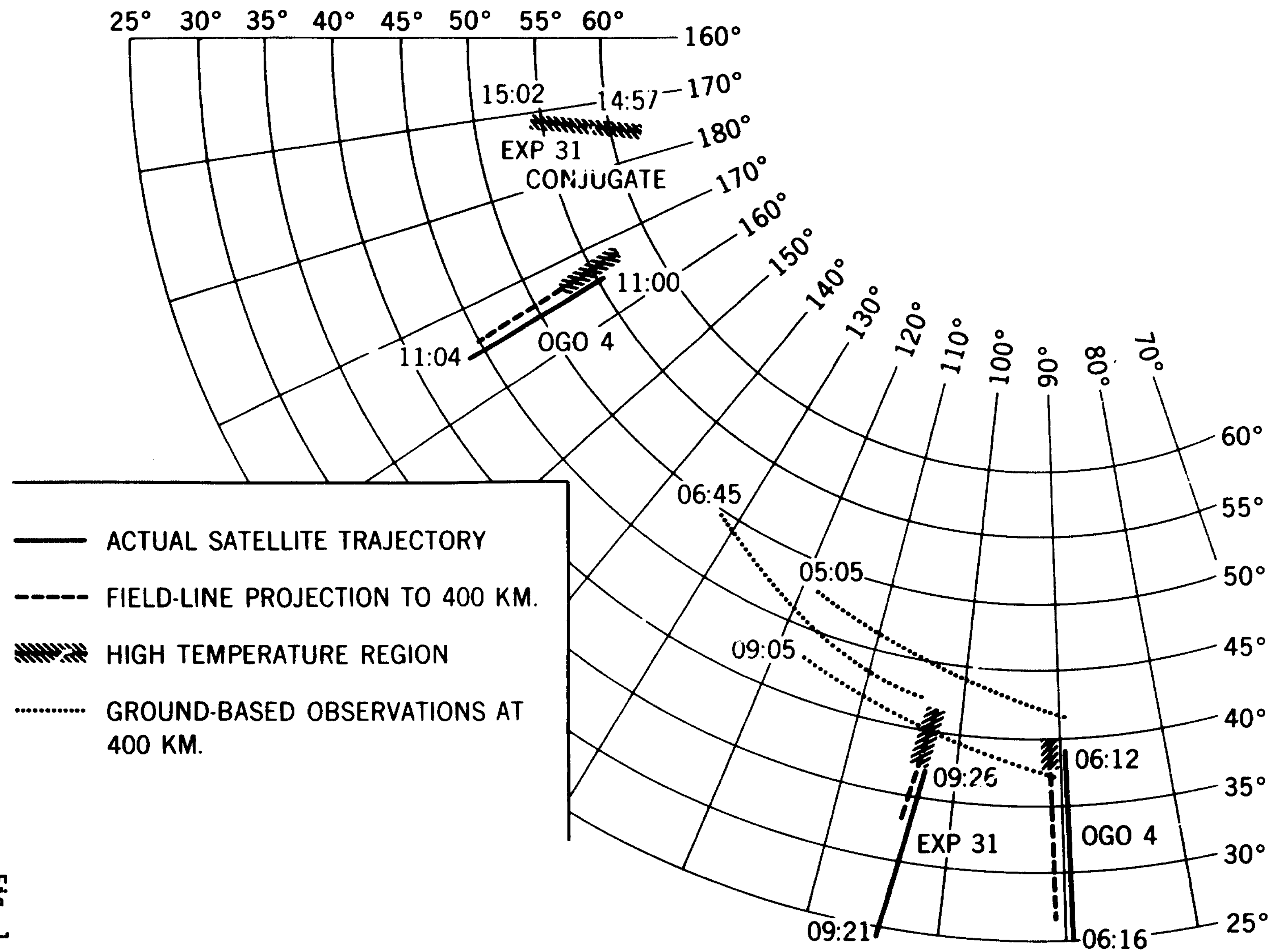
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100°
90°
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70°
60°
55°
50°
45°
40°
35°
30°
25°
15:02
14:57
EXP 31
CONJUGATE
11:00
11:04
OGO 4
06:45
05:05
09:05
09:26
06:12
EXP 31
OGO 4
09:21
06:16
ACTUAL SATELLITE TRAJECTORY
FIELD-LINE PROJECTION TO 400 KM.
HIGH TEMPERATURE REGION
GROUND-BASED OBSERVATIONS AT 400 KM.

Fig. 1

DATE	U.T.	ALT.(KM)	LONG.	L.T.
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29 SEPT.	06:15	865	−90°	00:12
29 SEPT.	11:02	890	−165°	00:02

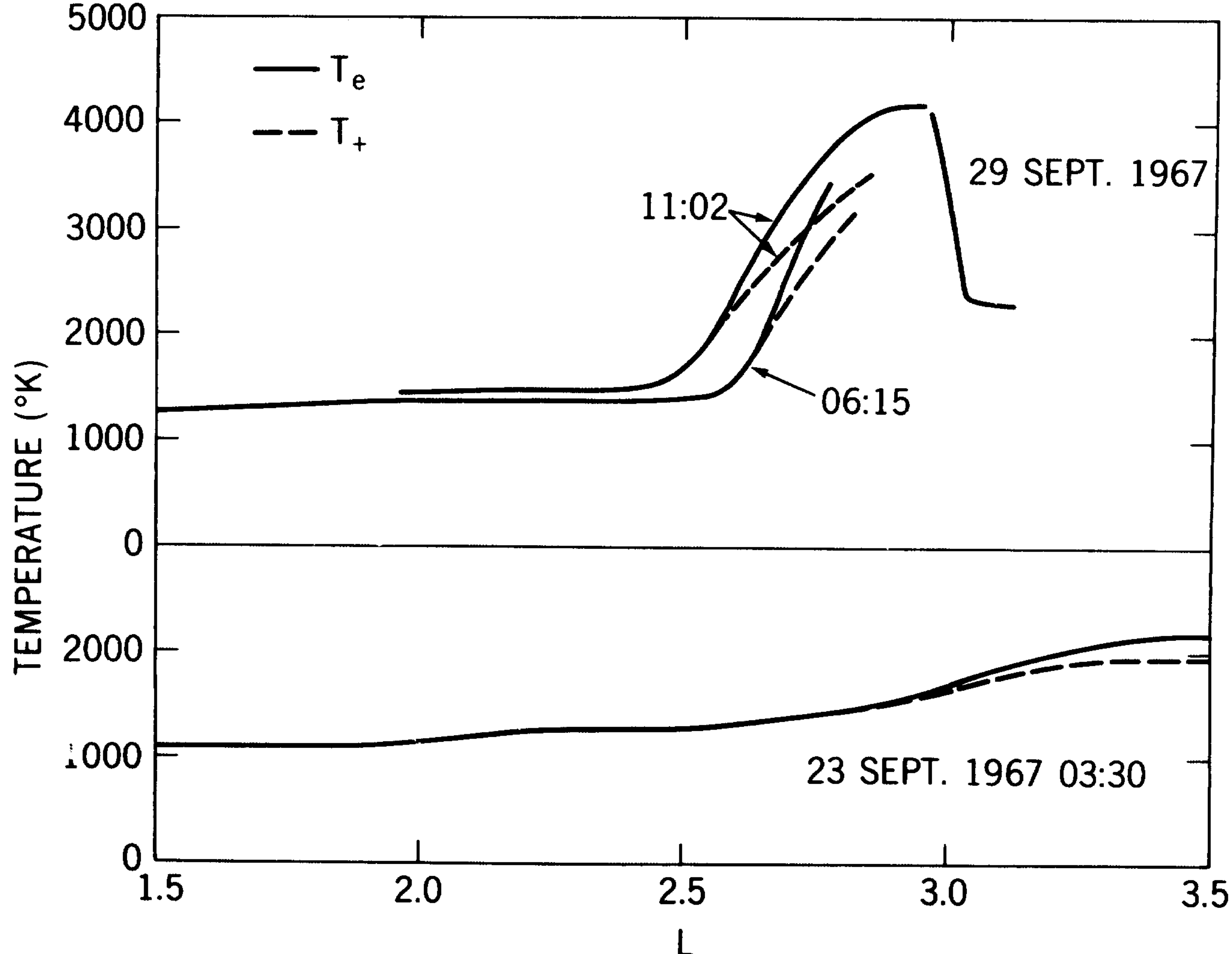

Fig. 2

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23 SEPT.	07:38	2300	−68°	03:00

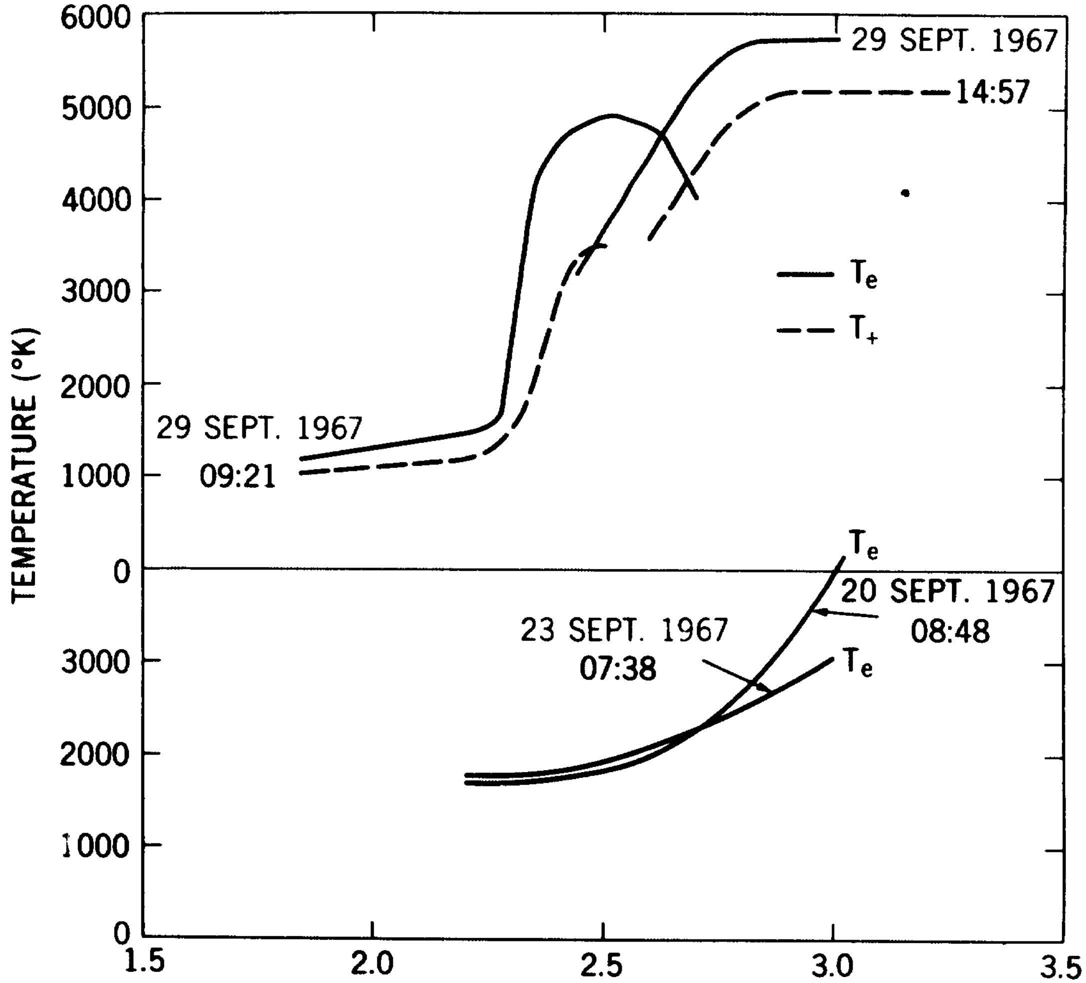
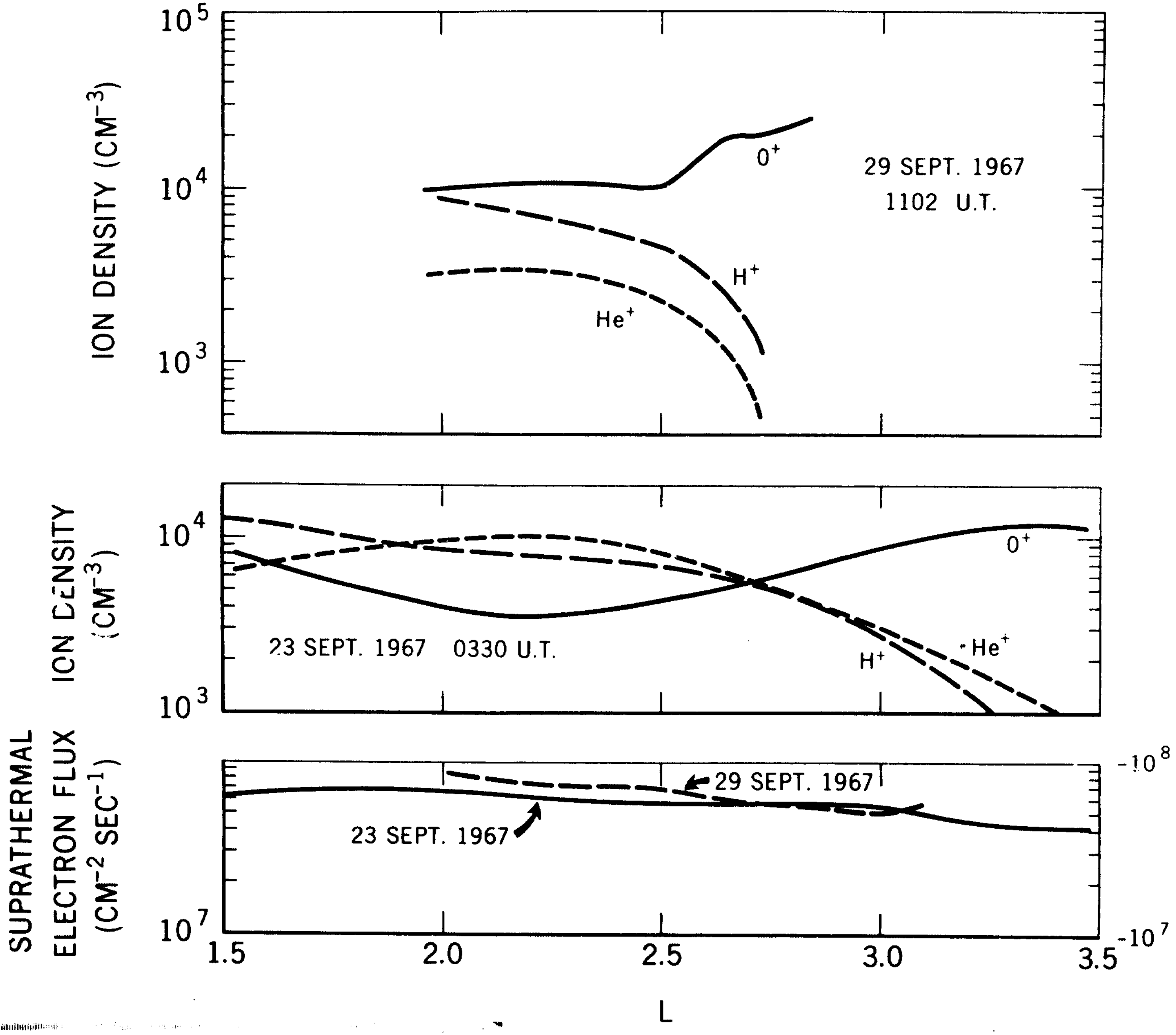


Fig. 3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29 SEPT. 1967
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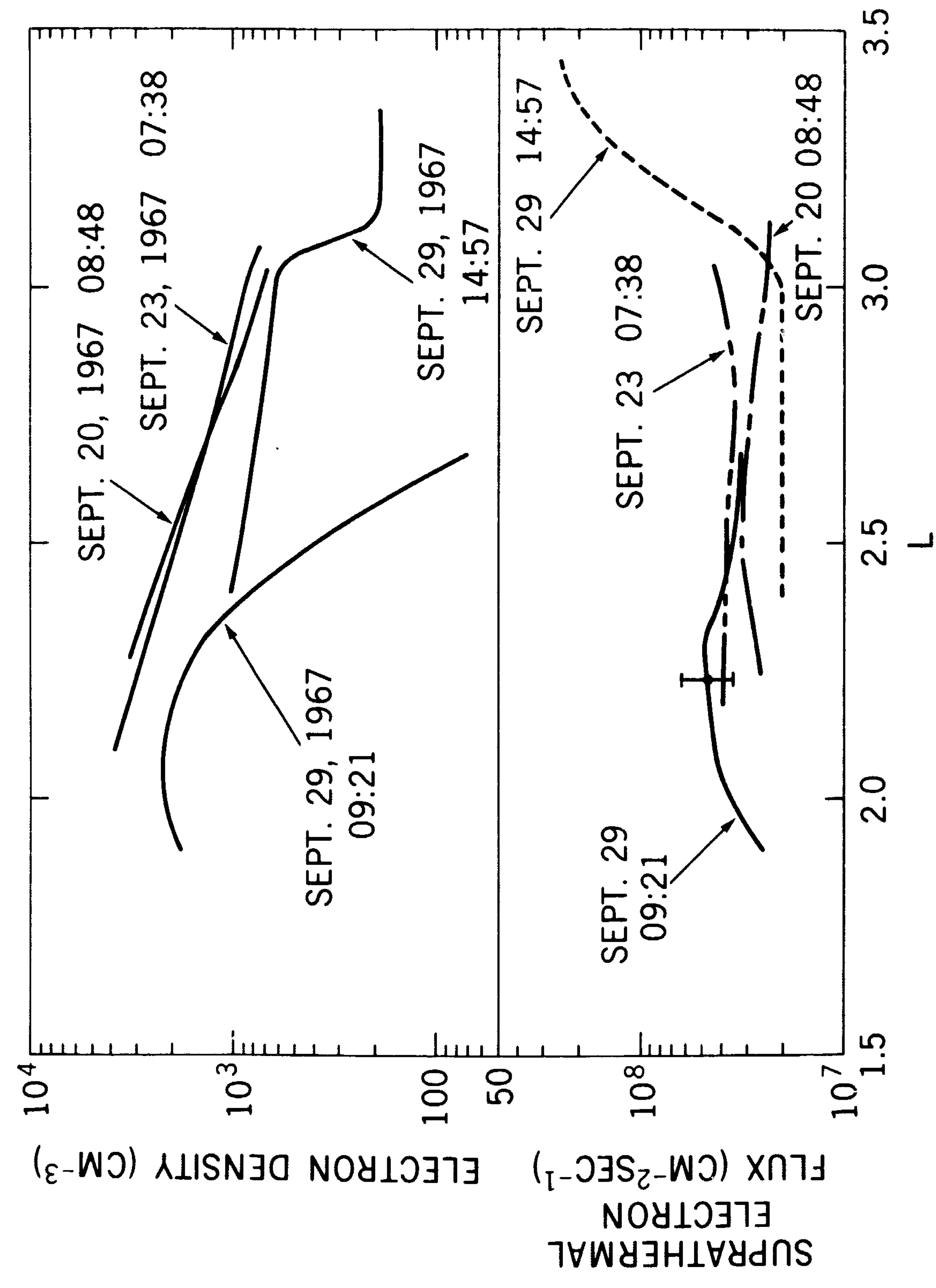
H+
He+
ION DENSITY
(CM-3)
23 SEPT. 1967 0330 U.T.
SUPRATHERMAL
ELECTRON FLUX
(CM-2 SEC-1)
29 SEPT. 1967
23 SEPT. 1967
10^5
10^4
10^3
10^7
10^8
1.5
2.0
2.5
3.0
3.5
L

Fig. 4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SUPRATHERMAL ELECTRON FLUX (CM-2SEC-1)
L
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SEPT. 23, 1967 07:38
SEPT. 29, 1967 14:57
SEPT. 29, 1967 09:21
SEPT. 29 14:57
SEPT. 20 08:48
SEPT. 23 07:38
SEPT. 29 09:21

Fig. 5