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ELECTRON AND ION DENSITY DEPLETIONS MEASURED IN THE STS-3 ORBITER WAKE*

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The third Space Shuttle flight on Columbia carried instrumentation to measure thermal plasma density and temperature. Two separate investigations, the Plasma Diagnostics Package (PDP) and the Vehicle Charging and Potential Experiment (VCAP), carried a Langmuir Probe, and the VCAP also included a Spherical Retarding Potential Analyzer (SRPA). The Langmuir Probe on the PDP made measurements while the PDP was attached to the pallet in the Orbiter bay and while the PDP was articulated by the RMS. Only those measurements made while the PDP is in the payload bay are discussed here since the VCAP instrumentation remains in the payload bay at all times and the two measurements are compared.

Figure 1 illustrates the location of the PDP and VCAP instrumentation on the science payload pallet.

The principle thrust of this paper is to discuss the wake behind a large structure (in this case the Space Shuttle Orbiter) flying through the ionospheric plasma. Much theoretical work has been done regarding plasma wakes (ref. 1) and to a certain extent laboratory plasmas have provided an experimental and measurement basis set for this theory. The instrumentation on this mission gives the first data taken with a large vehicle in the ionospheric laboratory.

First, the PDP Langmuir Probe and its data set will be presented, then the VCAP Langmuir Probe and SRPA with associated data. A discussion of agreement between the two data sets is then followed by some other PDP data which infers an even lower wake density.

Lastly, conclusions, caveats and a description of future work which will further advance the measurement techniques and data set are put forth.

PDP LANGMUIR PROBE RESULTS

The PDP Langmuir Probe is a 6 cm diameter gold-plated sphere which is operated in two modes, the $\Delta N/N$ mode and the swept mode. The swept mode which is of concern

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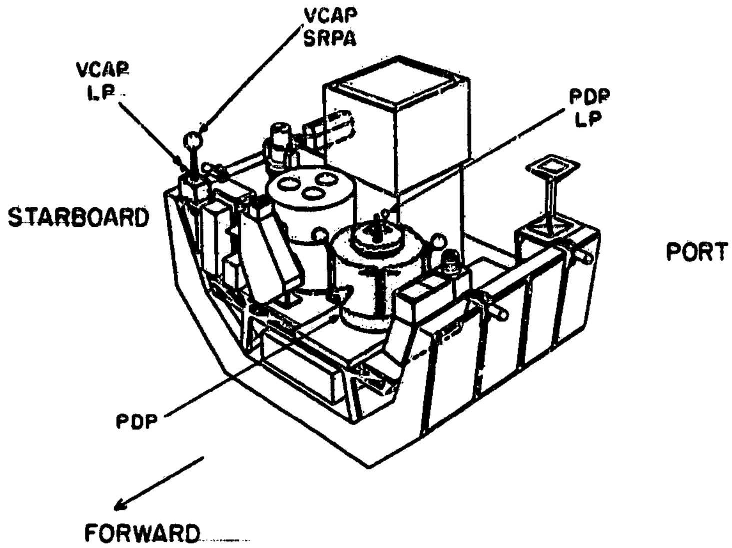

Figure 1. - Science pallet configuration on STS-3 showing location of instrumentation.

here is a 120 step voltage sweep which lasts 1.2 seconds and is executed 5 times per minute. The nominal density range of the probe is approximately 5×10^2 to $5 \times 10^6/cm^3$, the precise sensitivity depending on temperature. Operating in this mode, the Langmuir Probe has a current voltage characteristic whose slope is proportional to $1/T_e$ and which has a "knee" in the curve proportional to N_e.

There are two limitations to the PDP Langmuir Probe measurements. The first occurs when the plasma is too dense to really see the entire knee of the curve resulting in instrument saturation and an underestimate of density. The second occurs when the plasma temperature is too high and density too low to get a reliable slope resulting in only an upper bound on density and lower bound on temperature.

Figure 2 illustrates the electron density and temperature for one orbit as a function of vehicle attitude. (The data is repeated for a second orbit to provide clarity for the graph and illustrate a periodicity which is real). The vehicle attitude is described by θ_1 and θ_2 which are illustrated at the top of the figure. Maximum wake occurs when the vehicle flies tail first with the plasma ramming into the Orbiter belly (e.g. GMT 83:20:48). At this point in time, the vehicle is flying a nose-to-sun attitude with a 2 times orbit roll. (See figure 2 in the paper "Suprathermal Plasma Observed on the STS-3 Mission by the Plasma Diagnostics Package, by Paterson et al. (ref. 2) in this issue for a description of this attitude.) This results in a once per orbit ram/wake cycle which is evident in figure 2 by the e^- density and neutral density (pressure) measurements.

Several important observations summarize figure 2:

1. Although density is near ambient while the paylaod bay is neither pointing directly into the velocity vector or into the wake, there is evidence that the density may be 2 to 10 times ambient when the bay points close to the velocity vector. The probe saturates making reliable measurement above 2×10^6 difficult. The region cross hatched in figure 2 is where this higher density regime is encountered.

2. Density decreases rapidly as the Orbiter rolls into wake condition.

3. The minimum reliable measurement of density with the PDP probe is approximately 5 x $10^2/cm^3$. At least another order of magnitude decrease is required to pull the sweep totally offscale which is subsequently observed to happen. The sweep remains offscale for approximately 25 minutes centered around 83:20:48.

4. During all non-wake conditions, the temperature remains relatively constant at about 1000° (±30%).

5. Temperature rises rapidly as density decreases.

6. The highest reliable temperatures occur at 6000°K. However, the trend continues suggesting temperatures in excess of 7000°K in the deep wake.

It is also worthwhile to note that in near ram condition the neutral density (pressure) was almost two orders of magnitude above ambient ionospheric conditions and fell below 10^{-7} torr (the instrument sensitivity limit) during wake conditions.

THE VCAP LANGMUIR PROBE AND SRPA

Data on the characteristics of the ambient thermal plasma are extracted from the probes using a technique similar to that described by Raitt et al. (ref. 3). This AC technique employed for the probes enables direct measurement of the second derivative of the SRPA current-voltage characteristic and the first derivative of the LP current-voltage characteristic.

The SRPA signal is obtained by adding two sinusoidal AC signals (at 8.5 kHz and 10.7 kHz) to a sawtooth sweep voltage. The probe current is passed through a narrow band amplifier that selects the difference freqency of 2.2 kHz, which is a measure of the non-linearity of the probe current-voltage characteristic, and results in a signal proportional to the second derivative of the current-voltage characteristic. Two ac current ranges are available: one from -76 dB to -24 dB and the other from -40 dB to 0 dB relative to 10^{-7} amp rms. Each successive sweep of the probe alternates between the two ranges. Since the sweep period is 17 seconds the complete dynamic range is covered each 34 seconds.

The LP has only one AC signal (at 3.2 kHz) added to the sweep voltage. The amplitude of the alternating component of the probe current derived by using a narrow band amplifier tuned to 3.2 kHz enables the first derivative of the current voltage characteristic to be measured directly. A single dynamic current range, from -80 dB to +10 dB relative to 10^{-6} amp rms, is used for all sweeps. The range of the sawtooth voltage is from -2 V to +3 V, the period and phase of the sweep being synchronized to the SRPA sweep.

Figure 3 illustrates data taken under similar conditions as that taken by the PDP, although at a different time. In this case the vehicle attitude is different, but the same angles are used to characterize the direction of the velocity vector. The addition of the dark bar on this figure serves to show when day and night occur during the orbit.

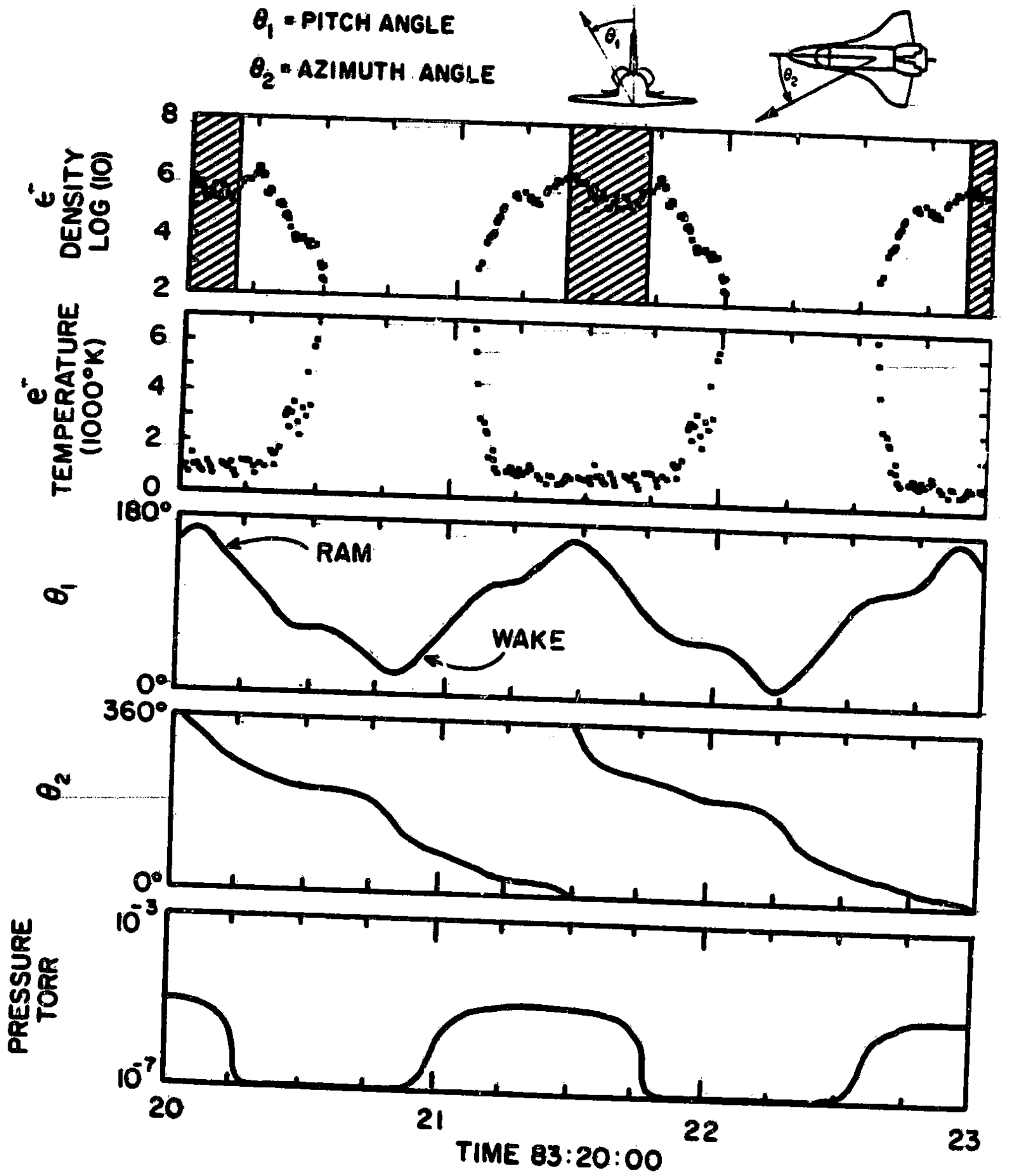

Figure 2. - Summary of PDP Langmuir probe electron density and temperature as function of vehicle attitude. Neutral pressure measurements are included for reference. Cross-hatched areas are where probe sweep saturates and routine used to calculate N_e underestimates density by as much as an order of magnitude.

The results of the Langmuir Probe (dotted line) and SRPA (solid line) generally confirm results of the PDP Langmuir Probe. VCAP Lan uir Probe temperatures are not plotted, but the following results are notable:

1. Close to ambient (1000°K) ionspheric temperatures are measured during non-wake condition.

2. As the Orbiter rolls into wake, a turbulence at all frequencies adds noise to the 3.2 kHz LP first derivative, but measurements indicate an increase in temperature to beyond 4000°K.

VCAP LP densities indicate the following:

1. An upper bound of electron density when the payload bay faces close to the velocity vector is $10^7/cm^3$.

2. Density during wake conditions drops to below the instrument sensitivity of 10^4 e/cm^3.

The SRPA measurements are difficult to interpret since the peak in the second derivative as a function of sweep voltage for the dominant ionospheric O^+ ion is often contaminated by locally produced H_2O^+ and NO^+. When the O^+ peak is clearly observable, several observations prevail:

1. Densities consistent with ambient ionospheric O^+ are observed for most conditions which shall be referred to as non-wake.

2. > 2 orders of magnitude depletion occurs in the near wake.

ADDITIONAL EVIDENCE FOR LARGE DEPLETION

Additional evidence for a many order of magnitude depletion in the electron density in the near wake is provided by what amounts to a sounder experiment. Recall that the VCAP SRPA is excited with a signal at 8.5 and 10.7 kHz. The PDP contains a 16 channel (± 15% bandwidth) spectrum analyzer capable of detecting electrostatic or electromagnetic waves over a frequency range from 30 Hz to 178 kHz. The instrument has a saturation of approximately 1 V/m electric field amplitude and a usable dynamic range of about 95 dB.

During most of the orbit, the Spectrum Analyzer output is dominated by broadband orbiter generated electrostatic noise, (ref. 4) thruster firings or other events. Figure 4 illustrates that as the wake boundary is approached, the electrostatic noise disappears in all channels simultaneously and as the payload bay is immersed deeper in the orbiter's wake a signal in the 10 kHz channel grows to a point of dominance in the spectrum. This in fact is the VCAP SRPA signal. As the density drops so that the plasma frequency nears or drops below 10.7 kHz, this signal can propagate to the PDP sensor. Detailed calculations and modeling are being done taking field strengths and sensor separation into account, but preliminary work suggests that although the PDP Langmuir Probe infers densities, $< 50/cm^3$, the density probably drops at least another order of magnitude to $< 5/cm^3$. This would be approximately six orders of magnitude of plasma depletion in the near wake from that measured under ram condition.

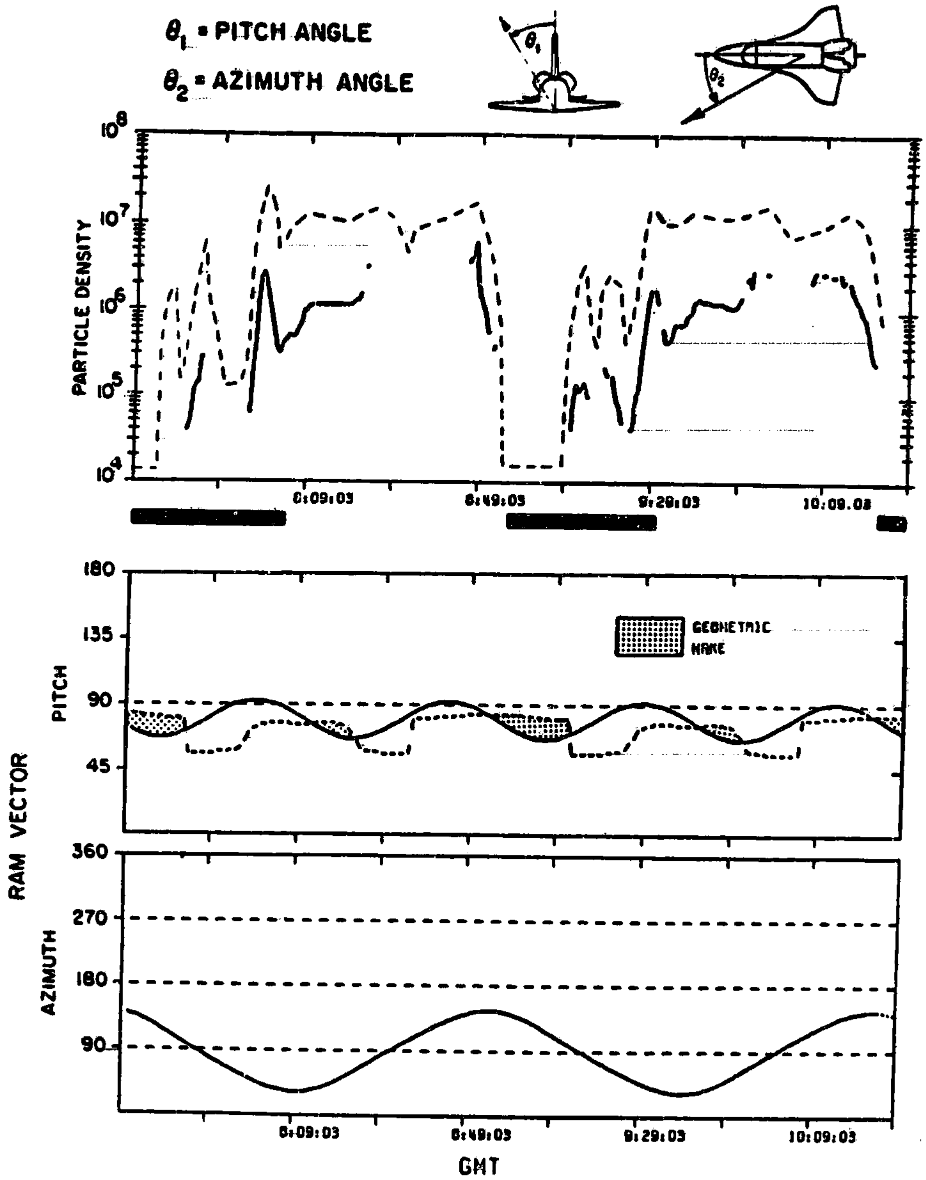

Figure 3. - Summary of VCAP Langmuir probe (dotted line) and SRPA (solid line) results as function of vehicle attitude.

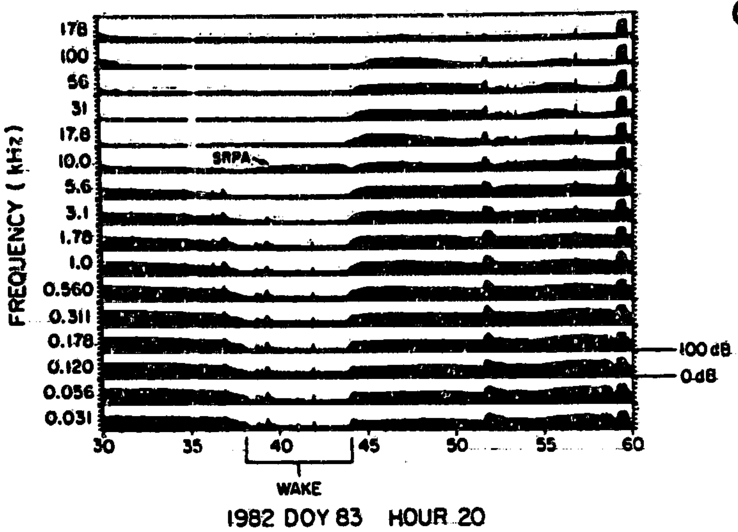

Figure 4. - VLF electric field spectrum showing increasing intensity of received SRPA signal.

SUMMARY

Although measurements are still in a primitive state, several conclusions can be drawn from the STS-3 PDP and VCAP data.

1. Ram conditions seem to result in a higher than expected electron density.

2. Density depletions of at least 4 orders of magnitude in the wake plasma are observed and there is evidence to suggest this depletion may be as high as six orders of magnitude.

3. Effective temperature measured by the thermal plasma probes indicate an increase in electron temperature in the wake to > 6000°K.

4. The thermal ions are excluded rapidly as the orbiter bay rolls into wake and only those locally produced H_2O^+ and NO^+ are measurable.

5. Both LP's and the SRPA indicate a degree of plasma density or velocity turbulence which peaks in the transition region between ram and wake.

Several concerns about these measurements are that: first, the VCAP probes' outputs are often contaminated by the turbulence which causes bias in the data; second, the ability of the PDP LP to measure density and temperature reliably beyond a certain limited range is questionable; and third, whether the sounder experiment setup between the VCAP SRPA and PDP Spectrum Analyzer is "calibratable" is still an open question.

The first concern is being worked and there is confidence that corrections for the turbulence can be computed. Recall that the PDP LP has a $\Delta N/N$ mode which can provide upper bounds on the turbulence within a given frequency band.

The second concern, which applies to a lesser degree to the VCAP LP, is harder to solve. As the density decreases and temperature increases, the size of the probe in relation to a debye length and thermal electron gyroradius changes drastically. This means that approximations used to derive temperature and density are no longer valid and new formulations must be used. A long-term research effort is underway to better understand the behavior of swept probes in these extreme regimes. (See ref. 5 for a description of the probe theory). Meanwhile, effort has been made to include data in this report derived from regimes where approximations hold. Thus, the densities and temperatures are probably good to a factor of two.

It is encouraging to note that when comparisons are made to measurements made by the DE satellite, which flew through the same altitude and latitude regime within the same day, general agreement is found. The DE data show dayside conditions of N_e = .9 -1.1 x $10^6/cm^3$ and T_e = 1500° - 2000° while the PDP and VCAP data taken dayside out of wake and also out of maximum ram condition indicate N_e = 2 to 10 x $10^6/cm^3$ and T_e = 1000° (± 30%).

The third concern is currently being worked and if the "sounder" is calibratable, it should provide valuable input for theory.

The fact that elevated temperatures are observed in the near wake of a spacecraft is not without precedence. Samir et al. (ref. 6) found evidence for elevated electron temperatures in the wake of Explorer 31, a much smaller vehicle than the Shuttle Orbiter.

Additional measurements by the PDP and VCAP instruments will be made on Spacelab-2 where detailed experiments have been designed to study the structure of the wake out to approximately one kilometer from the vehicle.

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