JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 90, NO. A5, PAGES 4027–4034, MAY 1, 1985

Analyses of Experimental Observations of Electron Temperatures in the Near Wake of a Model in a Laboratory-Simulated Solar Wind Plasma

D. S. INTRILIGATOR AND G. R. STEELE

Carmel Research Center, Santa Monica, California

Laboratory experiments have been performed that show the effect on the electron temperature of inserting a spherical conducting model, larger than the Debye length, into a free-streaming high-energy (1 kv) unmagnetized hydrogen plasma. These experiments are the first electron temperature experiments conducted at energies and compositions directly relevant to solar wind and astrophysical plasma phenomena. The incident plasma parameters were held constant. A large number of axial profiles of the electron temperature ratios $T_{e_{in}}/T_{e_{out}}$ behind the model downstream in the model wake are presented. A rigorous statistical approach is used in the analysis of the electron temperature ratio data in both our experimental laboratory data and in our reanalysis of the published data of others. The following new results are obtained: (1) In energetic plasma flow there is no overall temperature enhancement in the near wake since the best fit to the $T_{e_{in}}/T_{e_{out}}$ data is a horizontal straight line having a mean value of 1.05; (2) No statistically significant electron temperature enhancement peaks or depressions exist in the near-wake region behind a model at zero potential in a high-energy plasma even at distances less than or equal to Ma, where M is the acoustic Mach number and a is the model radius. This implies a "filling in" of electrons in the wake region which may be due to the higher mobility of these energetic electrons. This mechanism may permit the solar wind electrons to significantly contribute to the maintenance of the nightside ionosphere at Venus.

INTRODUCTION

In this paper we present the results of the first laboratory experiments in a high-energy plasma that investigate the electron temperature T_e in the body wake. Moreover, we employ a large number of T_e samples in the very near- and near-wake regions downstream from a conducting body. We compare our results to the experimental findings of *Oran et al.* [1975], *Samir and Wrenn* [1972], *Samir et al.* [1979], *Stone* [1981], and *Troy et al.* [1975]. We discuss our results in the more general context of theoretical studies and of other relevent considerations. We also discuss how our findings may be relevant to the maintenance of the nightside ionosphere of Venus and we suggest some specific spacecraft observations that should be carried out using the Pioneer Venus orbiter.

Our results are also relevant to increasing our knowledge of the underlying physics of the electron heating process. Based on theoretical considerations [e.g., *Gurevich et al.*, 1966; *Denavit*, 1979], there is evidence that indirect processes for electron heating exist even though there are no collisions between particles or any other obvious heating mechanisms. From the viewpoint of a collisionless plasma expansion into a vacuum, *Gurevich et al.* [1966] have demonstrated through the self-similar theory that in the course of filling the vacuum, ions are accelerated by the action of the resulting electric field up to velocities of the order of the thermal velocity of the electrons. At the same time the effective temperature of the ions drops sharply to many times smaller than the electron temperature. Also, *Denavit* [1979] has demonstrated through numerical simulation that when a collisionless plasma expands into a vacuum, $T_e/n_e^{\gamma-1}$ equals a constant, where γ is defined as $[Z(m_e/m_i)]^{1/2}$, where Z is the ion charge number.

Laboratory experiments can be used to meaningfully simulate space physics phenomena. These experiments have the advantage that they afford investigation of the basic features of the physical processes in a controlled environment. Several types of space physics phenomena have been studied in the laboratory. *Podgorny and Sagdeev* [1970], *Alfvén*[1981], *Stenzel and Gekelman* [1981], *Stone* [1981], *Intriligator and Steele* [1982], *Samir et al.* [1983], and others have specifically discussed laboratory experiments relating to space physics and in situ phenomena. *Podgorny and Sagdeev* [1970] discuss various aspects of the solar wind interaction with the earth. *Alfvén* [1981] emphasized critical velocity phenomena. *Stenzel and Gekelman* [1981] (and subsequent papers by this group) investigate various aspects of magnetic field line reconnection that are relevant to the magnetotail, solar flares, and cometary phenomena. *Stone* [1981] and *Samir et al.* [1983] (and other papers by these authors) concern laboratory and in situ studies of the expansion of a low-energy plasma in a vacuum, plasma flow past an obstacle, and relevant space physics phenomena. *Intriligator and Steele* [1982] related high-energy (1 kV) laboratory results concerning a stable narrow turbulent layer and a shadow region downstream of a model to the region downstream of Venus. In the present paper we discuss the electron temperatures in the near wake of an obstacle in a simulated solar wind flow and their possible relevance to the solar wind interaction at Venus, including the maintenance of the nightside ionosphere.

There have been considerable experimental and in situ measurements of the electron temperature (T_e) in the wake of a spherical object in a low-energy plasma. This topic has been explored both in the laboratory [*Illiano and Story*, 1974; *Oran et al.*, 1975; *Stone*, 1981] and from earth-orbiting satellites [*Henderson and Samir*, 1967; *Samir et al.*, 1979; *Samir and Wrenn*, 1972; *Troy et al.*, 1975]. Two review articles that discuss both the laboratory and spacecraft measurements are by *Samir and Stone* [1980] and *Samir et al.* [1983].

Samir et al. [1979, 1983] indicated the need to more fully resolve the conditions for the existence or nonexistence of the

Paper number 4A1475.
0148-0227/85/004A-1475$05.00

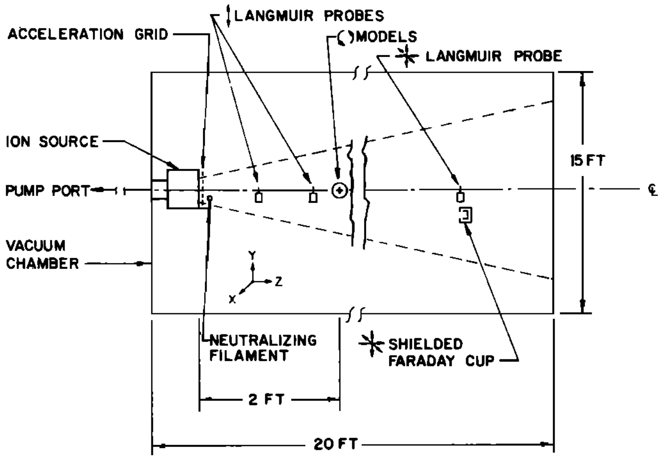

Fig. 1. Schematic representations of the Astrophysical Plasma Laboratory plasma chamber showing the relative locations of the high-energy plasma source, the model, and the various detectors.

T_e enhancement in the wake of a conducting body, and they also indicated the need for further theoretical and experimental work. *Samir et al.* [1979] stress the need for the experimental work to employ large samples of T_e measurements in the body wake.

In the Astrophysical Plasma Laboratory (APL) we developed a large plasma facility capable of producing a well-controlled high-energy hydrogen plasma to simulate the environment of the interplanetary/astrophysical medium [*Intriligator and Steele*, 1982]. The plasma facility (see Figure 1) consists of a large vacuum chamber (20 feet (6.1 m) long and 15 feet (4.6 m) in diameter), the high-energy plasma source (1 kV), and the detectors. The ambient geomagnetic field was present in the chamber. The operating base pressure in the chamber was less than 5×10^{-6} torr when the source was operating.

A Langmuir probe [*Langmuir and Mott-Smith*, 1924; *Intriligator and Steele*, 1982], consisting of a looped wire 1.5 cm long by 0.008 cm in diameter, similar to those described by *Hall et al.* [1965] and *Sellen et al.* [1965], floating at the plasma potential was used to measure the ambient plasma parameters for repeatability and stability. These measurements were used to determine a set of baseline source parameters for control purposes. This probe could be inserted in and removed from the plasma beam (using controls external to the vacuum environment) at a location upstream ($z \approx -9.5$ cm) along the model centerline. A second Langmuir probe of the same type was mounted so that it could be moved, by a mechanical shaft through the vacuum wall, along the model centerline throughout the region downstream of the model.

A model was inserted into the plasma beam, and the downstream Langmuir probe was aligned with the model centerline and then located at various downstream z locations ($z/a = 1.6$–7.5, where z is the distance from the model centerline and a is the model radius). The bias voltage on the probe was stepped through a range of ± 600 V at each z/a location, and the net probe current was measured and recorded for each voltage step. The electron temperature was derived in the usual manner from the *ln I/V* curve, where I is the net electron current and V is the probe voltage [*Schott*, 1968; *Stone*, 1981; *Intriligator and Steele*, 1982]. The linear portion of the curve extended for several orders of magnitude, indicating a Maxwellian distribution of electrons. These electron temperatures were then compared to the corresponding electron temperatures obtained when the model was removed

TABLE 1. Laboratory and Solar Wind Free Stream Parameters

Parameter	Solar Wind At Venus	Laboratory
Velocity (km/s), V_i	30–700	440
Density (ions/cm³), N_i	20–40	2×10^6
Ion temperature (°K), T_i	1–5×10^4	1.5×10^4
Ion composition	H^+	H^+
Electron temperature* (°K), T_e	1–5×10^5	4.5×10^4
Debye length (cm, $\lambda_d = 6.9(T_e/N_e)^{1/2}$	$>10^2$	5.8×10^{-1}
Ion acoustic Mach No. $M = V_i/(2kT_e/M_i)^{1/2}$	6	16
Debye ratio, a/λ_d	10^5	8
Model radius (cm), a	6.1×10^8	4.1

*T_e was determined by using conventional methods associated with I/V curves, the straight section of our *ln I/V* curve extended for several orders of magnitude.

from the plasma. In this study a model with $a/\lambda_d = 8.0$ was used in the high-energy plasma beam.

A set of scans, consisting of one I/V scan taken behind the model with the model in the high-energy plasma and one I/V scan with the model removed from the plasma, was taken at each z/a location. After a set of scans, the model was removed from the plasma, and the upstream Langmuir probe was inserted into the plasma. The plasma parameters were remeasured, and the new values were compared to the baseline values for repeatability. The maximum deviation was $\pm 10\%$.

After a set of scans was completed at each z/a location, another set of scans was performed at the same location to verify the reliability of the temperature measurements. The maximum deviation between the two corresponding sets of scans was $\pm 10\%$.

We have calculated temperature ratios $T_{e_{in}}/T_{e_{out}}$, where $T_{e_{in}}$ is the electron temperature with the model in the high-energy plasma and $T_{e_{out}}$ is the electron temperature with the model removed from the high-energy plasma. In this paper we present the temperature ratios $T_{e_{in}}/T_{e_{out}}$ taken on the model centerline in the wake region downstream from the model at

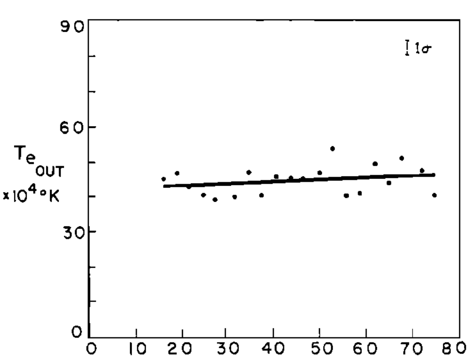

Fig. 2. A plot of plasma electron temperature $T_{e_{out}}$, taken downstream on the line which coincides with the model centerline when the model is in the beam, with the conducting model ($a/\lambda_d = 8.0$) removed from the plasma beam. The vertical axis is the dimensionless number $T_{e_{out}}$, where $T_{e_{out}}$ is the electron temperature with the model removed from the plasma beam, ranging from 0 to 9.0×10^4°K. The horizontal axis is the dimensionless number z/a ranging from 0 to 8.0, where z is the distance downstream along the model centerline and a is the model radius. The least squares line calculated from the data ($T_{e_{out}} = 0.1(z/a) + 4.2$) and the one-sigma bar are also shown. The slight increase in value of the least squares line with increasing z/a is not statistically significant (see text).

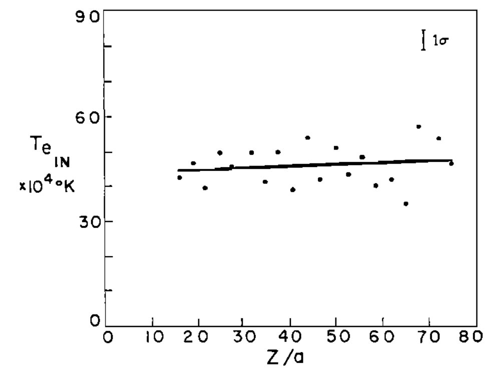

Fig. 3. A plot of the plasma electron temperature $T_{e_{in}}$ on the model centerline downstream from a conducting model with the model in the plasma beam. The least squares line calculated from the data points ($T_{e_{in}} = 0.1(z/a) + 4.2$) and the one-sigma bar are also plotted. The vertical and horizontal axes are the same as in Figure 2. The slight increase in value of the least squares line with increasing z/a is not statistically significant (see text).

distances ranging from $z/a = 1.6$ to 7.5. The model was maintained at zero volts bias.

OBSERVATIONS

The ambient plasma parameters shown in Table 1 were maintained at their respective values throughout the entire data series presented in this paper. Figure 2 shows an axial plot of the electron temperatures obtained with no model in the plasma beam ($T_{e_{out}}$) taken downstream locations, on the line which coincides with the model centerline when the model is in the plasma beam, ranging from $z/a = 1.6$ through 7.5, where a is the radius of the model used to obtain the data shown in Figure 2. In Figure 2 the separation between the z/a locations was 0.3 with the exception of between 2.8 and 3.2 and between 6.8 and 7.2. The vertical axis is the electron temperature $T_{e_{out}}$ and ranges from 0 to 9.0 × 10⁴°K. The horizontal axis is the dimensionless number z/a and ranges from 0 to 8.0. This parameter was employed to enable us to compare our data with other published data [e.g., *Oran et al.*, 1975; *Stone*, 1981]. We calculated the least squares fit to the $T_{e_{out}}$ data and have shown the least squares line which has a value of 4.5 × 10⁴°K, as determined by the equation $T_{e_{out}} = 0.1(z/a) + 4.2$, and a standard deviation, shown by the one-sigma bar, of 4 × 10³°K. The apparent slight increase in value of the least squares line with increasing z/a is not statistically significant as determined by the T ratio for the regression coefficient [*Draper and Smith*, 1966].

Figure 3 shows an axial plot of the electron temperatures $T_{e_{in}}$ taken downstream on the model centerline obtained with the model ($a/\lambda_d \approx 8$) in the plasma beam. The vertical axis is the electron temperature $T_{e_{in}}$ and ranges from 0 to 9.0 × 10⁴°K. The horizontal axis is the same as in Figure 2. We calculated the least squares fit to the $T_{e_{in}}$ data and have shown the least squares line, which has a mean value of 4.6 × 10⁴°K, as determined by the equation $T_{e_{in}} = 0.1(z/a) + 4.2$, and a standard deviation, shown by the one-sigma bar, of 6 × 10³°K. The slight increase in value of this least squares line with increasing z/a is also not statistically significant as determined by the T ratio for the regression coefficient.

Figure 4 shows an axial plot of the electron temperature ratios $T_{e_{in}}/T_{e_{out}}$. The vertical axis is the dimensionless number $T_{e_{in}}/T_{e_{out}}$ and ranges from 0 to 3.0. The horizontal axis is the same as in Figure 2. The least squares fit to the $T_{e_{in}}/T_{e_{out}}$ data was calculated and we have shown the least squares line, which has a mean vlaue of 1.05, as determined by the equation $T_{e_{in}}/T_{e_{out}} = (6.0 \times 10^{-3})(z/a) + 1.1$, and a standard deviation, shown by the one-sigma bar, of 0.15. Thus while at $z/a = 2.5$, 3.2, 3.8, 4.4, and 5.6 there are apparent electron temperature enhancement peaks and at $z/a = 3.5$, 4.0, 5.3, 6.2, and 6.5 there are apparent electron temperature depressions, these peaks and depressions are greater than one sigma but less than two sigma, so that these peaks and depressions are not statistically significant (i.e., they are less than 95% confidence).

Figure 5 shows a plot of the data $T_{e_{in}}/T_{e_{out}}$ from *Oran et al.* [1975]. We have calculated the least squares fit to their data points taken with zero volts bias on the model, where the model is in a 3.2-eV plasma beam. We have shown the least

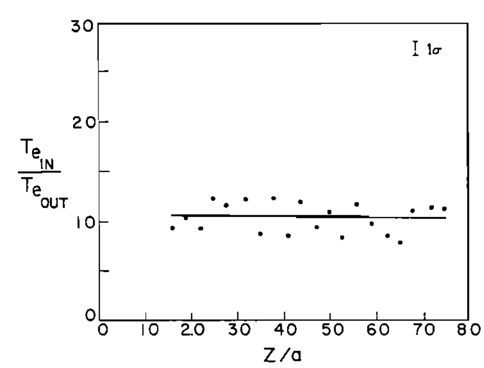

Fig. 4. A plot of the plasma electron temperature ratio $T_{e_{in}}/T_{e_{out}}$ on the model centerline downstream from a conducting model ($a/\lambda_d = 8.0$). The vertical axis is the dimensionless number $T_{e_{in}}/T_{e_{out}}$ ranging from 0 to 3.0. The horizontal axis is the same as in Figure 1. The least squares line calculated from the data ($T_{e_{in}}/T_{e_{out}} = (6 \times 10^{-3})(z/a) + 1.1$) and the one-sigma bar are also shown. The mean value of 1.05 was obtained from the least squares best fit to the data. This figure shows that the evolution of the ratio of the electron temperature in the shadow of a conducting model inserted in a free-streaming high-energy plasma beam is consistent with a straight horizontal line from $z/a = 1.6$ to 7.5. This plot also shows that downstream on the model centerline, in the near-wake region, there are no electron temperature ratio excursions greater than two sigma. Therefore the apparent ratio structure in the temperature ratio data is not statistically significant.

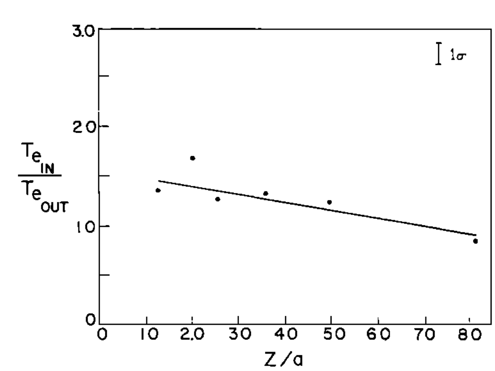

Fig. 5. A plot of the data for zero volts bias from *Oran et al.* [1975]. The vertical axis is the same as in Figure 4. The horizontal axis is the dimensionless number z/a ranging from 1.0 to 8.5, where z is the distance downstream and a is the model radius. The least squares line that we calculated from the data ($T_{e_{in}}/T_{e_{out}} = -0.1(z/a) + 1.6$), which has a mean value of 1.3, and the associated one-sigma bar are also shown. This plot shows that there is a ~30% temperature enhancement in their wake data and that there is a small decreasing trend in the data with increasing z/a. The reported electron temperature enhancement peak at a z/a of 2.0 is less than our calculated two-sigma value.

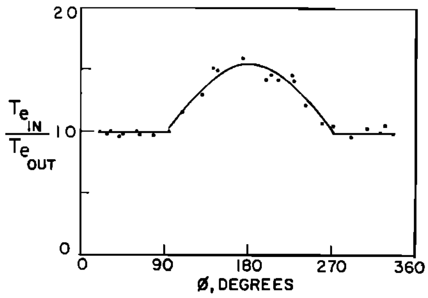

Fig. 6. A plot of the wake electron temperature ratio data from *Samir and Wrenn* [1972] with the least squares best fit ($T_{e_{in}}/T_{e_{out}} = (1.2 \times 10^{-4})\phi + 1.0$) line we calculated for the ambient data and the sinusoidal best fit for the wake data. The vertical axis is the dimensionless number $T_{e_{in}}/T_{e_{out}}$ ranging from 0 to 3.0, where $T_{e_{in}}$ is the electron temperature in the satellite wake and $T_{e_{out}}$ is the ambient electron temperature. The horizontal axis is ϕ, where ϕ is the angle associated with the satellite rotation.

squares line, which has a mean value of 1.3, as determined by the equation $T_{e\text{in}}/T_{e_{out}} = -0.1(z/a) + 1.6$, with a standard deviation, shown by the one-sigma bar, of 0.2. The vertical axis is the same as in Figure 4. The horizontal axis is the dimensionless number z/a ranging from 0 to 8.5.

Shuvalov [1980] reported an apparent small electron temperature enhancement in the very near wake downstream from a cylinder where z/a is less than or equal to 1.4. We calculated the $T_{e_{in}}/T_{e_{out}}$ values for the two reported locations and obtained a value of 1.5 where $z/a = 1.1$ and a value of 1.2 where $z/a = 1.4$. It is unfortunate that there were not sufficient data points presented to allow a statistical analysis of his observations.

Figure 6 shows a plot of the $T_{e_{in}}/T_{e_{out}}$ data, where $T_{e_{in}}$ is the electron temperature in the satellite wake and $T_{e_{out}}$ is the ambient electron temperature measured upstream from the satellite, obtained by the Langmuir probe on Explorer 31 [*Samir and Wrenn*, 1972]. We have calculated the best fit to these data points, and we have plotted this best fit to both the ambient and the wake data. The best fit to the ambient data is a least squares line with a mean value of 1.0, as determined by the equation $T_{e_{in}}/T_{e_{out}} = (1.2 \times 10^{-4})\phi + 1.0$ and a standard deviation of 0.03. The best fit to the wake data is a sine wave. In Figure 6 the vertical axis is the same as in Figure 3. The horizontal axis is ϕ, where ϕ is the angle associated with spacecraft rotation and ranges from 0° to 360°.

Electron temperature data were also taken with the retarding potential analyzer [*Troy et al.*, 1975] on the Explorer 31 satellite. We will summarize the results from the Explorer 31 retarding potential analyzer in the next section.

DISCUSSION

Laboratory Results on Electron Temperatures

The data presented in Figures 2, 3, and 4 are the first presentation of experimental data investigating the electron temperature in the model shadow in a high energy hydrogen plasma. Moreover, compared with other laboratory experimenters, we have obtained a large number of data points. Unlike some other authors [*Illiano and Storey*, 1974; *Oran et al.*, 1975; *Samir and Wrenn*, 1972; *Troy et al.*, 1975], we have taken a rigorous statistical approach to the analysis of our electron temperature data. When the data are compared with a least squares fit to the respective points, we find that an electron temperature enhancement does not exist in the wake of a model maintained at zero volts bias in a high-energy plasma (i.e., the enhancement peaks are less than two sigma). That is, while the electron temperature ratios associated with zero volts potential on the model (see Figure 4) show apparent temperature ratio peaks and depressions throughout the near wake region (i.e., from $z/a = 1.6$ to 7.5), they are not statistically significant. We emphasize that these peaks and depressions are greater than one sigma but less than two sigma and that the data are consistent with a straight horizontal line having a mean value of 1.05, as shown in Figure 4.

Stone [1981] and *Samir et al.* [1983] predict that any electron temperature enhancement in the wake of a model will be confined to the near-wake region where z is less than Ma, M is the ion acoustic Mach number, and a is the model radius. Their prediction is based on the assumption that this is the approximate location where the converging streams in the near wake cross the z axis and fill in the ion void. In contrast to this expectation, our data, which were taken in the wake region where z is less than $1/2\ Ma$, show statistically that no temperature enhancement exists.

In apparent agreement with our findings, *Stone* [1981] suggests, on the basis of some additional low energy experiments, that the more energetic the initial electron population, the less dramatic will be the degree of electron temperature enhancement. The data from *Stone* [1981] taken with zero volts bias on the model and an electron temperature of 8.5×10^2°K show a temperature ratio peak at $z/a = 2.0$ and ratio depressions at $z/a = 1.25$ and 5.0. He states that the peak at $z/a = 2.0$ is not indicative of a temperature enhancement. We calculate that this peak and the depressions are greater than one sigma but less than two sigma. Thus all the values are consistent with a straight horizontal line. When the electron temperature is increased to 2.45×10^3°K and the model bias is maintained at zero volts, the temperature ratio peak appears at $z/a = 5.0$ and has decreased in value (we calculate that it is still greater than one sigma), and we calculate that all the points are also consistent with a straight horizontal line. The temperature ratio peak which appeared as $z/a = 2.0$ has decreased to a value which is less than one sigma from the line. Thus we calculate that statistically both of these data cases are consistent with straight horizontal lines and that no temperature enhancement existed in the model wake for either of the initial electron populations. It should be noted, however, that the Stone 8.50×10^2°K case was obtained when there was a higher neutral gas pressure in the chamber. *Stone* [1981] has suggested that increased gas pressure also diminishes the temperature enhancement (the higher gas pressure the more the charge exchange and the less the enhancement). *Stone* [1981] reports downstream electron temperature enhancements with lower gas pressure for an electron temperature of 10.5×10^3°K, but in these experiments the model was not at zero volts bias.

Figure 5 shows the data from *Oran et al.* [1975] with zero volts potential on the model, where the model is in a low-energy (3.2 eV) plasma beam. The Mach number in their chamber ranged between 6.9 and 12.8, and R_0/λ_d ranged between 11.7 and 25. Their electron temperature was 1050°K and the ion temperature 300°K. Thus while T_e/T_i is ~ 3 in both our and their experiments, the beam energies are vastly different, and T_i/E_i also differ. Since the mean value of our calculated best fit to their data is 1.3, this implies that there is an overall temperature enhancement of $\sim 30\%$ in their data. They report that with an ambient electron temperature of 1.05×10^3°K, there is an enhancement peak at $z/a = 2.0$. We note from our least squares fit to their data that this peak is greater than one sigma but less than two sigma. Our least squares fit to the Oran et al. data also shows an apparent negative slope with increasing z/a. The value of this slope is -0.08. The T ratio indicates that this small negative slope is significant, so that the Oran et al. data are consistent with a trend of a small temperature enhancement in the very near wake, even though their apparent enhancement at $z/a = 2.0$ is not statistically significant. Our further examination of the data from *Oran et al.* [1975] shows that there exists a temperature ratio depression which is greater than one sigma but less than two sigma at $z/a = 8.1$. However, all the other points lie within one sigma of the line. Thus we conclude that statistically their observations are consistent with an electron temperature enhancement in the near wake.

Stone [1981] suggests that the temperature enhancement observed by *Oran et al.*, [1975] may have been caused by plasma instabilities that gave rise to heating of electrons throughout their chamber (i.e., in the ambient flow and in the wake region). He speculates that they did not realize that heating actually took place throughout the chamber because in the ambient electrons any effects of heating were swamped by the more populous unheated electrons. In the wake, however, since most of the ambient electrons were excluded, the electron heating was more readily observable.

As the negative potential is increased on the model, both *Oran et al.* [1975] and *Stone* [1981] show that an enhancement peak occurs close to the model surface and increases in amplitude with an accompanying decrease in the distance downstream at which any apparent enhancement exists. They find that at negative potentials greater than -0.7 V on the model the apparent enhancement is confined to the very near wake region (e.g., distances less than $z/a = 2.0$). We note that their enhancement peak at this distance is greater than two sigma.

It has been suggested to us (S. T. Wu, private communication, 1983) that the increased mobility associated with our high-energy electrons enables them to more readily "fill in" behind the model. *Nakagawa and Wu* [1969] discuss temperature structures within a shock layer. The fundamental physical process of mobility of ions and electrons should be applicable for both cases.

Many authors [*Illiano and Story*, 1974; *Liu*, 1969; *Samir et al.*, 1979; *Stone*, 1981] note the possible relation between the apparent electron temperature enhancement occurring downstream in the region of the model wake from $z/a = 1.25$–8.0 to the possible effects of a negative potential well. *Samir et al.* [1979] point out that the existence of such a potential well can lead to misinterpretation of the inflection point of the I/V characteristic of a Langmuir probe, leading to an erroneous apparent electron temperature enhancement in the model wake. *Stone* [1981], *Samir et al.* [1979], and others, however, are obviously aware that wave-particle interactions can occur with or without a potential well and that these wave-particle interactions may play a significant role in the wake region. *Troy et al.* [1975] point out that there is definitely some process much more complex than a uniform electrostatic barrier which controls the electron collection and causes an apparent electron temperature enhancement in the model wake.

Samir et al. [1983] recently reviewed the expansion of a plasma into a vacuum. They interpret the available laboratory and in situ measurements as indicating the existence of a rarefaction wave propagating into the ambient plasma downstream of an obstacle. This interpretation is consistent with some of the theoretical results of *Gurevich et al.* [1973] and *Singh and Schunk* [1982]. While *Singh and Schunk* [1982] point out some inadequacies in the Gurevich et al. boundary conditions and results, the existence of the expansion region and much of the theoretical formalism they employ are similar. Gurevich et al. present the hypothesis that electron heating caused by a two-stream instability can cause an electron temperature enhancement in the model wake.

Stone [1981] states that if this hypothesis is correct and ambient plasma stream electrons are heated by a wave-particle interaction, then the more energetic the initial electron population, the less dramatic will be the temperature enhancement. In this context, our laboratory high-energy plasma results showing a lack of electron temperature enhancement in the near wake supply some important information that has been hitherto unavailable.

In Situ Results on Electron Temperatures

The in situ studies were primarily intended for study of spacecraft/thermal plasma rather than solar wind/obstacle interaction, but they are relevant to our work. *Samir and Wrenn* [1972], as shown in Figure 6, and *Troy et al.* [1975] present data taken with the Langmuir probe and with the retarding potential analyzer, respectively, mounted flush on the Explorer 31 satellite. Samir and Wrenn report an apparent electron temperature enhancement, determined by comparing the ambient electron temperature measured upstream of the satellite with the wake electron temperature measured downstream of the satellite in the wake region where ϕ ranges from 120° to 270°. Samir and Wrenn report that the data show an electron temperature enhancement in the satellite wake, and they draw a sinusoidal type curve through the downstream data.

We have shown that the ambient data of Samir and Wrenn are best fit with a straight line. We also have obtained a best fit sinusoidal curve for the Samir and Wrenn wake data. Our calculations clearly indicate that there is a temperature enhancement in the wake region for the Samir and Wrenn observations.

Troy et al. [1975] present data that show a variety of behavior in the downstream region. They present one case which indicates that there was no electron temperature enhancement present downstream from Explorer 31. They also present two cases which indicate electron temperature enhancements downstream: one showing an apparent electron temperature increase of more than 50%, the other showing an apparent electron temperature enhancement of less than 20%. The final case presented by Troy et al. shows an oscillatory type behavior, but these data were obtained during a period of changing ionospheric activity.

Henderson and Samir [1967] report that with a Langmuir probe mounted at $5R_0$ (where R_0 is the spacecraft radius) from the Ariel 1 spacecraft centerline there is no evidence of an electron temperature enhancement in the spacecraft wake. Therefore both *Samir and Wrenn* [1972] and *Troy et al.* [1975] conclude that the apparent electron temperature enhancement may be confined to the very near wake region where z/a is less than 5.0. No in situ measurements of the region between $2R_0$ and $5R_0$ have been reported.

Samir et al. [1983] point out that because these in situ measurements were made by probes that were either mounted flush on the spacecraft or on a short boom, they are limited in their spatial and temporal extent. These limitations allow the examintion of only the very near wake region. Contrary to these results our laboratory data show that while there is an apparent electron temperature structure consisting of peaks and depressions throughout the near wake region from $z/a = 1.6$–7.5, these are all greater than one sigma but less than two sigma and therefore are consistent with a horizontal line.

Relevance to Space Plasma Phenomena

The downstream electron temperatures we obtained are the first laboratory measurements at high energies directly relevant to the solar wind interaction with planets, comets, and other astrophysical objects. While our solar system affords the only opportunity for carrying out in situ measurements of astrophysical phenomena, these in situ determinations are not carried out in a controlled environment. In our laboratory experiments we have successfully performed in a controlled environment repeatable, reliable experiments at energies comparable to those of the solar wind. On the basis of our experiments we conclude that at these high energies there are no temperature enhancements in the near wake.

On the basis of our rigorous statistical reanalysis of the low-energy laboratory experiments of others and of the in situ ionospheric experiments there appears to be evidence for a temperature enhancement in the near wake in the *Oran et al.* [1975] observations and in the Explorer 31 wake as measured by *Samir and Wrenn* [1972]. The *Stone* [1981] laboratory observations, which included a good number of samples, are best fit by a horizontal line having a mean value which indicates no significant temperature enhancements. While Shuvalov and others report some enhancements, their data are so sparse that it is difficult to determine if they are statistically significant.

One of the important unresolved issues concerning the Venus environment regards the maintenance of the nightside ionosphere. *Intriligator et al.* [1979] reported evidence for measurable electron fluxes in the plasma analyzer observations. However, to data, the majority of the PVO plasma analyzer electron observations have been obtained near periapsis in the vicinity of the ionopause/ionosphere. At these low altitudes one would not expect to observe measurable electron fluxes of diverted solar wind electrons since even if the solar wind electrons are "filling in" behind the planet, they are confronted with an obstacle that is larger than $2R_V$ in diameter (i.e., owing to interplanetary magnetic field pileup, etc). Moreover, they must penetrate the turbulent ionosheath [*Intriligator and Scarf*, 1982], the boundary region of the tail [*Intriligator and Scarf*, 1984], the interaction region associated with mass addition (i.e., the pick-up of planetary O^+ ions [*Intriligator*, 1982]), and the thermalization process near the top of the ionosphere (H. Perez-de-Tejada et al., preprint, 1983).

One could speculate that some of the incoming solar wind electrons which penetrate the Venusian bow shock leave the turbulent ionosheath and penetrate the boundary region of the tail. Thus these high-mobility solar wind electrons are filling in the void region downstream of Venus. After the electrons enter the void region, eventually it is necessary for them to have a significant component of velocity directed toward the planet if they are to impinge on the nightside ionosphere. Analogously to some earth magnetotail models, it is possible that the electrons first stream down the tail away from the planet and that subsequently (either in impulsive events or in a more continuous manner) they flow toward the planet and impinge on the ionosphere (in the polar regions, for example).

The Pioneer Venus Orbiter (PVO) orbit is evolving, and in the few remaining seasons of nightside observations it would be meaningful to acquire some electron observations that would enable us to further resolve this issue. On the basis of our laboratory results reported above we suggest that the PVO plasma analyzer be configured to measure electrons when the spacecraft is at downstream distances less than Ma, where M is the solar wind ion acoustic Mach number and a is the radius of Venus, R_V. In other words, when the spacecraft is at distances less than $\sim 6R_V$ downstream from the planet so that possible evidence may be obtained of solar wind electrons filling in the void region. Perhaps on several orbits the plasma analyzer can perform these measurements when periapsis is downstream in the range of 2 to $6R_V$. It would also be useful to perform some electron observations further downstream near apoapsis. The electron observations in this region may provide evidence of electrons streaming toward and/or away from the planet. In this connection it should be recalled that *Perez-de-Tejada et al.* [1982] showed that at a distance of $\sim 12R_V$ downstream from Venus the flow direction of the plasma protons and Venus-derived oxygen ions was consistent with the bulk flow direction associated with fluid flow and independent of the local orientation of the magnetic field. Observations of converging plasma electron streams in this downstream region or in the downstream region closer to the planet would provide striking evidence for the filling in of the void.

The PVO plasma analyzer can measure electrons in the range of 0–250 V. The instrument has the flexibility to obtain these measurements in two different modes [*Intriligator et al.*, 1980]: the step mode and the scan mode. For these electron observations it would be useful to obtain measurements in the usual scan mode and also in the step mode since the step mode transmits the complete azimuthal distribution of the electrons at each energy step, while the scan mode transmits only the peak flux and peak azimuthal direction at each energy step. The instrument also transmits information concerning the polar flow [*Intriligator et al.*, 1980].

While the filling in process for solar wind electrons at Venus may be more complicated than that which we observed in the laboratory, the PVO electron observations outlined above may provide sufficient observations to ascertain the significance of this electron flux in these regions. Moreover, the simultaneous PVO plasma wave observations may provide information concerning the role of plasma instabilities (e.g., *Stone* [1981] suggested that plasma instabilities may have been responsible for heating the ambient and wake electrons in *Oran et al.*'s [1975] chamber). Because of the large difference ($\simeq 10^4$) in the scaling parameter a/λ_D (radius/Debye length) between the laboratory and Venus, in the large wake of Venus, instabilities may play a more significant role than in the laboratory wake, of a few Debye lengths in radius, which lacks a comparable shock structure. It is also possible that the induced magnetic field at Venus might play a role in the energy coupling between ions and electrons in the wake.

CONCLUSIONS

We find that the electron temperature ratios measured downstream behind a conducting model, at zero volts potential, in a high-energy (1 kV) plasma do not show an electron temperature enhancement. The temperature ratio peaks appearing behind the model at $z/a = 2.5$, 3.2, 3.8, 4.4, and 5.6 and the temperature ratio depressions at $z/a = 3.5$, 4.1, 5.3, 6.2, and 6.5 are all greater than one sigma but less than two sigma from our horizontal line having a mean value of 1.05, which is the least squares best fit to the data.

From the viewpoint of a collisionless plasma expansion into a vacuum, *Gurevich et al.* [1966] have demonstrated through the self-similar theory that in the course of filling the vaccum, ions are accelerated by the action of the resulting electric field up to velocities of the order of the thermal velocity of the electrons. At the same time the effective temperature of the ions drops sharply to many times smaller than the electron temperature. Furthermore, *Denavit* [1979] has also demonstrated through numerical simulation that when a collisionless plasma expands into a vacuum, $T_e/n_e^{\gamma-1}$ equals a constant, where γ is defined as $[Z(m_e/m_i)]^{1/2}$, with Z as the ion charge number.

These two theoretical examples provide evidence that indirect processes for electron heating exist even though there are no collisions between particles or any other obvious heating mechanisms. Thus our experimental results showing no electron temperature enhancement are important in this respect.

We speculate that the increased mobility of these high-energy electrons may enable the electrons to more readily fill in behind the model. We suggest that the mechanism responsible for this filling in in our laboratory experiments may be relevant for the solar wind interaction at Venus. This mechanism may permit the solar wind electrons to significantly contribute to the maintenance of the nightside ionosphere of Venus. We suggest some specific experiments that can be carried out by the PVO plasma analyzer to investigate the solar wind electron interaction with Venus downstream from the planet.

We performed a statistical analysis of the data presented by *Oran et al.* [1975] and *Stone* [1981] taken downstream, on the model centerline, in a low-energy laboratory plasma with the model at zero volts potential. We find that in both data sets all the data points are less than two sigma from our calculated least squares best fit to their respective data. We conclude, therefore, that the data from *Stone* [1981] are consistent with a straight horizontal line and no electron temperature enhancements exist in these low energy observations in the model wake. The *Oran et al.* [1975] data show an overall 30% temperature enhancement and an apparent negative slope with increasing z/a. Our calculated T ratio indicates that this small negative slope is significant. Therefore we conclude that the data from Oran et al. are consistent with a temperature enhancement in the near wake, although their reported enhancement peak at $z/a = 2.0$ is less than two sigma from our calculated least squares line. *Stone* [1981], however, speculated that plasma heating occurred throughout the chamber used by *Oran et al.* [1975] but that it was only observed in the wake region since outside this region the ambient plasma swamped the possibility of observing the heating.

Many authors [*Samir et al.*, 1979; *Samir and Wrenn*, 1972; *Troy et al.* 1975] reported the existence of electron temperature enhancements in the near and very near wake regions of earth orbiting satellites. All these measurements were limited to the near-wake region because the probes were mounted either flush on the spacecraft or on short booms and no data have been presented that include the region between $2R_0$ and $5R_0$.

We find that the best fit to the data points in the wake region from *Samir and Wrenn* [1972] is a sine wave as determined by the calculated F ratio, whereas their data points from the ambient region are best fit by a least squares line as determined by the calculated T ratio. Therefore we conclude that the data from *Samir and Wrenn* [1972] are consistent with an electron temperature enhancement in the spacecraft wake. However, the wake data from *Troy et al.* [1975] show evidence of a lack of electron temperature enhancement on one occasion and evidence of significant electron temperature enhancements on several other occasions.

Additional observations in the laboratory, downstream of bodies in the earth's ionosphere (e.g., in the wake of spacecraft and the shuttle tether), and downstream of Venus should enable us to ascertain the specific nature of the relevant phenomena and ultimately should result in an increased understanding of the underlying physical mechanisms that give rise to these phenomena.

Acknowledgments. This paper represents one aspect of research carried out at the University of Southern California under NASA grant NGR-05-018-181 and at Carmel Research Center under NASA contracts NASW-3513, NASW-3914, and NASW-4019. Many students at USC participated in the laboratory work. We particularly acknowledge the contributions of R. Dinning and D. Woodruff. The authors are very grateful to M. Dryer, U. Samir, N. Stone, and S. T. Wu for useful discussions of this research.

The Editor thanks W. Bernstein and another referee for their assistance in evaluating this paper.

REFERENCES

Alfvén, H., *Cosmic Plasma*, Kluwer Boston, Hingham, Mass., 1981.

Denavit, J., Collisionless plasma expansion into a vacuum, *Phys. Fluids*, *22*, 1384, 1979.

Draper, N. R., and H. Smith, *Applied Regression Analysis*, John Wiley, New York, 1966.

Gurevich, A. V., L. V. Pariiskaya, and L. P. Pitaveskii, Self-similar motion of rarefied plasma, *Sov. Phys. JETP* Engl. Transl., *22*, 449, 1966.

Gurevich, A. V., L. V. Pariiskaya, and L. P. Pitaevskii, Ion acceleration upon expansion of a rarefied plasma, *Sov. Phys. JETP* Engl. Transl., *36*, 274, 1973.

Hall, D. F., R. F. Kemp, and J. M. Sellen, Jr., Generation and characteristics of plasma wind-tunnel streams, *AIAA J.*, *3*, 1490, 1965.

Henderson, C. I., and U. Samir, Observations of the disturbed region around an ionospheric spacecraft, *Planet. Space Sci.*, *15*, 1967.

Illiano, J. M., and L. R. O. Storey, Apparent enhancement of electron temperature in the wake of a spherical probe in a flowing plasma, *Planet. Space Sci.*, *22*, 873, 1974.

Intriligator, D. S., Observations of mass addition to the shocked solar wind of the Venusian ionosheath, *Geophys. Res. Lett.*, *9*, 727, 1982.

Intriligator, D. S., and F. L. Scarf, Plasma turbulence in the downstream ionosheath of Venus, *Geophys. Res. Lett.*, *9*, 1325, 1982.

Intriligator, D. S., and F. L. Scarf, Wave-particle interactions in the Venus wake and tail, *J. Geophys. Res.*, *89*, 47, 1984.

Intriligator, D. S., and G. R. Steele, Observations of structuring in the downstream region of a large spherical model in a laboratory simulated solar wind plasma, *J. Geophys Res.*, *87*, 6053, 1982.

Intriligator, D. S., H. R. Collard, J. D. Mihalov, R. C. Whitten, and J. H. Wolfe, Electron observations and ion flows from the Pioneer Venus orbiter plasma analyzer experiment, *Science*, *205*, 116, 1979.

Intriligator, D. S., J. H. Wolfe, and J. D. Mihalov, The Pioneer Venus orbiter plasma analyzer experiment, *IEEE Trans. Geosci. Remote Sensing*, *GE-18*, 39, 1980.

Langmuir, I., and H. Mott-Smith, Jr., Studies of electric discharges in gases at low pressures, *General Electr. Rev.*, *27*, 449, 1924.

Liu, V. C., Ionospheric gas dynamics of satellites and diagnostics, *Space Sci. Rev.*, *9*, 423, 1969.

Nakagawa, Y., and S. T. Wu, On multifluids description of shock structure with radiation, *J. Quant. Spectrosc. Radiat. Transfer*, *8*, 555, 1968.

Oran, W. A., U. Samir, N. H. Stone, and E. G. Fontheim, Laboratory observations of electron temperature in the wake of a sphere in a streaming plasma, *Planet. Space Sci.*, *23*, 1081, 1975.

Perez-de-Tejada, H., D. S. Intriligator, and C. T. Russell, Orientation of planetary O^+ fluxes and magnetic field lines in the Venus wake, *Nature*, *299*, 325, 1982.

Podgorny, I. M., and R. Z. Sagdeev, Physics of interplanetary plasma and laboratory experiments, *Sov. Phys. Usp. Engl. Transl.*, *98*, 445, 1970.

Samir, U., and N. H. Stone, Shuttle-era experiments in the area of plasma flow interactions with bodies in space, *Acta Astronaut.*, *7*, 1091, 1980.

Samir, U., and G. L. Wrenn, Experimental evidence of an electron temperature enhancement in the wake of an ionospheric satellite, *Planet. Space Sci.*, *20*, 899, 1972.

Samir, U., R. Gordon, L. Brace, and R. Theis, The near-wake structure of the atmospheric explorer satellite: A parametric investigation, *J. Geophys. Res.*, *84*, 513, 1979.

Samir, U., K. H. Wright, Jr., and N. H. Stone, The expansion of a plasma into a vacuum: Basic phenomena and processes and application to space plasma physics, *Rev. Geophys. Space Phys.*, *21*, 1631–1646, 1983.

Schott, L., Electrical Probes, in *Plasma Diagnostics*, edited by W. Lochte-Holtgreven, 668 pp., North Holland, Amsterdam, 1968.

Sellen, J. M., Jr., W. Bernstein, and R. F. Kemp, Generation and diagnosis of synthesized plasma streams, *Rev. Sci. Instrum.*, *36*, 316, 1965.

Shuvalov, V. A., Structure of the near wake behind a cylinder in a nonequilibrium rarefied plasma flow, *Geomagn. Aeron. Engl. Transl.*, *20*, 293, 1980.

Singh, N., and R. W. Schunk, Numerical calculations relevant to the initial expansion of the polar wind, *J. Geophys. Res.*, *87*, 9154, 1982.

Stenzel, R. L., and W. Gekelman, Magnetic field line reconnection experiments, 1, Field topologies, *J. Geophys. Res.*, *86*, 649, 1981.

Stone, N. H., The aerodynamics of bodies in a rarefied ionized gas with applications to spacecraft environmental dynamics, *NASA Tech. Pap. 1933*, 1981.

Troy, B. E., Jr., E. J. Maier, and U. Samir, Electron temperatures in the wake of an ionospheric satellite, *J. Geophys. Res.*, *80*, 993, 1975.

D. S. Intriligator and G. R. Steele, Carmel Research Center, P. O. Box 1732, Santa Monica, CA 90406.

(Received July 26, 1983;
revised November 26, 1984;
accepted December 12, 1984.)