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THERMAL PLASMA MEASUREMENTS
WITHIN THE MAGNETOSPHERE

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GODDARD SPACE FLIGHT CENTER —
GREENBELT, MARYLAND

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ABSTRACT

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It has been observed that both the ion and electron components of the plasma present within the magnetosphere exhibit, at most times, a Maxwell-Boltzmann energy distribution. The temperature of the electron gas increases by a factor of about 10 from above the ionosphere to an altitude of 2.5×10^4 km ($5R_E$ geocentric). Over this same region, the density decreases to a minimum of about 50 cm^{-3}. Less pronounced variations of temperature and density with radial distance are noted beyond $5R_E$.

The simultaneous observation of ion and electron density profiles provides verification of charge neutrality over vertical dimensions of the order of kilometers.

Author

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INTRODUCTION

The satellite IMP-II was launched on 4 October, 1964, into an elliptical orbit with a period of 36 hours. The initial perigee was 200 km and the apogee was 95,000 km ($15.9R_E$ geocentric).

Figure 1 is a polar plot of the IMP-II orbit as seen in geographic latitude and earth radii (R_E) coordinates. At launch the apogee was 20° below the ecliptic plane, with the sun-earth payload angle (LSEP) of 11°. This orbit has offered a good opportunity to investigate the magnetosphere on the dayside of earth near the equatorial plane.

On-board IMP-II was a retarding potential analyzer, which measured the integral spectrum of ions and electrons in the energy interval from 0 to 45 eV. The details of this experiment have been discussed elsewhere, [1]. Briefly stated, the experiment consists of performing a measurement of the collector current as a function of retarding potentials. The retarding potentials used in the measurement are programmed as indicated in Figure 2. The voltage program defines the electron, ion, and net current modes. The electrometer polarity is programmed to give an analog output from 0 to 5 volts for negative currents during the electron mode. The electrometer polarity is then reversed in order to measure only positive currents during the ion mode. The effective aperture area of the Faraday cup sensor is 5 cm^2. Particles within an acceptance cone of 170° are accelerated through the aperture and subsequently collected. Photoemission currents from the collector have been successfully suppressed during the electron mode and the 45 volt ion mode. Photoemission currents from the suppressor grid can, however, reach the collector and must be accounted for in the analysis.

RESULTS

In Figure 3 are plotted two retardation curves obtained on 27 March 1965 while IMP-II was in the nightside magnetosphere on an inbound orbit at a distance between 3.9 and 3.4R_E. Shown on the left is the negative current response plotted on a log scale as a function of the retarding potential in volts in the interval from +5 to -45 volts. The dots and crosses represent two individual curves which were obtained
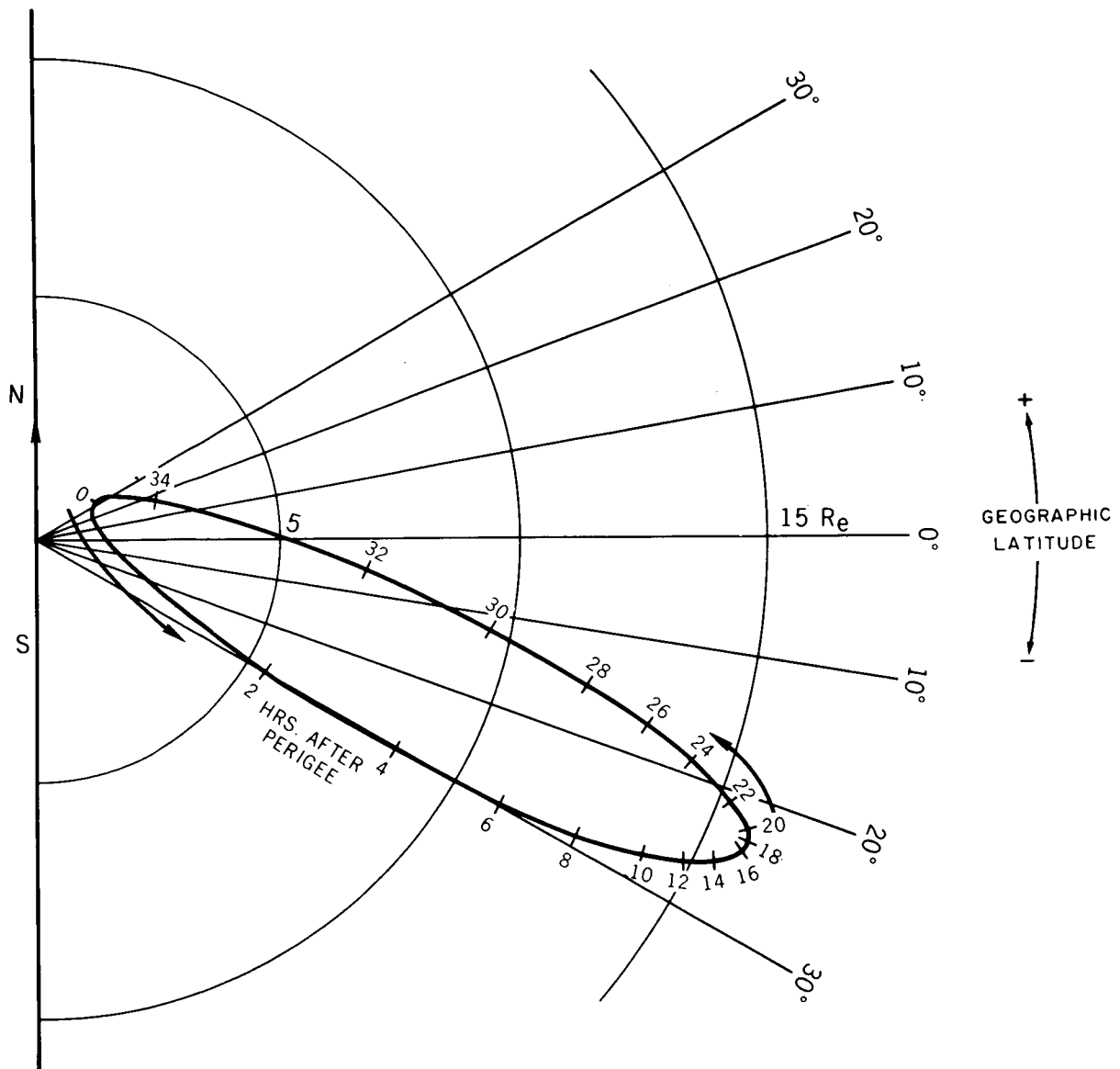
Figure 1. A view of the latitudinal excursion of the IMP-II spacecraft. IMP-II was launched with the line of apsides extending toward the sun, but inclined about -20° to the ecliptic.

sequentially within 11 minutes of each other, during this time interval the satellite traversed $0.3R_E$. The arrow in the figure at -35 volts indicates that at this time the plane containing the sun-payload vector was normal to the sensor. The measurements made to within ±85° of the sun contain photoemission currents from the suppressor grid and a correction for this current component should be made on the five data points, symmetric about the sun vector arrow.

IMP-B
RETARDING POTENTIAL ANALYSER

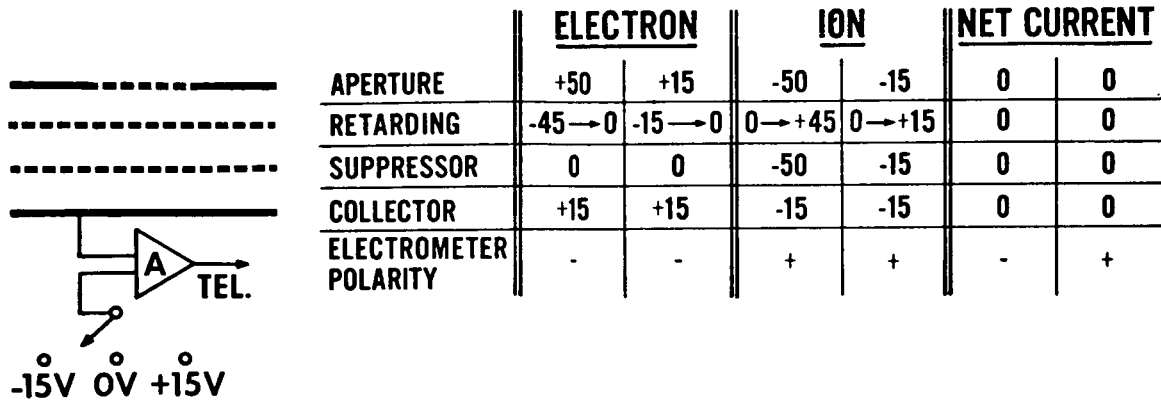|	ELECTRON		ION		NET CURRENT	
APERTURE	+50	+15	-50	-15	0	0
RETARDING	-45→0	-15→0	0→+45	0→+15	0	0
SUPPRESSOR	0	0	-50	-15	0	0
COLLECTOR	+15	+15	-15	-15	0	0
ELECTROMETER POLARITY	-	-	+	+	-	+

-15V 0V +15V

Figure 2. Schematic representation of the sensor and the experiment voltage program.

The wave form of the current response as a function of retarding potential in the interval from +5 to -10 volts can be analyzed in accordance with the Langmuir probe theory for the collection of diffusive currents, which are due to a plasma component having a Maxwell-Boltzmann distribution of velocities. Using this analysis procedure, the electron temperature as measured from the slope of the curve is 3.2 ± 0.2 eV at $3.9R_E$ and 2.5 ± 0.2 eV at $3.6R_E$.

We have observed, in the dayside magnetosphere, on selected days [1] that a well ordered electron temperature structure is present independent of the LSEP angle. For example, in the region from 2 to $5R_E$ the electron temperature increases from 0.3 eV at $2R_E$ to 1.6 eV at $5R_E$. The temperature increase over this region as a function of radial distance can be expressed as $T_e \propto R_e^{+1.9}$. A less pronounced temperature increase is noted at distances beyond $5R_E$.

The data for 27 March 1965 was obtained in the nightside magnetosphere, LSEP ~ 190°. These nightside electron temperature values are about a factor of 3 higher than the corresponding values taken from the dayside temperature profile. Whether spatial or temporal variations are involved cannot be resolved on the basis of these isolated temperature measurements. The 27 March 1965 data, Figures 3 and 4, have been selected to illustrate in detail how electron and ion curves are analyzed; we will be discussing additional data obtained in the dayside magnetosphere.

3

IMP II
27 MARCH,1965

TIME	DISTANCE	T_E	N_E	T_I	N_I
● 21:35	3.9 R_E	3.2 EV	130 CM^{-3}		
✕ 21:46	3.6 R_E	2.5 EV	210 CM^{-3}		
● 21:40	3.7 R_E			2.5 EV	270 CM^{-3}
✕ 21:51	3.4 R_E			2.5 EV	380 CM^{-3}

POSITIVE CURRENT (AMPERES)

10^{-8} 10^{-9} 10^{-10} 10^{-11}

NEGATIVE CURRENT (AMPERES)

10^{-7} 10^{-8} 10^{-9} 10^{-10}

RETARDING POTENTIAL (VOLTS)

−5 0 +5 +15 +25 +35 +40
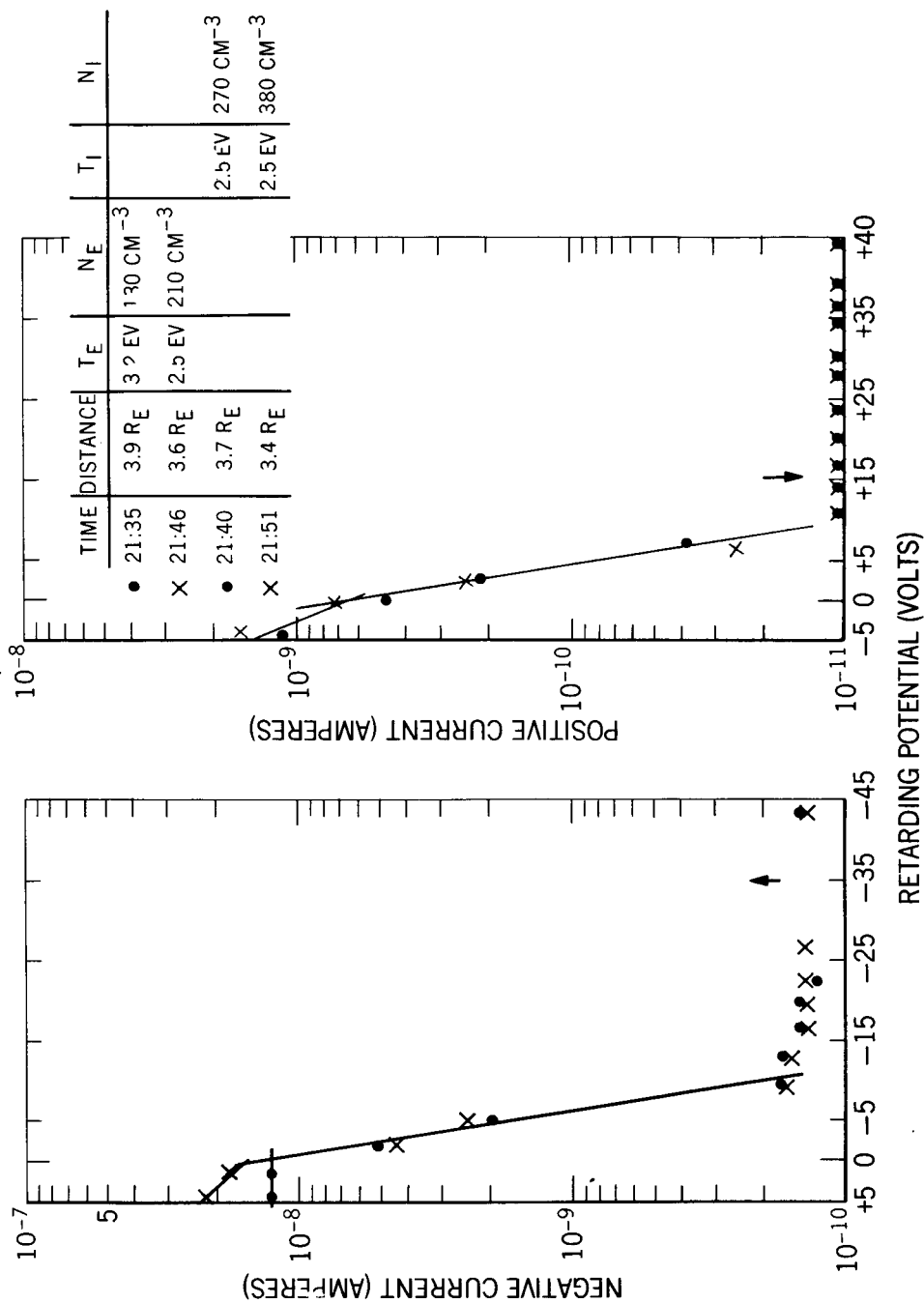
+5 0 −5 −15 −25 −35 −45

Figure 3. Sample plots of negative and positive current response as a function of retardation voltage. This data was obtained while IMP-II was on an inbound orbit in the nightside magnetosphere.

4

From the inflection near zero volts of the electron retardation curve in Figure 3 we measure the satellite to plasma potential to be 0 ± 0.5 volts. At attractive potentials, i.e., to the left of 0 volts, the curve exhibits electron current saturation. Using the measured electron temperature in conjunction with the value of the current at the satellite potential we obtain an electron density of 130 electrons cm^{-3} at $3.9R_E$ and 210 cm^{-3} at $3.6R_E$.

The right hand side of Figure 3 shows the measured positive current plotted on a log scale as a function of the retardation voltage. The wave form of the ion current also exhibits a Maxwell-Boltzmann distribution and so Langmuir probe analysis can be used to determine the ion temperature and density. Since the positive current is retarded almost two orders of magnitude as the retarding voltage is changed from $^-5$ to $+7$ volts, we can measure the slope of the line as drawn through these data points in order to obtain the ion temperature. From this measurement we obtain a value of 2.5 ± 0.5 eV. Assuming that the predominant ion at this altitude ($3.9R_E$) is H^+, we compute the most probable ion velocity to be about 30 km/sec. for a 2.5 eV temperature, at $4R_E$ where the satellite velocity is 4 km/sec. Since at this altitude the ion velocity is much larger than the satellite velocity, no corrections for the sensor orientation with respect to the velocity vector [2] need to be made.

It is evident in the figure that an inflection in the ion curves occurs at about zero volts, the $^-5$ volts data point is thus in the ion current saturation region. It is not readily evident when examining the curves at precisely what voltage current saturation occurs; obviously, there is an inflection between $^-5$ and 0 volts but the shape of the curve in this interval is not known. Since the saturation point occurs at the satellite potential, its value can be determined with accuracy from the negative current measurement and used to obtain the value of the ion current at saturation. Knowing the value of the ion current at saturation, and the measured ion temperature, we compute ion densities of 270 cm^{-3} at $3.7R_E$ and 380 cm^{-3} at $3.4R_E$.

In computing densities we assign an augmentation factor of 4 to the entrance aperture; this is due to the attractive potential of the aperture. For a more detailed discussion of the augmentation factor, the interested reader is referred to our previous paper [1].

In the legend of Figure 3, we have tabulated the electron and ion densities (N_e, N_i) and the electron and ion temperatures (T_e, T_i). Good agreement is noted between the measured electron and ion

temperatures. The ion density is, within a factor of two, in agreement with the electron density. The factor of two discrepancy is due in part to the previously discussed errors associated with the exact value of the ion current at saturation. Thus, within the limits of the measurement we have determined that the plasma is neutral, at a temperature of about 3.0 eV, and that the spacecraft potential with respect to the plasma is near zero volts.

On this same inbound orbit of 27 March 1965, we have obtained a series of measurements which illustrate how a detailed density profile can be obtained. In Figure 4, we plot five separate ion retardation curves. For reasons of space, we do not show the data beyond +7 volts of retardation since they are all similar to the previously shown curves. In the legend, we note that from 21:35 UT. to 22:24 UT. the satellite was inbound from 3.9 to $1.9R_E$; the trajectory was near the magnetic equator and northbound. From the electron curves, not shown here, we have determined that for this time interval the satellite potential is 0.5 ± 0.25 volts. The previously discussed analysis procedure has been used for each of the curves to obtain a detailed density profile in the nightside magnetosphere region from 3.7 to $1.9R_E$. Note that for the curve marked $2.3R_E$ the data point at ⁻5 volts is a factor of ten lower than expected, thus no specific value of density at this radial distance can be obtained; however, the remaining portion of that curve is in general agreement with the preceding and subsequent curves.

The results of our density measurements are plotted in the lower right hand corner of Figure 4 on a log scale as a function of the radial distance. Included in the plot of density vs. R_E are values of electron density (asterisk symbol) and values of ion density. The error bar for the ion density is taken to be a factor of 2, whereas the electron density error bar is less than 15%. It is seen that within the limits of the error bar, the values of ion and electron densities are equal, and thus the measurement indicates a neutral plasma with a density of the order of 10^3 cm⁻³ at 2 R_E which falls off according to a power law of the radial distance.

In Figure 5, we plot the measure' (' nsity and temperature profiles for both ions and electrons, obtained v. th. th. dayside magnetosphere for the two successive inbound orbits of 2ε and 30 October 1964. These two orbits occurred at a sun-earth-payload angle (LSEP) of 38°, thus they are representative of the dayside magnetosphere. Log-log scales have been used to plot the particle density cm⁻³, and temperature (eV) as a function of geocentric distance R_E. In the figure the crosses
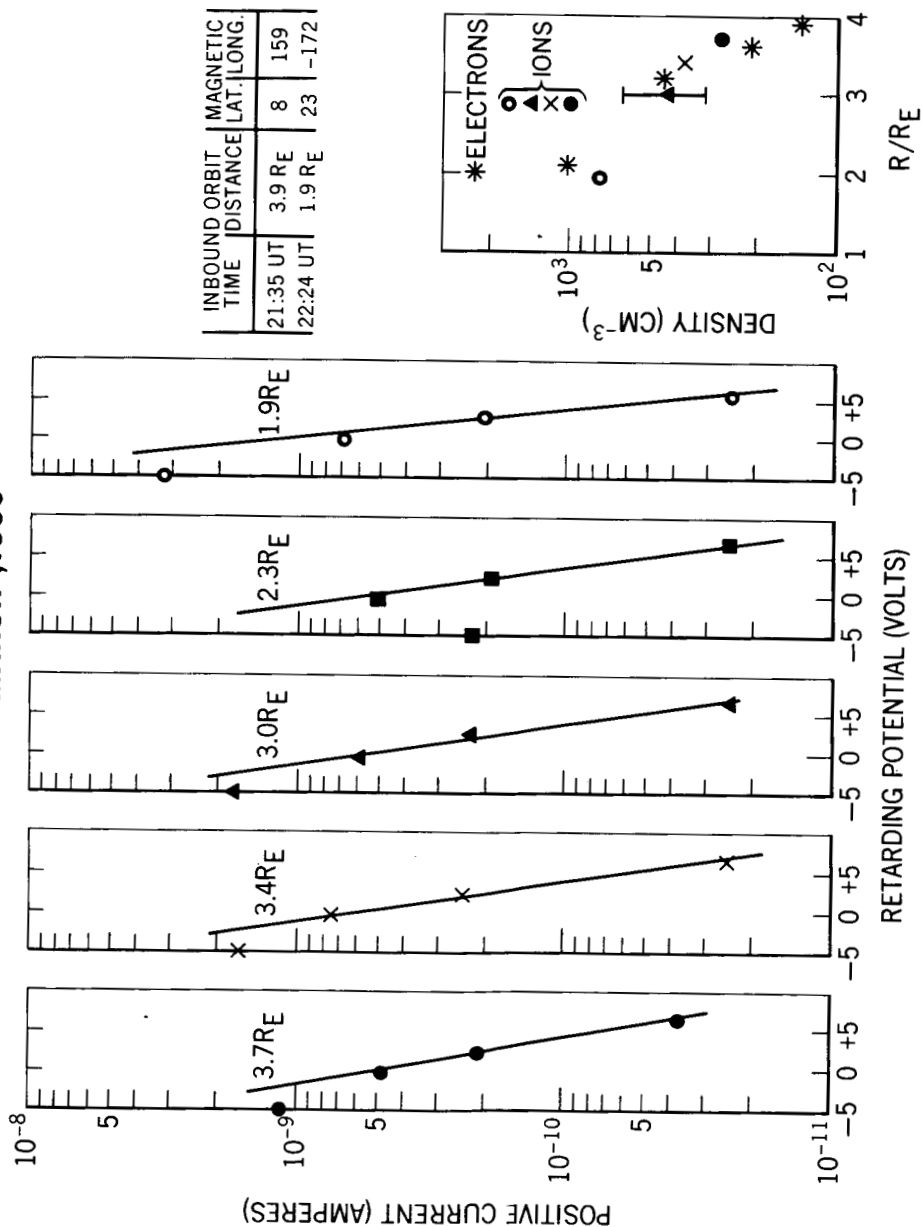
Figure 4. Five consecutive ion retardation curves are plotted for the inbound orbit of 27 March 1965. The ion density computed from these curves is plotted along with the electron density as a function of geocentric distance.
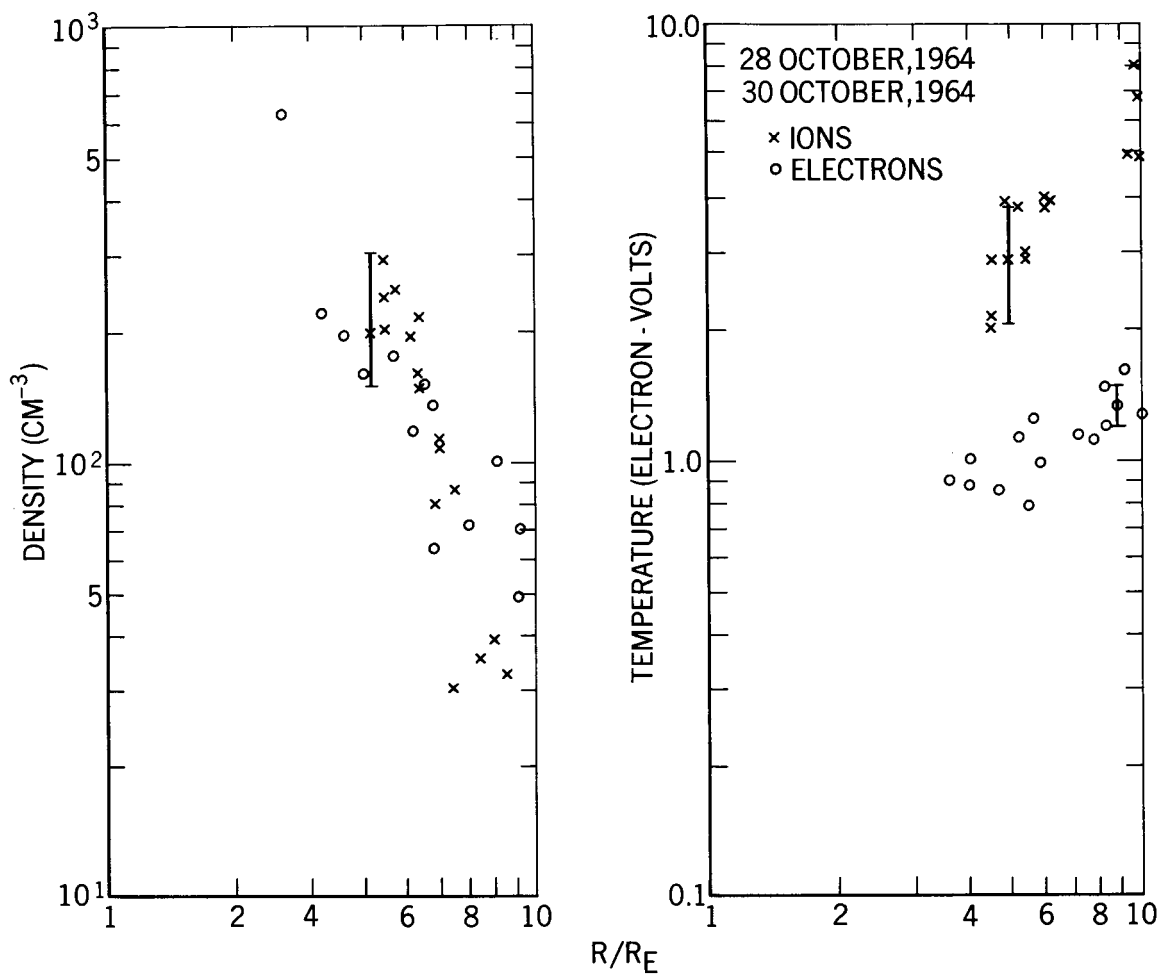
7

IMP II
INBOUND ORBITS

Figure 5. Electron and ion density and temperature are plotted as a function of geo-centric distance. These data were obtained while IMP-II was near the ecliptic plane in the dayside magnetosphere.

represent the ion data and the open circles are for the electron data. The average fall-off rate of the density profile may be approximated by a R_E^{-4} relationship. Spatial deviations from a smooth fall-off rate are noted; however, there is no evidence for a large drop of "KNEE" in the density profile, as has been reported by Carpenter [3].

Slish [4] has recently reported the results of an antenna impedance measurement associated with cosmic noise observations by an experiment on the spacecraft Zond II, launched November 1964. Two independent observations are presented. A peak attributed to electron plasma resonance was observed in the 210 kc/s receiver response at $4R_E$ geocentric. This observation yields a local density of 550 electrons cm^{-3}. The second observation is an analysis of the receiver response to a signal above the plasma frequency in terms of the effect of the local plasma density on the radiation resistance of the antenna. Interpreted in this manner, a radial dependence $N_e = 1.3 \times 10^5 (R/R_0)^{-4}$ valid from 4 to $7R_E$ is obtained. Both the general radial dependence and the specific value of 100 electrons cm^{-3} at $6R_E$ are in agreement with our results.

Obayashi [5] has used the differential Doppler shift of the harmonically related transmitters (40 and 360 Mc/s) on OGO-A to determine the local electron density in the vicinity of the spacecraft. He obtains an average local density at local noon on 16 November 1964, of 1 to 2×10^3 cm^{-3} at a geocentric distance of $3.2R_E$. The IMP-II satellite was at $3.3R_E$ on 16 November 1964 at 11:03 UT.; the density value as measured by us was 1.04×10^3 electrons cm^{-3}.

In Figure 5, the temperature profiles for ions and electrons as a function of geocentric distance are in general agreement in the rate of temperature increase with distance; however, we note that the ion temperature is higher than the electron temperature, taking into account the appropriate errors. It appears that near the magnetopause, approximately $10R_E$, the ratio of ion-to-electron temperature is higher than that at $5R_E$. We suggest that this preliminary observation might possibly be interpreted as follows: In the magnetosheath, solar wind energy is transferred to the thermal ions raising their temperature well above that of the thermal electrons. The electron temperatures in the magnetosheath have been observed to be between 1 and 3 eV [1]. Theoretical treatments of the detailed process involved in thermalization of the solar wind have been presented by Scarf, et.al. [6] who suggested that solar wind ions lose speed in the sub-solar magnetosheath resulting in the generation of ion-waves and that the electric fields

associated with the waves allow fast diffusion of plasma into the magnetosphere. Eviatar [7] finds that the interaction with electron plasma oscillations are effective in scattering super-thermal electrons and that ion waves are the dominant mechanism for the diffusion of subthermal (1 eV) electrons across the magnetopause.

It appears that within the magnetosphere, the ion temperature decreases from its relative high value in the magnetosheath, due to heat transfer to the electrons. Such a mechanism could explain the thermal gradients in the magnetosphere, and account for the fact that the ion-to-electron temperature ratio decreases with distance from the magnetopause.

CONCLUSIONS

The results of successive and continuous measurements of positive and negative retardation currents within the magnetosphere have been presented. Our interpretation of these measurements are summarized as follows:

1. Electrons and ions have a Maxwell-Boltzmann distribution of velocities in the thermal energy range of the order of eV; these particles constitute a neutral plasma.

2. Within $5R_E$ in the magnetosphere we observe a temperature profile which increases approximately as the square of the radial distance, while the density profile exhibits a decay that can be approximated by the inverse third to fourth power of the radial distance.

3. Our measurements of particle density do not indicate a whistler "KNEE" phenomenon. In fact, we observe 10 to 50 times as large a density beyond the "KNEE" as has been reported from whistler results.

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