A Review of the Findings of the Plasma Diagnostic Package and Associated
Laboratory Experiments: Implications of Large Body/Plasma
Interactions for Future Space Technology

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1.0   Introduction

The purpose of this report is to review the discoveries and experiments
of the Plasma Diagnostic Package (PDP) on the OSS 1 and Spacelab 2 missions,
to compare these results with those of other space and laboratory experiments,
and to discuss the implications for the understanding of large body
interactions in a LEO plasma environment. The paper is logically divided into
three sections. First a brief review of the PDP investigation, its
instrumentation and experiments is presented. Next a summary of PDP results
along with a comparison of those results with similar space or laboratory
experiments is given. Last of all the implications of these results in terms
of understanding fundamental physical processes that take place with large
bodies in LEO is discussed and experiments to deal with these vital questions
are suggested.

2.0   PDP instrumentation and experiments

The PDP is a small cylindrical satellite with a complement of instruments
designed to measure plasma density and temperature, give ion composition,
temperature and flow direction, provide complete electron and ion distribution
functions, and measure electron flux from electron beams. In addition to
these comprehensive particle measurements the PDP contains instrumentation to
provide a complete set of single axis wave and field measurements. Waves
(both electric and magnetic) are measured from approximately 10^1 to 10^5 hz and
electric fields are measured both at DC and from 10^1 to 10^7 hz. A complete
description of the PDP instrumentation is available in Shawhan 1984c.

The PDP was designed not only as a satellite, but because it was to be
flown and deployed from the Orbiter; it was also capable of measuring the
plasma environment in and around the orbiter bay by being maneuvered through
various positions on the Shuttle Remote Manipulator System (RMS) arm. The
initial experiments and measurements made by the PDP on the OSS-1 (STS-3)
Mission were all made either in the payload bay on a pallet or within
approximately 10 meters of the bay on the RMS. As will be seen in the next
section these early shuttle experiments helped provide insight into the
shuttle orbiter environment, conducted the first orbiter-based active plasma
experiments, and provided some of the first insights in large body
interactions at LEO. In addition, the OSS-1 experiments provided the baseline
from which many of the future detailed interaction issues could be addressed.
Spacelab 2, which repeated (with some modifications) some of the OSS-1
experiments and extended the range of interaction studies to nearly a
kilometer from the orbiter, benefited greatly from the earlier OSS-1
experience. The PDP investigation was initiated by Prof. Stanley D. Shawhan
(who is now at NASA Headquarters) and is currently under the leadership of
Prof. Louis A. Frank at the University of Iowa. Other members of the PDP team

include Donald A. Gurnett and Nicola D'Angelo (U. of Iowa), Nobie H. Stone, David L. Reasoner (NASA/MSFC) and Joseph M. Grebowsky (NASA/GSFC). Numerous other scientists and engineers both at the U. of Iowa and NASA have played a major role in the program since its inception in 1978.

3.0 The early results

Early papers from the OSS-1/PDP program focused on defining the environment of the shuttle orbiter. This environment was a critical question mark in the eyes of many future users of the shuttle particularly in the areas of contamination, plasma, and electromagnetic environment.

3.1 The neutral environment

Early measurements of the neutral pressure environment of the orbiter revealed that the ambient pressure at orbital altitudes was only obtainable in the near wake of the vehicle and then only after a long period of outgassing. Even after seven days in orbit, pressure averaged at least an order of magnitude greater than ambient (Shawhan, 1984c). Not until Spacelab-2 analysis was available would the probable source of such a large vapor cloud be revealed.

More detailed investigation of the source of large pressure enhancements led to the study of thruster operations. It was reported that the thrusters (in particular Primary RCS and to a much less degree Vernier RCS) introduce major changes in plasma density, ion composition, neutral density, electric fields, and electrostatic plasma waves (Shawhan, 1984c; Murphy, 1983; Pickett, 1985). Other investigators have since reported similar results noting neutral density increase of up to $10^{18}/m^3$ inside the payload bay ($\sim 7 \times 10^{-5}$ Torr) with NO a major component of the enhancement (Wulf, 1986).

3.2 The plasma environment

The plasma density and apparent DC electric field shifts observed near the orbiter are not yet totally understood but may be related to interactions of the neutral constituent of the gas plume with the ambient plasma or to the plasma component per se.

Grebowsky et al. (1983) reported the surprising result that H_2O^+ is a major constituent of the plasma near the orbiter sometimes even dominating the ambient O^+ ionosphere. The source of these water ions is believed to be in charge exchange reactions between the ambient O^+ ions and a cloud of H_2O molecules generated by outgassing around the orbiter. This H_2O cloud may indeed be a major contributor to the enhanced neutral pressure environment.

The plasma environment near the orbiter not only has an altered ion composition but reveals the influence of a large body moving supersonically through its medium. Stone et al. (1986) observe the ions streaming by the orbiter and study in detail the structure of the wake behind the vehicle. They took particular note of multiple "beams" of ions with different apparent source directions and theorize that this is consistent with not only an additional source of ions close to the orbiter but may imply an E-field sheath associated with a boundary between the ion source region and the undisturbed plasma. It could in fact be that this additional source region is consistent

with observations of Grebowsky (1983) on the production of H_2O^+ near the orbiter.

Reasoner et al. (1986) have underscored the problem of making reliable ambient ionospheric density/temperature measurements near the orbiter. Combinations of contaminant ions, plasma turbulence generating heating, and ram/wake effects make it imperative to move well away from the orbiter before relying on an RPA to reliably characterize the ionosphere. This observation is of course consistent with all previously discussed results.

Electron densities and temperatures near the orbiter are reported by Murphy et al. (1986). To first order, electron densities are dominated by the ram/wake effects associated with large bodies. The orbiter is not only large compared to the debye length (10^3–$10^4 \lambda_D$) but also large compared to the electron and ion gyroradius. This size results in the investigation of a unique and unexplored region in parameter space and creates perhaps more questions than it answers. Murphy et al. (1986) report density depletions of as much as 5 orders of magnitude in the near wake of the orbiter (within the payload bay) and less dramatic though significant depletions of 1-2 orders of magnitudes at distances reachable by the RMS. Moreover, apparent temperature enhancements of $\geq$ factors of 5 are observed in the wake transition region. This transition region is also characterized by plasma "turbulence" with $\Delta N/N$ values of typically several per cent. Secondary effects controlling the electron density spacial variation involve: 1.) the possible enhancement of electron density in ram (compared to ambient), Shawhan (1984c), Raitt (1984); 2.) the effect of the neutral cloud around the vehicle and the photoionization of that cloud, Pickett (1985); 3.) the role of the magnetic field both in the filling in of the wake and the production of V × B potentials in the orbiter reference frame.

3.3 Electromagnetic environment

The AC and DC electric and magnetic fields on and near the orbiter are driven by two sources: 1.) orbiter EMI associated with the hardware per se; 2.) fields associated with the interaction between the orbiter and its environment.

The orbiter EMI under JSC's leadership and Rockwell's cooperation proved to be much more benign than the original ICD specifications would indicate. Shawhan (1984b) and Murphy (1984b) reported in detail the measurement of that environment. By using the PDP's sensitive plasma wave receivers and various RMS maneuvering sequences a "map" of orbiter EMI revealed that the environment was dominated not by orbiter generated noise but by plasma interaction noise. This Broadband Orbiter Generated Electrostatic (BOGES) noise (Shawhan, 1984b) seemed to be associated with plasma turbulence around the orbiter and had field strengths as great as .1 v/m with a relatively flat spectrum up to ~ 10 khz. Although the exact mechanism was not understood, Murphy et al. (1984a), suspecting that it was similar to the turbulence observed by the Langmuir probe, indicated that it was noise of relatively short wavelength ($\lesssim$ 1 m). This noise was observed to be enhanced by any sort of gas release (thruster, water dump, etc.) implicating the gas cloud as a production mechanism. Theoretical work by Papadopolous (1984) suggested that the gas

cloud may provide the "fuel" for enhanced plasma densities by the critical ionization velocity phenomenon and may be intimately involved in the production of this BOGES noise.

Thus we see that the understanding and characterization of the orbiter environment requires detailed investigation of the inter-reactions between the orbiter body, its contaminant cloud, and the ionospheric plasma.

For purposes of completeness it should also be emphasized that a large part of both the OSS-1 and Spacelab-2 missions were devoted to detailed study of the behavior and interactions of an electron beam propagating in the ionosphere. These studies were conducted jointly with the Vehicle Charging and Potential (VCAP) experiment (Banks, 1986). The OSS-1 results are reviewed by Banks (1986) and Shawhan (1984a). Since another paper in this proceedings describes the VCAP/PDP results in detail no further discussion will be given here.

4.0 Spacelab 2, laboratory results, and the emerging picture

Many of the results discussed above began to be published after the Spacelab-2 mission which was launched in July 1985 but early results had a significant influence on the science objectives and experiment planning of Spacelab-2. The landmark nature of the plasma experiments of Spacelab-2 will gradually emerge over the next several years and, in particular, the importance of the PDP free-flight activity, described briefly below, in understanding large vehicle interactions, will become quite obvious. This is especially true in light of the hiatus of Spacelab type missions in the coming years.

After performing about 12 hours worth of experiments on the RMS which consisted of wake studies, EMI surveys, and joint experiments with VCAP, the PDP was prepped for release as a sub-satellite of the orbiter. The PDP free-flight scenario consisted of approximately 6 hours of complex maneuvers by the shuttle orbiter which controlled, in a carefully planned sequence, the relative positions of the PDP and orbiter.

First, a release and back-away maneuver moved the PDP down the "throat" of the orbiter wake to a distance of ~ 100 meters. After several station-keeping experiments the orbiter began a "fly-around" of the PDP. Part of the fly-around was executed in plane so the PDP would transit the orbiter wake at distances from 40 to 200 meters. The other part of the fly-around was out of plane moving the orbiter above and behind the PDP and targeting two flux-tube-connections (FTC's) per orbit. These FTC's were planned so that they occurred out of the orbiter's wake with one in the daytime ionosphere and one at night. The FTC's were quite successful in placing the PDP and the orbiter on the same magnetic field line at a relative distance of ~ 200 meters. These FTC's were believed to be accurate to within several meters at best to a little more than 10 meters at worst. After two "fly-arounds" and several wake transits were completed the orbiter approached and captured the PDP along the velocity vector, again allowing the PDP to examine the near wake. Dealing with topics as a continuation and refinement of the OSS-1 results we first discuss the neutral environment.

4.1 Neutral environment and the contaminant gas cloud

Further measurements by the PDP neutral pressure gauge taken during pallet operations verified the high pressure environment due to early on-orbit outgassing. Analysis of vernier thruster operations verified that only the aft down pointing verniers affected pressure in the bay (Pickett, 1986). No further observations of primaries are possible because of an instrument malfunction. A strong point to be made from Pickett's observations are that large instruments which vent gases can also have dramatic effects of the payload bay environment, raising pressure to as high as 10^{-5} Torr. The orbiter's outgassing is now known to have a major effect on the local environment.

The contaminant ion gas cloud observations were extended to ~ .5 km from the orbiter. Grebowsky, 1986 observed contaminant H_2O^+ ions in all directions around the orbiter. The presence of contaminant NO and O_2^+ ions was also reported. It is important to note that the dominant ion in the wake of the shuttle appeared to be H_2O^+ instead of ambient O^+.

If these ions are created by change exchange with O^+ analysis of their distribution function would indicate a ring in velocity space. Reports by Paterson, 1985 provide evidence that this is indeed the case and an attempt to model the outgassing and chemical reactions associated with it is currently under way. Observations of the Infrared telescope on Spacelab-2 may provide additional data on outgassing rates and the structure of the water cloud which appears to surround the vehicle.

4.2 Further studies of the orbiter wake

Investigation of the structure and dynamics of the orbiter wake both on the RMS and as a free flyer are being continued. More detailed examination of the wake turbulence indicate that the magnetic field orientation may affect the structure of the turbulent zone (Tribble, 1986). Comparisons of the electron density observed in the wake are being made with predictions of the NASA POLAR code (Katz et al., 1984) and early results indicate the code may be quite accurate at predicting at least the first order effects on electron density. The details associated with magnetic field effects, the role of the plasma turbulence and pick up ions, and processes which produce the heated electrons (Murphy, 1986) still must be investigated. Although a detailed review of wake investigations conducted both in the laboratory and in space is presented elsewhere in the proceedings it is relevant to discuss briefly some laboratory results which complement the Spacelab studies.

4.3 Complementary laboratory investigations

In addition to observing the wake region behind large objects as they pass through the near earth plasma, it is found profitable to perform laboratory experiments in order to gain some insight into the plasma-wake environment. Although the parameters may not scale directly to the plasma that has been examined above, such experiments suggest new avenues for the spacelab investigations of the future. Herein, we shall review a few recent experiments performed in laboratory plasma environments whose volume is of the order one cubic meter, possessing plasma numbers of $n_e = n_i \approx 10^6 - 10^8$ electrons/cm^3; $T_e \approx$ 1-3 eV and $T_i < T_e/10$.

Alikhanov et al. (1971) studied the flow into the wake region created by a flowing plasma passing a rectangular plate that was at floating potential. In an extended study, Eselevich and Fainshtein (1980) noted that the expansion of the plasma from the undisturbed region into the wake could be modeled with a self similar description. This can be understood from the governing fluid equations of continuity

$$v_b \delta n/\delta z + \delta(nv)/\delta x = 0$$

and motion

$$v_b \delta/\delta z + v\delta v/\delta x = -c_s{}^2 \delta(\ln n)/\delta x$$

where the quasineutral plasma has been assumed to be moving as a beam in the z direction with a velocity of v_b. The ion acoustic velocity is c_s. These equations are identical to the problem of a neutral gas or a quasineutral plasma expanding into a vacuum and solutions in terms of the self similar variable $\zeta = x/(z/v_b)$ can be obtained. The POLAR model discussed previously uses such a quasineutral approximation. Similar results concerning the self similar expansion into the wake region behind a grounded metal plate were reported by Wright et al. (1985). In the very near wake region where quasineutrality would be violated, it was found that the potential would be the important self similar dependent variable by Diebold et al. (1986). In this case, the dependent self similar variable becomes $\zeta = x/(z/v_b)^2$ as shown by Lonngren and Hershkowitz (1979).

As the wake region has a lower density than the ambient flowing plasma, one might conjecture that the electrons due to their higher mobility would rapidly enter the wake, creating an electric field which would accelerate the ions to velocities greater than the ion acoustic velocity. The accelerated ions have been noted in the experiments of Wright et al. (1985), (1986) and Raychaudhuri et al. (1986). The potential well that would result from such a space charge was observed in the orbiter wake by Murphy et al. (1986). That the electrons can speed ahead of the ions was recently detected by Chan et al. (1986). Ions could also enter the wake region by being deflected around the perturbing objects as was recently noted by D'Angelo and Merlino (1986a), (1986b) in an experiment performed in a plasma in a weak magnetic field oriented in the direction of the plasma flow. These experiments show results reminiscent of those by Stone 1986 where streams of converging ions were observed behind the orbiter. Finally, a series of experiments designed to examine the flow of plasma around magnetized objects has been described by Hill et al. (1986). These would be related to the TERRELLA type of experiments except that the present experiments were performed in a very low β plasma environment ($\beta \approx 10^{-4}$). A general characteristic of the observations in this experiment was that the magnetic object "appeared" to be larger for the electrons than the ions since the electron wake had dimensions that were larger than the ion wake.

Hence, we see that the laboratory experiment provides a controllable environment in which to suggest future paths for space experiments or to explain certain space observations. Future work needs to better define the role of the magnetic field and the charge on the object in question. It should be noted however that it is difficult to simulate in the laboratory conditions similar to the orbiter where the magnetic field can be perpendicular to the flow vector and where gas cloud interactions modify the

observations.

4.4 Electromagnetic environment and active experiments

Further definition of the electromagnetic environment has shown that the BOGES noise extends as far from the orbiter as the PDP observed, and was strongest along field lines connecting to the orbiter and in the turbulent wake zone (Gurnett, 1986a). Gurnett has also verified that the noise is electrostatic in nature and has very short wavelength. Considerable theoretical efforts are currently under way to determine the fundamental process creating such noise.

Of further interest may be a series of joint experiments with VCAP where, during two flux tube connection experiments, dramatic comparisons to the physics of whistler mode radiation in auroral arcs has been discovered (Gurnett, 1986b).

Further active experiments conducted by using the orbiter OMS engines to produce a cloud of water vapor and deplete the ionosphere (Mendillo, 1981; Mendillo et al., 1978) showed significant plasma depletion, as measured in the orbiter payload bay, recovering on the timescale of seconds after engine shutdown (Tribble et al. 1985). Tribble also reported a high level of plasma "turbulence" which lasted tens of seconds indicating the presence of instabilities. This phenomenon may be similar to that observed by RCS ignition and reported by Murphy et al., 1984a, and Shawhan et al., 1984b.

5.0 Summary

It is important, with such a wide range of data, to put together an emerging picture of the Shuttle orbiter interactions and then systematically address the experiments which need to be conducted in order to further the science/technology of large body interactions.

Although laboratory and small satellite observations can shed light on details of wake structures, and the electric fields associated with them, large bodies such as the orbiter pose some unique problems. Is the orbiter a comet? In many respects, there are similarities. It definitely carries its own gas cloud and understanding how large objects such as the orbiter, platforms, or space station interact with the plasma depends on more than a scaling of laboratory experiments.

Part of the interactions around large objects are due to the "scale size" effect while others are distinctly interrelated to outgassed products and the change in the balance of the ambient chemical equilibrium. As described by Grebowsky et al., 1986, the instrumentation required to completely disgrace the ionospheric chemistry and simultaneously determine all key plasma parameters requires careful consideration of the specific problems the spacecraft must study. The PDP is only a first generation experiment with instrumentation that was not optimized for studies such as "comet" problems.

Future experiments must be designed both for space and in complementary laboratory setting which can, if not solve the following problems, at least determine by appropriate empirical means their impact on future technologies. These problems include:

1. What is the effect of gas clouds associated with large objects on their interaction with the neutral atmosphere and plasma?

    a. How does the cloud affect the wake fill process?

    b. Is the orbiter cloud large enough to create a pick-up current of such magnitude that it partially screens the motional electric field? (Pickett, et al., 1985; Goertz, 1980; Katz et al., 1984).

    c. For large objects such as space station, could the energy dissipation associated with such a cloud create significant anomalous drag?

    d. How does the cloud affect the charge neutralization process and current loops associated with tethers, or particle beams?

    e. What is the effect of such a cloud on the operation of a plasma contactor?

2. The interactions of large structures with the ionosphere through electromotive forces associated with differential charging, absolute charging, and closed current loops are not well understood.

3. The phenomena of vehicle glow, its relationship with the plasma, the neutral cloud and the interacting surface have given rise to conflicting theories with insufficient data to resolve the issue. (Green, 1985)

4. Understanding of the total picture associated with large body wakes involves more than models of electron and ion density. Wave particle interactions, atmospheric chemistry, vehicle charge, and magnetic fields must be included in the analysis.

5. Joint particle beam experiments such as those between PDP and VCAP have raised many questions about the propagation of beams from structures like the orbiter. This is an immature experiment because until SL-2 no experiments (other than short sounding rocket flights) have provided remote diagnostics on such beams. (See the paper by Banks et al. in this proceedings for more detail.)

6.0 Recommendations

The Challenger accident has dealt a severe setback to the space experiments associated with large body/plasma interactions. It is unfortunate that the space station is set to proceed on course with little opportunity in the next 6 years for detailed study of the technical issues that should be resolved before it proceeds.

Studying such problems requires a commitment by NASA to a program which must involve the development of instrumentation adequate to measure the appropriate parameters, flights of opportunity within the next five to six years for such instruments, support of working groups consisting of experimentalists who may have relevant data from past missions and theorists attempting to model the phenomena and, last of all, well designed and executed laboratory experiments.

Last of all it is of paramount importance that those scientists and engineers involved with the state of the art of large body interactions, gas cloud dynamics, high voltage effects, etc. have effective knowledge transfer to those individuals and organizations making the design decisions of the future.

Acknowledgements

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