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# RAM/WAKE EFFECTS ON PLASMA CURRENT COLLECTION OF THE PIX II LANGMUIR PROBE

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Data returned from the NASA PIX II flight of January 1983 were analyzed and the results are presented herein. The PIX II experiment carried a Langmuir probe, an electron emitter, biasable solar array segments, a Sun sensor, temperature sensors, and other instruments. Its approximately 900-km polar orbit allowed measurements of the currents collected from the magnetospheric plasma in polar and equatorial regions.

PIX II Langmuir probe readings of the same polar magnetospheric regions taken on consecutive orbits showed occasional apparent densities as much as 10 times lower than the average, although each pass clearly showed density structures related to the day/night boundary. At other points in the orbit, Langmuir probe currents varied by as much as a factor of 20 on a time scale of minutes.

The hypothesis is advanced that these apparent inconsistencies in Langmuir probe current are the results of the probe's orientation relative to the body of the spacecraft and the velocity vector. Theoretical studies predict a possible depletion in collected electron current by a factor of 100 in the wake of an orbiting spacecraft of the velocity and dimensions of the PIX II Delta upper stage. Experimental results from other spacecraft indicate that a wake electron depletion by a factor of 10 or so is realistic. This amount of depletion is consistent with the PIX II data if the spacecraft was rotating. Both the Sun sensor and temperature sensor data on PIX II show a complex variation consistent with rotation of the Langmuir probe into and out of the spacecraft wake on a time scale of minutes. Furthermore, Langmuir probe data taken when the Sun sensor indicated that the probe was not in the spacecraft wake are consistent from orbit to orbit. This supports the interpretation that ram/wake effects may be the source of apparent discrepancies at other orientations.

Analyses of variations in the Sun sensor and temperature sensor data are in progress that in combination with limited information obtainable about the spacecraft orientation may allow the attitude to be modeled to determine the ram/wake orientation at any time. Empirical corrections can then be made to the Langmuir probe data and to the solar array plasma current collection data. The amount of the corrections and the corrected data themselves contribute to our knowledge of the electrical interaction of spacecraft with the orbital environment.

## INTRODUCTION

The PIX II satellite was launched into a polar orbit on January 25, 1983, to investigate interactions between high-voltage solar arrays and the orbital plasma environment. During analysis of the PIX II data it has become evident that the plasma density as indicated by currents collected by the PIX II Langmuir probe varied in a way inconsistent with real ambient plasma density variations. In this paper the nature of the problem is discussed, and the hypothesis is presented that the currents measured while the Langmuir probe was in the spacecraft wake were much smaller than would be measured by a probe outside the wake. The amount and kind of corrections that must be applied to the readings to derive true plasma densities from straightforward probe theory provide information about large spacecraft wakes.

## THE NATURE OF THE PROBLEM

The current collected by a spherical probe of radius $r$ and positive voltage $V$ in a plasma of electron number density $n_e$ and temperature $T$ is, according to probe theory (ref. 1),

$$I = \frac{n_e\sqrt{\frac{2kT}{m_e}}\,4\pi r^2}{2\sqrt{\pi}}\left(1 + \frac{Ve}{kT}\right)$$

for a probe whose radius is small compared with the plasma sheath. Here $k$ is Boltzmann's constant, $e$ is the electron charge, and $m_e$ is the electron mass. The Langmuir probe on the PIX II satellite was about 1 cm in radius and nominally extended about 0.6 m from the spacecraft on a boom. At the nominal 900-km PIX II orbital altitude and 50-V applied potential, the Langmuir probe was in the thick sheath limit and $Ve >> kT$, so that

$$I \propto n/\sqrt{T}$$

if the influence of the spacecraft can be neglected.

There are indications that for the PIX II Langmuir probe, the influence of the spacecraft cannot be neglected. Being in a polar orbit, PIX II traversed regions near the north and south poles where consecutive orbital paths intersected as seen from the rotating Earth. Figure 1 shows the orbital paths near the north geomagnetic pole for several orbits. The convention used here for orbit numbering is that orbit 1 begins at the first south polar passage after launch. Thus orbit 2 begins at approximately program count 267. Each orbit is about 384 16-sec program counts long. In the conference paper by N. T. Grier the start of revolution 1 coincides with the Langmuir probe deployment at program count 116. Thus orbit 1 here starts 233 program counts before revolution 1 of Grier. Figure 2 shows the PIX II Langmuir probe current readings for the two consecutive orbits near the north pole labeled orbits 2 and 3 in figure 1. Although the behaviors of the current with time before and after the night/day crossing were similar for the two orbits, the absolute levels differed by about 1 on the $\log_{10}$ scale, or about a factor of 10. Quantitatively, the correlation coefficient between the logs of the currents for these passes with the times of the night/day crossing aligned is 0.78 (for a confidence level of greater than 99 percent), but the difference in <log> is 0.939. Similar effects are shown for other orbits. Unless the magnetospheric electron densities or temperatures can vary <u>uniformly</u> over the polar cap by a factor of 10 in less than 100 min, we must infer that the Langmuir probe currents are sometimes much higher or lower than the electron densities would necessitate in naive probe theory.

Another indicator of the reliability of the Langmuir probe currents as density and temperature indicators can be obtained by comparing them with readings from other satellites. Fortunately, the Defense Meteorological Satellite Program satellite DMSP/F6 was simultaneously taking data in an orbit nearly identical in inclination to the PIX II orbit at an altitude of 833 km (not too different from the ~890-km PIX II altitude). The data obtained by this satellite (and kindly supplied by Frederick Rich of the Air Force Geophysics Laboratory) were compared with the PIX II data for orbits corresponding most closely in day/night orientation and geomagnetic longitude and latitude. The calculated DMSP ion densities (to be used because there was a negative bias on the DMSP satellite) were compared with the PIX II Langmuir probe electron collection currents for consecutive equatorial passes of the two satellites (fig. 3). The qualitative behaviors were quite similar and the correlation coefficients were quite high for these data, an indication that changes in electron/ion density were followed by both satellites. However, again the multiplicative factor relating the two measured currents was quite different from orbit to orbit, varying by as much as a factor of 6.5 from orbit 2 to orbit 3. Again, the PIX II currents seemed to be uniformly lower in orbit 3 by a large factor for the same regions of the magnetosphere as measured by DMSP/F6. Note that all of the PIX II Langmuir probe currents used in this analysis were made with the solar panels biased at voltages more negative than 30 V to eliminate any effects of vehicle charging.

A logarithmic plot (fig. 4) was made of the PIX II Langmuir probe current versus the DMSP/F6 ion density for a large sample of closely corresponding magnetospheric data points. Here, points where the DMSP/F6 ion density was a rapidly varying function of time or geomagnetic latitude have been thrown out. Although the correlation is high (0.78) and significant (at the >>99 percent level), the 50 data points seem to show a well-defined narrow upper range, with a downward trail of a few Langmuir probe currents to a factor of about 10 lower than the upper limit. It is significant, and consistent with the picture obtained in figures 2 and 3, that the Langmuir probe current on PIX II was occasionally depressed by as much as a factor of 10 from that expected from the true electron density and simple probe theory.

Although the PIX II Langmuir probe current was highly correlated with that of the DMSP/F6 sensors, neither was well correlated with a calculated model ionosphere supplied by H. B. Garrett of JPL. Evidently the Langmuir probe on PIX II and the ion sensor on DMSP/F6 both measured highly correlated physical quantities, but occasionally the Langmuir probe's readings were abnormally low. It is desirable to understand the discrepancy fully.

## THE RAM/WAKE HYPOTHESIS

A rapidly moving body traveling through a plasma will leave a wake disturbance. This is easily seen to be true for ions when the velocity of the body exceeds the ion thermal velocity. It is also true that the electrons will feel a wake influence because of the predominantly negative space charge built up in the wake by the partial ion evacuation there. The shape of the wake region for a moving sphere is a trailing cone with a half-angle $\theta$ given by (ref. 1)

$$\tan \theta = \frac{\sqrt{2kT_i/m_i}}{v} \tag{1}$$

where $m_i$ and $T_i$ are the ion mass and temperature and $v$ is the velocity of the moving body. The potential in the wake cone may be more negative than that of the body by an amount (ref. 1)

$$V_- = -\frac{2kT}{e} \ln \frac{R}{\sqrt{\epsilon_0 kT/n_i e^2}} \tag{2}$$

where $\epsilon_0$ is the permittivity of free space, $n_i$ is the ion density, and $R$ is the body radius. For a neutral body this limits the thermal electrons that might collect on the trailing edge of the body to those able to surmount this negative potential barrier. Calling the density of such electrons $n_b$, one has

$$\frac{n_b}{n} = e^{-2\ln R/\sqrt{\epsilon_0 kT/n_i e^2}} = \frac{\epsilon_0 kT}{n_i e^2 R^2} \tag{3}$$

Taking the radius of the PIX II Delta upper stage ($R = 0.76$ m) and putting in $n_i \doteq 10^{10}$ $m^{-3}$ and $T = 2900$ K (extrema from Garrett's model) yield

$$V_- = -1.5 \text{ V}$$

$$\frac{n_b}{n} \leq 2.4 \times 10^{-3}$$

for PIX II. If it is further assumed that only these electrons could be attracted by a positively charged Langmuir probe in the vehicle wake, the collection current of the Langmuir probe could go down by a factor of 400 in the wake of a neutral spherical body with the Delta's radius.

The extent of the Delta wake can be estimated from equation (1). The distance $d$ of the tip of the wake cone from the surface of the Delta upper stage is

$$d = R\left(\frac{1}{\sin \theta} - 1\right) = R\left(\sqrt{1 + \frac{1}{\tan^2 \theta}} - 1\right) \tag{4}$$

which, assuming equation (1) and spherical geometry, is

$$d = R\left(\sqrt{1 + \frac{v^2 m_i}{2kT}} - 1\right) \tag{5}$$

Since the spacecraft environment contains ions of different species, which is indicated in parentheses after $d$, each ion will have a wake region of different extent. Putting in $v = 7.4$ km/sec, $T = 2000$ K, and $R = 0.76$ m results in

$$d(O^+) = 3.23 \text{ m}$$

$$d(H^+) = 0.48 \text{ m}$$

$$d(He^+) = 1.34 \text{ m}$$

The boom on the Delta on which the Langmuir probe is deployed extends it to about 0.6 m from the Delta surface. Thus the Langmuir probe is never in the hydrogen ion wake but can be in the oxygen and helium ion wakes. From the model data of Garrett the lowest percentage by number of hydrogen ions is about 36 percent. If the wake potential barrier is then lessened by the presence of $H^+$ ions at the Langmuir probe location, the total reduction in collection current is expected to be substantially less than calculated earlier.

More realistic estimates of the wake effect on electron current collection can be obtained by examining data from other satellites. Figure 2 of Samir and Stone (ref. 3) shows that the Ariel I, Explorer 3, and AE satellite data are consistent with a maximum reduction of wake electron collection current by a factor of about 10 at a 900-km altitude. Thus the occasional factor-of-10 reduction in PIX II Langmuir probe current is consistent with the hypothesis that the probe is in the $O^+$ and $He^+$ wake when the reduction occurs.

There is evidence that during the flight the PIX II satellite was in a complex rotation that allowed the Langmuir probe to be carried into the spacecraft wake. Both the Sun sensor (a photocell mounted on the solar array panel) and the array temperature sensor showed readings that varied in a manner consistent with rotation or precession with respect to the Sun. In addition, data returned by Delta launch telemetry and kindly provided by Elizabeth Beyer of Goddard Space Flight Center (private communication) indicate that in the early stages of the flight the Delta upper stage was precessing and rotating with at least one period near 100 min. Unfortunately, the time span over which the data were taken was too short to allow an adequate determination of the geometry and frequency of rotation and precession.

Further analysis of all available Sun sensor, temperature, and telemetry data is needed with the goal of modeling the PIX II attitude to allow determination of the ram/wake orientation at all times in the flight.

## EVIDENCE FOR THE RAM/WAKE HYPOTHESIS

Although the absolute orientation of the PIX II satellite at all times in the flight has not been determined, there are some rough indications of the attitude at certain times. For instance, the Sun sensor can indicate times when the Sun is high on the solar array. Since the Sun was at a very high angle to the orbital plane and the array was roughly opposite the Langmuir probe on PIX II, a condition of high Sun on the array implied that the Langmuir probe was probably not in the vehicle wake. A map constructed of Langmuir probe currents for the high-Sun condition showed no discrepancies between adjacent orbits of more than a factor of 3, consistent with most points in figure 4 (presumed not to be in the wake).

Perhaps the best test of whether the Langmuir probe currents were at times not indicative of the true plasma density is to show that a real physical effect follows not the Langmuir probe current but another indicator of the plasma density. N. J. Stevens (ref. 4) has shown that for solar arrays in the laboratory, the negative breakdown voltage decreases with increasing plasma density. Such an effect should also be seen in orbit if the indicator of plasma density used is reliable and the biased array is not in the vehicle wake. To insure this, the PIX II data were searched for breakdowns that occurred when the Langmuir probe (LP) current was much lower than the DMSP/F6 satellite current. Such an occurrence was taken to mean that the Langmuir probe was in the vehicle wake, so that the solar array opposite was not in the vehicle wake. The voltage at which the solar arrays arced versus the corresponding DMSP/F6 ion density was plotted (fig. 5) for all breakdowns occurring when

$$\log_{10} \text{(LP current)} \leq \log_{10} \text{(DMSP ion density)} - 9.90$$

For these points there is a relation between breakdown voltage and ion density in the same sense as Stevens found. Quantitatively, $\log_{10} V_{arc}$ is correlated with $\log_{10}$ (DMSP ion density) with a correlation coefficient of -0.73, significant at more than the 99.9 percent level for these 20 data points.

$$\log_{10} V_{arc} = -0.34 \log_{10} \text{(DMSP ion density)} + 4.26$$

The same breakdown voltage was plotted versus the Langmuir probe current presumed to have been read in the spacecraft wake (fig. 6). This diagram has a correlation coefficient of -0.68, which is lower than the correlation with the density found by another satellite. Also, most of the correlation was due to one data point of very low current. The least-squares fit here is

$$\log_{10} V_{arc} = -0.20 \log_{10} \text{(LP current)} + 1.59$$

Thus for these data the LP current is a worse indicator of the PIX II plasma density than the readings of the DMSP/F6 satellite. Furthermore, although these data were selected in a way that should have produced a correlation between $\log_{10}$ (LP current) and $\log_{10}$ (DMSP ion density) even for originally uncorrelated data, the correlation for these points was only 0.27, not significant at the 80 percent confidence level and consistent with a large degree of randomness. It may be concluded that when the Langmuir probe currents were abnormally low they were no longer a valid indicator of the plasma density at the solar array.

The Langmuir probe currents (fig. 4) can sometimes be as much as 10 times lower than normal, so that a maximum correction factor of 10 may be appropriate for plasma densities derived from LP currents when the probe is deepest in the vehicle wake.

## CONCLUSIONS AND IMPLICATIONS

The ram/wake hypothesis seems to satisfactorily explain the variations in Langmuir probe current from orbit to orbit on the PIX II satellite. The time scale for vehicle rotation or precession may be short enough to place the Langmuir probe in the vehicle wake in one orbit and outside the wake on the succeeding orbit. Theoretical considerations make the amount of the variation plausible, and comparisons with ion densities found by a satellite in a similar orbit show the same range of discrepancy. Furthermore, when the probe might have been in the wake, probe currents were poorly correlated with the array breakdown voltage, as compared with the correlation of other plasma density indicators.

The importance of these results can be summarized in the following way: first, the PIX II Langmuir probe data must be used with caution if simple probe theory is used to infer plasma densities. Second, when the probe is in the wake, correction factors of up to 10, depending on the geometrical circumstances, must be applied to the Langmuir probe currents to derive plasma densities simply. Third, wake effects can be significant for collection currents on large spacecraft and may be a consideration in the geometrical design of large solar arrays. Whenever possible, for instance, an array should perhaps be fitted with "blinders" on each side or other devices to put the array in a plasma wake and to minimize leakage currents while maximizing breakdown voltages. Finally, the amount of diminution of the PIX II Langmuir probe current when the probe is in the vehicle wake may be important to understanding vehicle/plasma interactions.

The PIX II data analysis should be continued in order to model the vehicle orientation. It may be possible to find the correction factor necessary for any angle of attack with respect to the vehicle velocity vector. This would make PIX II a laboratory for studying not only collection currents and breakdowns but also the dynamic interaction between a large space vehicle and its stationary plasma environment.

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4. Stevens, N. J.: Interactions Between Large Space Systems and Low Earth Orbit Plasmas. AIAA 83-0310, Jan. 1983.

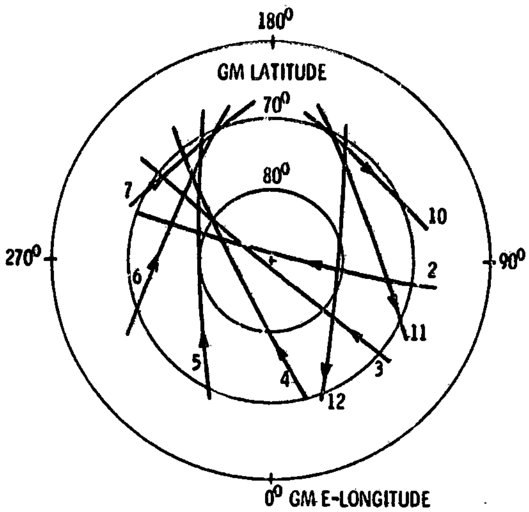


Figure 1. - Orbital paths near north geomagnetic pole.

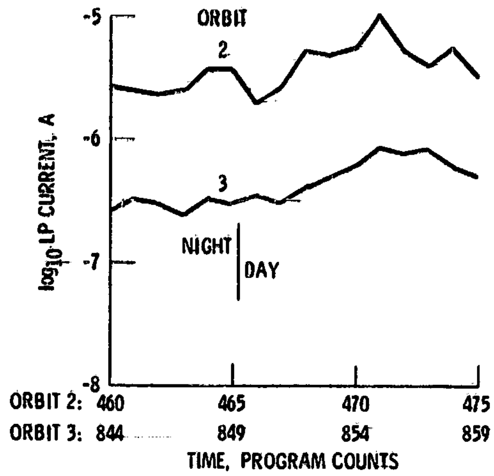


Figure 2. - PIX II Langmuir probe current readings for two consecutive polar passes. (Corresponding points are never more than 5° apart in geomagnetic latitude nor 9° apart in geomagnetic longitude. Geomagnetic latitude, >68°.)

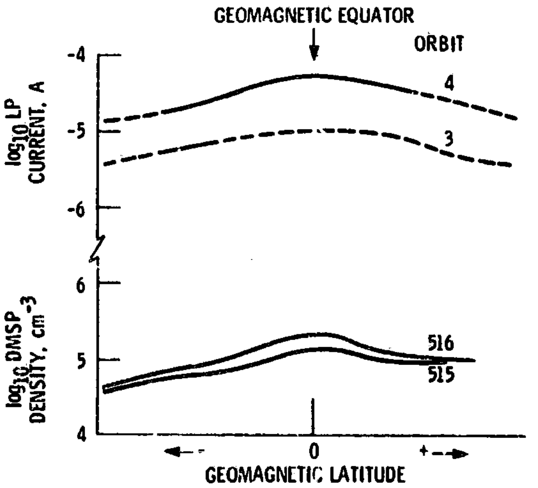


Figure 3. - PIX II orbits and corresponding DMSP/F6 orbits.

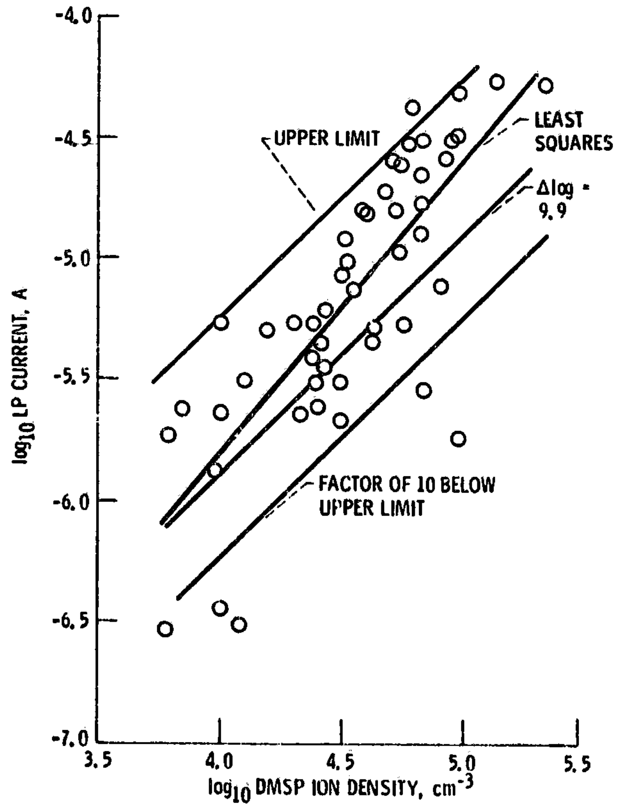


Figure 4. - Langmuir probe current versus ion density.

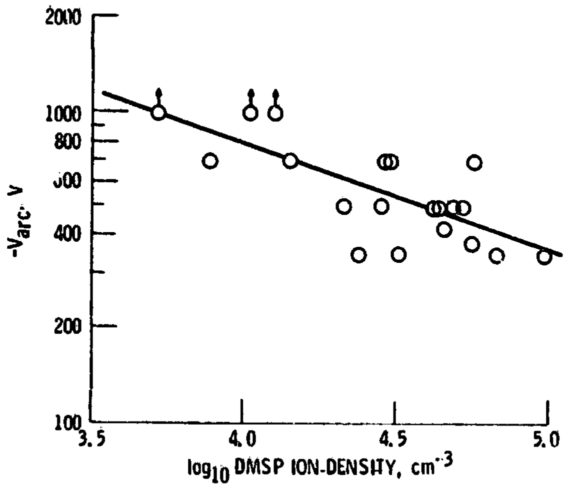


Figure 5. - Array arcing voltage versus ion density - array not in wake.

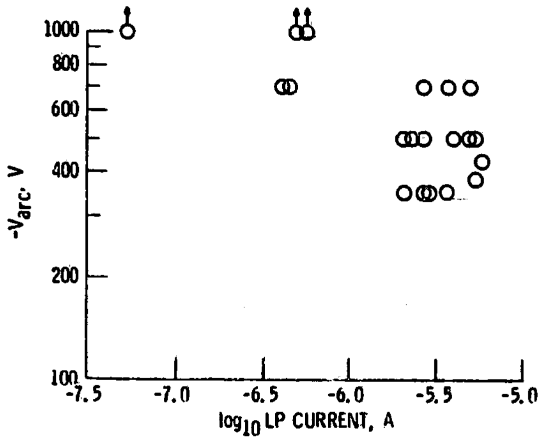


Figure 6. - Array arcing voltage versus Langmuir probe current - Langmuir probe presumed in wake.