Plasma Diagnostics Package Measurements of Ionospheric Ions and Shuttle-Induced Perturbations

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The plasma diagnostics package (PDP) on the space shuttle STS-3 mission in March 1982 carried among its instrument complement a retarding potential analyzer. This instrument measured both the ambient ion plasma density and temperature, and perturbations to the plasma produced by shuttle orbiter effects. Whenever the plasma flow streamline at the instrument was more than a distance of the order of thermal ion gyroradii away from any orbiter surface, the measurements were characteristic of the ambient ionosphere. In several situations, the PDP was positioned so as to scan the wake in the plasma flow produced by orbiter surfaces. The density profile of the major species O⁺ was consistent with a classic Mach cone. However, strong perturbations extended for several meters outside the Mach cone which resulted in failure of flowing Maxwellian distributions to represent the data.

The PDP was lifted out of the orbiter bay by the remote maneuvering system (RMS) and moved according to a set of preprogrammed sequences. At other times, the PDP was manually positioned by the orbiter crew. In order to perform a series of scientific experiments, the PDP was manually positioned by the orbiter crew.

1. INTRODUCTION

The flight of the STS-3 shuttle mission during March 22–30, 1982, carried a pallet of science investigations (OSS-1) sponsored by the NASA Office of Space Science [Neupert et al., 1982]. Among the experiments on the mission was the University of Iowa’s plasma diagnostics package (PDP) [Murphy et al., 1983]. This instrument complement of the PDP included a retarding potential analyzer (RPA). The RPA was designed to measure the density and temperature of the major thermal ion species, both the ambient ionospheric plasma and perturbations to the ambient plasma produced by the presence of the shuttle orbiter. Other scientific objectives of the PDP included measurement of the electromagnetic environment around the orbiter, the neutral gas pressure in the orbiter cargo bay, and the effects of the electron beam of the vehicle on the ambient thermal ion parameters and perturbations to the ambient plasma produced by the shuttle orbiter. Among the experiments on the mission was the University of Iowa’s plasma diagnostics package (PDP) [Murphy et al., 1983].

Preliminary results from the PDP and from the electron beam experiments have been reported in the papers referenced above. More comprehensive studies, including the effects of water dumps and thruster firings, have been reported by Shawhan et al. [1984] and Pickett et al. [1985]. In this paper we concentrate upon measurements made by the RPA. The objectives of this experiment were to study interactions between the ambient ionospheric plasma and the orbiter, to determine under what conditions the RPA, in proximity to the orbiter, could make a valid measurement of ambient thermal ion parameters, and how the presence of the large orbiter body may have affected the measurements. The orbiter was large in the sense that its dimensions (37 m in length; 24 m wing span) exceeded the Debye length and the thermal ion and electron gyroradii. For typical ionospheric density and temperature parameters (see, for example, Sharp [1966] and Benson et al. [1977]), the Debye length is less than 1 cm. The gyroradii for ions in the range m = 16 to 30 and T = 1000° to 1500°K ranges from 5 to 10 m for B = 0.3 G. The ion sound speed Vₐ = kT/mₑ is 0.72–1.0 km/s for Tₑ = 1000°–2000°K, and therefore the orbiter with a velocity of 7.85 km/s was highly supersonic with Mach numbers (M = V_orb/Vₐ) in the range 7.8–11.

The STS-3 mission was launched March 22, 1982 (day 81), into a near-circular orbit with apogee of 237.1 km, perigee of 228.3 km, and inclination of 38°. For the data period of interest reported here, the local time of the ascending node varied from 5.53 to 6.24 hours.

The retarding potential analyzer was a conventional four-grid instrument with a planar grid structure. All grids were fabricated from electroformed mesh with 90% transmission. The entrance grid was 1.6 cm diameter, or 2.0 cm² in area. The retarding grid, shield grid biased at ground potential, and suppressor grid biased at -40 V completed the grid system. A guarded collector with a diameter of 4.0 cm was connected to the electrometer input. The shield grid served to isolate the retarding region from the relatively high suppressor potential, as well as to reduce capacitive coupling between the retarding grid and the collector. The intergrid spacing was 0.3 cm, and the geometry was arranged such that the angular acceptance range of 45° half-angle was defined by the projection of the entrance aperture onto the collector.

The collector current from positive ions was measured and conditioned for telemetry by a four-decade range-switching electrometer. The most sensitive range was 1.0 × 10⁻⁹ A full scale with eight-bit (0–255) resolution. The electrometer noise level was about 2 × 10⁻¹² A.

The retarding potential program was a stairstep sequence from 0.0 to 15.0 V in 0.5-V increments. The 0.0-V step was repeated in order to allow the electrometer to settle when transitioning from the 15.0-V step with minimum current to the 0.0-V step with maximum current.

In order to perform a series of scientific experiments, the PDP was lifted out of the orbiter bay by the remote maneuvering system (RMS) and moved according to a set of preprogrammed sequences. At other times, the PDP was manually positioned by the orbiter crew.
crew in order to place the PDP in a favorable position to diagnose the VCAP electron beam. The PDP could be positioned in X, Y, and Z coordinates relative to the orbiter and oriented in pitch, yaw, and roll by the RMS.

2. DATA ANALYSIS METHODOLOGY

The initial goal of the RPA data analysis was to determine the density and temperature of the major ion species and to see what effect, if any, the presence of the orbiter had upon these determinations. As we shall see, it was also necessary to consider the potential of the PDP relative to the ambient plasma. In the flight situation the PDP was attached to the orbiter by the RMS and the $\mathbf{V} \times \mathbf{B}$ electric field of approximately 0.2 V/m created significant potentials over the length of the orbiter. The amount of conducting area of the orbiter in contact with the plasma ($\approx 50$ m$^2$) was an order of magnitude larger than that of the PDP ($\approx 3$ m$^2$). Hence the electromotive force ($\pm 5$ V) was able to drive and sustain the PDP potential to values significantly different than the thermal energies of the ambient plasma. As well, the PDP potential could be a significant fraction of the ram energy of the plasma flow relative to the orbiter.

An example of a plot of the collector current versus retarding potential from the RPA is shown in Figure 1. The RPA equation found, for example, by Hanson et al. [1970] was fit to the data with a multiparameter least squares fitting procedure based on the routine CURFIT from Bevington [1969]. The fitting procedure was first attempted with a seven-parameter fit. The parameters were the density and temperature of O$^+$, NO$^+$, and O$_2^+$ and the PDP potential. However, the 0.5-V resolution of the RPA was only slightly less than the difference in ram energy between NO$^+$ and O$_2^+$ at orbital velocity. It was found that the fitting procedure was highly unstable and did not converge well. Tests of the fitting program with simulated data plus random noise showed that the fitted values would be in error by a factor of 2 or more and were not invariant under choice of differing random number seeds. Therefore the fitting technique chosen was to assume a two-ion flowing Maxwellian distribution composed of O$^+$ and NO$^+$. Admittedly, the choice of NO$^+$ as opposed to O$_2^+$ was somewhat arbitrary, but data from an ion mass spectrometer on the same spacecraft (J. M Grebowsky, private communication; OSS-1/STS-3 Post Mission Interim Science Report, 1982) show that in most cases the NO$^+$ density exceeded the O$_2^+$ density by a factor of 2 or more. Unfortunately, the ion mass spectrometer and the RPA were on opposite sides of the spacecraft, and since the spacecraft was not spinning, near-simultaneous data from the two instruments were not possible. The fitting program had five free parameters, specifically the density and temperature of O$^+$ and NO$^+$ and the PDP potential. The ram angle (angle between the instrument normal and the flow velocity) of the RPA and the orbiter velocity were known from the orbiter and RMS ancillary attitude data. The normal component of the ion velocity relative to the RPA was an input to the fitting procedure. The fitting procedure applied to the data of Figure 1 resulted in the following parameters: O$^+$ density = $1.1 \times 10^6$, O$^+$ temperature = 1450\textdegree K, NO$^+$ density = $2.5 \times 10^4$, NO$^+$ temperature = 2640\textdegree K, and PDP potential = $-2.6$ V.

The RPA grid design was such that there was no internal shadowing of the RPA collector by the grid structure until the ion angle of the incidence reached 45\textdegree. That is, up to 45\textdegree the effective area followed a cos $\theta$ dependence but fell more rapidly at higher angles. Fitting at higher angles would have involved a complex iterative convolution procedure with questionable accuracy. Therefore the fitting procedure was only done if the ram angle was 45\textdegree or less. This was a significant restriction in terms of the amount of data available for analysis. The PDP was out of the orbiter bay attached to the RMS for the periods day 84, 1620–2330 UT and day 85, 1500–2200 UT, or a total of 14.1 hours. Of this, only 154 min of data met the criterion that the ram angle was 45\textdegree or less.

The effects upon the plasma environment from STS-3 emissions of water and water vapor from the holding tanks and the flash evaporator system have been discussed by Pickett et al. [1985]. The effects of these chemical releases were seen in plasma wave data and in observations of enhanced plasma turbulence. None of the periods of available RPA data overlapped water release periods except for a short interval on day 85, 1622–1630 UT. No obvious effects could be seen in this segment, and any conclusions based on this one short period of overlap could hardly be justified. Therefore this study was limited to periods that were free of long-duration perturbations due to water releases but includes periods of thruster operations. These periods have also been shown to cause plasma perturbations [Pickett et al., 1985]. However, thruster operations were of brief duration, typically tens to hundreds of milliseconds, and the time resolution of the RPA data plus the method of data analysis emphasized long-term trends and obscured short-term effects.
3. COORDINATE SYSTEM

A word about the coordinate system used as the orbiter/PDP reference is in order. The shuttle coordinate system is Cartesian with the X axis along the fore-aft direction and +X toward the nose. X = 0 is arbitrarily located in the plane containing the nose of the external tank. The Z axis is the yaw axis with -Z being upward out of the cargo bay, and Z = 0 being along the centerline. Y completes the system, and +Y is toward the starboard (right) wing. The location of the orbiter velocity vector and the $\vec{B}$ vector was given in a modified polar coordinate system of co-elevation and azimuth, with co-elevation being measured from the -Z axis and azimuth being measured clockwise looking from above from the -X axis. The ancillary ephemeris and attitude data gave the X, Y, and Z position of the PDP and the pitch, yaw, and roll angles of the PDP in the orbiter system. These data allowed determination of the geometry of the plasma flow and $\vec{B}$ vectors relative to the orbiter/PDP system.

4. DATA

The PDP was first deployed on the RMS on day 84 at 1610 UT. For all of the periods that the PDP was deployed on the RMS, the orbiter was oriented with the +X axis toward the sun (nose to sun), and rolling twice per orbit such that at the ascending and descending nodes the -Z axis, upward out of the bay, was perpendicular to the ecliptic plane.

An example of plasma data in the local night ionosphere is shown in Figure 2a for the period day 85, 1745–1750 UT. The plot shows the density and temperature of O+ and NO+ and the value of the PDP potential. The orbiter latitude ranged from -28ø to -18ø during this period. The O+ and NO+ densities were near $10^5$ and $5 \times 10^3$ ions/cm$^3$, respectively, and the ion temperatures were near 1000 K. Note that during this period the PDP potential ranged from +1 to -2 V, a consequence of the changing value of the $\vec{V} \times \vec{B}$ electric field with changing orientation of the $\vec{B}$ field relative to the orbiter. Figure 2b shows an example of data for the sunlit ionosphere for the period day 84, 2115–2118 UT. The orbiter latitude ranged from 26ø to 31ø. Here the O+ density was $0.9-1.5 \times 10^6$ ions/cm$^3$, and the NO+ density was $2 \times 10^4$ ions/cm$^3$, and the ion temperatures ranged between 1100ø and 1500øK.

The geometry of the PDP and the orbiter is illustrated in Figure 3 for the data periods discussed above. The PDP was positioned 20.5 m above the level of the payload bay doors and 1.8 m right of the centerline as viewed from the front of the orbiter. The directions of the instrument normal and the range of directions of the plasma ram flow vectors are shown. It is particularly important to note that the PDP-orbiter separation exceeded all of the plasma scale sizes discussed earlier (Debye length and ion and electron gyroradii). Furthermore, the distance between the plasma streamlines upstream of the PDP and any orbiter surface exceeded the plasma scale sizes.

These two examples of data from the dark and sunlit ionosphere gave computed values of the ion densities and temperatures which were certainly reasonable [Sharp, 1966; Benson et al., 1977], and we consider this as a proof of the instrument and of the data analysis methodology. These examples show as well that under certain conditions, examined in greater detail later in this paper, an instrument attached to the orbiter is able to make valid measurements of the characteristics of the ambient ionosphere. This is particularly important to future space plasma missions where active experiments injecting particle beams, electromagnetic waves, and chemicals will require measurements of the ambient medium and perturbations of the medium in order to understand fully the plasma physics involved.

The roll of the orbiter twice per orbit meant that the plasma velocity vector was constantly changing in the orbiter coordinate system, and therefore there should be periods when the plasma flow at the RPA should have been shadowed by some portion of the orbiter structure. Two clear examples were found in the data. These are shown in Figures 4a and 4b for the time periods day 84, 1835–1840 UT, and day 85, 1650–1653 UT. Both of these periods are characterized by fluctuations in the computed values of the NO+.
The geometry of the orbiter-PDP system applicable to the data of Figure 2. The envelope of the payload bay doors, shown as the horizontal line, was the critical surface for both examples. The figure shows the PDP position, the direction of the instrument normal, and the range of directions of the plasma flow vectors for the two periods shown in Figure 2.

Density and of the ion temperatures. We do not claim that the computed values of the ion temperatures and the NO+ density represent the actual state of the plasma. The value of the x^2 goodness-of-fit parameter was >5 in most cases which indicated that the two-ion flowing Maxwellian model failed to fit the data. This explains as well the erratic behavior of the computed value of the PDP potential. These traces are shown primarily to illustrate that the plasma was highly disturbed, and the subsequent discussion will consider this in greater detail. Contrast these data with those shown in Figures 2a and 2b where the PDP was in a region of undisturbed flow and the computed plasma parameters displayed smooth variations.

The computed O+ density continued to give reasonable values. This is understandable since O+ is the major ion in terms of number density by at least one order of magnitude and the flow is highly supersonic. Therefore the collector current at zero retarding voltage continued to be an accurate measurement of the O+ density even in the presence of significant perturbations of the thermal distribution. The O+ density shows a marked decrease in the first case at day 84, 1839, and in the second at day 85, 1650 UT. The electron temperature rose sharply to 2100ºK. Furthermore, the An/n value increased markedly during this interval, indicating that significant levels of plasma turbulence were being generated.

Assuming a daytime ionosphere electron temperature of 1200ºK, the ion sound speed was 0.79 km/s, and therefore the Mach cone angle was 5.7º for the orbital velocity of 7.85 km/s. For a PDP location 10 m downstream of the wake-generating surface we would expect to encounter plasma density decreases when the PDP was within 1 m of the geometric shadow line. Examination of the geometry shown in Figures 5a and 5b shows this to be the case. However, the data also show that the concept of a fluid dynamic Mach cone is not strictly valid, for it is clear that prior to entering the Mach cone the PDP was not in a region of undisturbed flow, but rather there were significant perturbations to the plasma distribution function which resulted in failure of the assumed two-ion flowing Maxwellian distribution to fit the data, even when the PDP was outside of the Mach cone. Compare the distance scales shown in Figures 3 and 5. In the former case the PDP-orbiter separation was larger than the plasma scale sizes. In the latter it was not, and the disturbances to the plasma are evident.

The data examples discussed thus far represent cases when the RPA was either in a region of undisturbed plasma flow or when a known disturbance source, in particular, wake effects from orbiter surfaces, was perturbing the ambient plasma distributions. There are several instances, however, when the computed density and...
Fig. 4. Examples of daytime ionosphere data when the PDP moved into the downstream wake created by the orbiter payload bay door. Figure 4a is for the period day 84, 1835–1840 UT, and Figure 4b is for the period day 85, 1650–1653 UT. In Figure 4a the NO⁺ temperature has been shifted one decade.

Fig. 5. The geometry of the orbiter-PDP system applicable to the data shown in Figure 4 above. The horizontal line is the envelope of the payload bay doors. The PDP positions are denoted by crosses. Plasma flow vectors are depicted as dashed lines.
temperature of the major ion and the density of the minor ion were reasonable, yet the minor ion temperature displayed abnormally high values. An example of this behavior is shown in Figure 7. The major and minor ion temperatures are approximately equal at the beginning of the segment, as would be expected at an altitude of 250 km. The minor ion temperature then began to increase and reached an apparent value of over 10,000øK. The behavior shows a smooth trend, and as well, the $\chi^2$ goodness-of-fit values were small. This is in marked contrast to the situations discussed earlier when the plasma was disturbed by wake effects and the fitted values of the plasma parameters were erratic.

It is difficult to accept that such high temperatures of the minor ion reflect the true state of the ambient distribution. We assume, therefore, that this is an effect either of the data analysis procedure or of orbiter-plasma interactions. Both possibilities are now examined.

The possibility exists that the seemingly abnormally high temperatures seen in the NO$^+$ ion were a consequence of a change in the ionospheric composition such that the minor ions were O$_2^+$ rather than NO$^+$. It would seem logical that if the fitting program assumed that the minor ions were NO$^+$ (m = 30), and in fact there were a significant population of O$_2^+$ (m = 32), then the curve fitting program would converge to a higher temperature than was actually the case.

To test this assumption, the fitting program was run for simulated data input. As was done for the flight data, the fitting assumed that the ions were O$^+$ and NO$^+$, but the simulated data generation routine allowed specification of satellite potential and the densities and temperatures of O$^+$, NO$^+$, and O$_2^+$. Various test plasmas consisting of mixtures of O$^+$, NO$^+$, and O$_2^+$ were tried, but it was not possible to concoct a distribution that resulted in an artificially high value of the NO$^+$ temperature. Thus we are led to conclude that there was a suprathermal ion component present, and we now examine the conditions that resulted in these observations.

There were four periods in the data set that displayed these high NO$^+$ ion temperatures, and there were three aspects of the geometry that were common to all. The first was that the PDP was parked over the centerline of the orbiter bay. The second was that the plasma flow vector was at low coelevation angles (<55ø) and the azimuth ranged from 180ø to 270ø, or from generally above the orbiter, over the cabin. Under these conditions the plasma flow upstream of the PDP was well clear of any orbiter surface, but the flow downstream of the PDP impacted the larger surface area presented by the payload bay and doors, the wings, and the engine pods. The third condition was that the ram angle between the instrument normal and the flow vector was larger than about 20ø, as illustrated in Figure 8. Here are plotted the inferred density and temperature of the O$^+$ and NO$^+$ ions, along with the ram angle. During this period the coelevation ranged between 40ø and 25ø, and the azimuth ranged between 160ø and 270ø. Beginning at day 84, 2244 UT, the O$^+$ and NO$^+$ temperatures were nearly equal. However, it is seen that as the ram angle increased between 2247 and 2253 UT, the inferred NO$^+$ ion temperature increased as well. Between 2253:20 and 2255:00 UT the ram angle decreased from 45ø to 15ø, and this was accompanied by a decrease in the indicated NO$^+$ temperature.

The data would indicate that an interaction with the orbiter produced a heating of the NO$^+$ ion or, possibly, created hot NO$^+$ ions. This hot population was masked by the colder ram plasma when the RPA instrument normal was at small angles to the flow but became ever more apparent as the detector viewed away from the ram direction. With the limited angular resolution of the RPA, it was not possible to measure the angular distribution of this suprathermal component.

A companion instrument to the RPA was the differential ion flux probe (DIFP) mounted in the same package with a view direction colinear with that of the RPA. This instrument and data therefrom are discussed in detail by Stone et al. [1983]. The DIFP had a fan-shaped field of view of 5ø by 90ø which was electronically swept in the PDP Y-Z plane. (See Stone et al. [1983] for a detailed description of the geometry.) A significant result was that on many occasions the instrument detected a primary ion stream aligned with the bulk flow velocity and, simultaneously, secondary streams with angles up to 60ø from the ram direction. The intensity of these secondary streams ranged from 3 to 20% of the primary stream intensity. Stone et al. showed a specific example for day 85, 2112–2114 UT, where the secondary stream was 64ø away from the primary stream with an intensity ratio of 8%. RPA data for this same period, where the ram angle for the RPA was near the 45ø limit, showed O$^+$ densities near $2 \times 10^9$ ions/cm$^3$, but with erratic values of the other three ion parameters and a large value of the goodness-of-fit parameter $\chi^2$.

Recall that the fitting procedure assumes a two-ion flowing Maxwellian plasma. Departures from this model, such as the presence of a secondary stream component, would produce such a behavior in the computed parameters.

5. DISCUSSION AND CONCLUSIONS

At the outset, measurements of ambient plasma parameters with an instrument in close proximity to the shuttle orbiter may seem an impossible task. The orbiter is by no means a passive vehicle but...
rather, as has been shown, creates significant perturbations in the local medium with water and water vapor ejections and with firings of thrusters. It creates as well significant levels of electrostatic wave activity as it moves at a high Mach number through the background plasma [Murphy et al., 1983].

However, the data presented here have shown that valid measurements of the ambient ion parameters can be made if the instrument is positioned such that the separation between the instrument and the orbiter and the separation between the plasma flow streamline and the orbiter, especially upstream, is greater than the plasma scale sizes. Here the limit was set by the thermal ion gyroradii of approximately 10 m. The instrument, therefore, must be positioned on a boom or the RMS. However, this extension from the orbiter has the effect of driving the instrument to a nonequilibrium potential of a few volts by the \( V \times B \) electric field. This potential, which can easily be significantly higher than the ambient plasma thermal energies of \(-0.1\) eV, must be taken into account in the data analysis procedures. Other conditions which should be met to insure a valid measurement are the requirements that the instrument have a narrow acceptance angle, less than about 40° full angle and that the instrument normal be aligned parallel to the plasma velocity vector.

The examples of shadowing of plasma flows by the orbiter surfaces have shown (Figures 4a and 4b) that the density profile of the major ion varied as would be expected according to a fluid dynamic Mach cone. However, the plasma is strongly perturbed so that the model of a flowing Maxwellian fails to match the data, as evidenced by the erratic values of the fitted temperatures and the large values of the \( \chi^2 \) fit parameter. Shewchun et al. [1984] have reported PDP observations of a persistent electrostatic background noise which dominated the electric field spectrum at frequencies between 30 Hz and 178 kHz with a maximum intensity of 130 dB \( \mu V/m/MHz \) in the range 300–500 Hz. The frequency range of these waves encompasses the ion gyrofrequency, ion plasma frequency, and lower hybrid resonance frequency. We suggest that these electrostatic wave modes, whatever their generation mechanism, do in fact interact with the ambient ion distributions and perturb the plasma thermal distributions in the manner indicated above. However, the ion data from periods when the plasma flow streamlines are more than an ion gyroradius away from any orbiter surfaces, as illustrated in Figures 2a and 2b, show that these perturbations are localized and do not extend to large distances in the plasma.

Perhaps the most significant finding of this study is the observations of high-temperature components of the NO\(^+\) ions and to lesser extent the O\(^+\) ions. These high-temperature components were seen under a special set of conditions in the sunlit ionosphere. The PDP was in a position such that the plasma flow downstream of the PDP impacted on orbiter surfaces, and the detector normal was at a sufficiently large angle to the flow direction so that the high-temperature distribution was not masked by the ambient cold ion plasma flow.

Hanson and Cragin [1981] have reported observations of irregularities in retarding potential analyzer derivative curves \( (dV/dI/dV) \) on the Atmospheric Explorer C and D satellites. They interpreted these as due to irregularities in the major ion density, with \( \Delta N/N \approx 2\% \) and wavelengths of approximately 2.2 m. They argued that a two-stream instability driven by reflected ions with twice the satellite velocity in the ambient plasma frame was responsible. The dis-
persion relation for electrostatic lower-hybrid waves was calculated, and growth rates of the order of a few milliseconds were computed. They predicted as well that the effects would probably be more obvious in the vicinity of larger spacecraft.

Optical instruments on various shuttle missions have detected a glow adjacent to orbiter surfaces with estimates of intensities at optical wavelengths ranging from a few hundred Rayleighs to 10 kR [Banks et al., 1983b; Mende et al., 1983]. Papadopolous [1984] has proposed a mechanism for the generation of seed ionization in the neutral gas cloud surrounding the orbiter by ionospheric ions reflecting from the surfaces with relative velocities exceeding the critical velocity [Alfvén, 1954]. The newly created ions form an unstable distribution which leads to growth of electrostatic wave modes. The mechanism is similar to that proposed earlier by Hanson and Cragin [1981], although the former work did not specifically involve the critical velocity hypothesis and obviously did not include a neutral gas cloud traveling with the satellite. These waves in turn heat electrons which close the chain in a positive feedback sense by creating new ions by impact ionization. The model predicts creation of ion distributions with temperatures up to 110 eV, beams of ions with energies of 5–10 eV, and an electrostatic wave spectrum with frequencies in the orbiter frame of reference up to 20 kHz.

The observations reported here and elsewhere (see references) from the PDP instrumentation of plasmas and waves support, at least qualitatively, the predictions of the model of Papadopolous [1984]. The secondary ion streams observed by the DIFP [Stone et al., 1983], the electrostatic wave modes which intensify with water ejections and thruster firings [Murphy et al., 1983; Pickett et al., 1985], and the hot ion distributions reported here all are in agreement with various aspects of this model. It is interesting to note that according to the analysis given in the model, the wavelengths of unstable waves in the plasma near the ion plasma frequency and ion cyclotron frequency are of the order of tens of meters, that is, of the order of the orbiter dimensions.

In summary, this experimental effort has shown that strong perturbations to the ambient ion plasma can occur in the presence of the orbiter. In the case of geometrical shadowing by a surface or edge, the density variation of the major ion (with distance from the streamline) behaves as would be expected from a fluid dynamic Mach cone geometry. However, orbiter-plasma interaction effects extend to a few meters outside of the Mach cone and cause significant departures from a flowing Maxwellian distribution. The impact of the plasma flow with the orbiter creates high-temperature components of the ion distributions which are observed when the ion collector is looking away from the ram direction. However, we have also shown that valid measurements of ambient ion parameters can be made with an instrument attached to the orbiter on the RMS or a boom if the geometry is arranged such that the instrument and the plasma flow streamline are greater than about 10 m from any orbiter surface and the instrument is collimated around the plasma flow vector.

The next investigation with this RPA instrument on the PDP has occurred on the Spacelab 2 mission in July–August 1985. The PDP was released from the orbiter and functioned as a free-flying spinning subsatellite. By means of a series of orbiter maneuvers, the PDP "flew around" the orbiter and thus allowed detailed and systematic measurements of the structure of the plasma wake and perturbation regions both upstream and downstream.

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REFERENCES


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