INTERACTION OF THE SPACE SHUTTLE ORBITER WITH THE IONOSPHERIC PLASMA

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ABSTRACT

The Plasma Diagnostics Package (PDP), which flew as part of the NASA Office of Space Science (OSS-1) payload on STS-3 consisted of an instrument complement capable of characterizing the plasma environment in and around the Space Shuttle Orbiter. These measurements coupled with those made by the Vehicle Charging and Potential (VCAP) experiment also on OSS-1, as well as diagnostics from subsequent flights, provide insight into the effects a large vehicle such as the Orbiter has on the ionospheric plasma. Modification of the environment by contamination such as Orbiter outgassing, thruster operation and water dumps results in altered neutral pressure, modified plasma density and an altered chemical composition. The physical size and velocity of the Orbiter vehicle produces a plasma wake, generates electric fields, results in surface effects and generates broadband electrostatic noise.

Keywords: Large Vehicle Interaction, Wake, Ionospheric Plasma, Shuttle Environment

1. INTRODUCTION

1.1 Background

Until the flight of STS-3 in March 1982 little opportunity was available to study the interactions of a vehicle whose scale was large compared to an ion gyroradius and that was moving at a high velocity with respect to a relatively dense and cool plasma. Table 1 summarizes the plasma parameters in the F2 ionosphere and includes Orbiter parameters of interest.

Extensive theoretical work has been done on the problem of plasma wakes. Stone (Ref. 1) provides an excellent summary of this research and more recently Samir et al (Ref. 2) have studied the expansion of a plasma into a vacuum and discussed such phenomena as ion streams, rarefaction waves, and plasma instabilities and suggest appropriate in situ measurements on the space shuttle.

1.2 Instrumentation

Instruments aboard the Plasma Diagnostics Package (PDP) were designed to measure thermal particle densities and temperatures, energetic particle distribution functions, electric and magnetic fields, and electrostatic and electromagnetic waves. Table 2 lists the complement of instruments aboard this experiment and the parameters they measure. The PDP was designed both for on pallet measurements and as an RMS (Remote Manipulator System) probe. The PDP was lifted out of the bay with the RMS and maneuvered around the Orbiter in sequences designed to measure the electric and magnetic fields, electrostatic and electromagnetic waves as well as the thermal and energetic particle environment.

Table 1.

Plasma Parameters		
Ambient Density	$n_e \cong 10^5 - 10^6 \text{ cm}^{-3}$	
Ambient Temperature	$T_e \cong 1200° - 2400°K$	
Electron Gyroradius	4.3 cm	
Ion Gyrodadius	~ 4m (O^+)	
Ion Thermal Speed	1.3 km/sec	
Orbiter Parameters		
V_{orb} = 7.8 km/sec	Surface Area:	
	Insulator	~ 1400m^2
Mach # 5-8	Conductor	~ 60m^2
Characteristic Length	37m long, 24m wingspan	

Other investigations of interest to this discussion that were part of the OSS-1 payload were the VCAP (Vehicle Charging and Potential) experiment and the FPEG (Fast Pulse Electron Gun). (For a complete description of the OSS-1 experiment complement see Neupert et al Ref. 3). The VCAP investigation consisted of charge and current probes (primarily for measuring vehicle capacitance with respect to the plasma), a Langmuir Probe (LP) for measurement of electron density and temperature and a Spherical Retarding Potential Analyzer (SRPA) for ion density and temperature.

1.3 The STS-3 Mission

Since STS-3 was still a flight test mission, the payload had a low priority for selection of flight attitude and the one chosen as a compromise for the payload/orbiter objectives lead to difficulties in sorting out day/night and ram/wake

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Table 2.

- LOW ENERGY PROTON AND ELECTRON DIFFERENTIAL ENERGY ANALYZER (LEPEDEA)
  - Nonthermal Electron and Ion Energy Spectra and Pitch Angle Distributions for Particle Energies between 2 eV and 50 keV
- AC MAGNETIC WAVE SEARCHCOIL SENSOR
  - Magnetic Fields with a Frequency Range of 30 Hz to 178 kHz
- TOTAL ENERGETIC ELECTRON FLUXMETER
  - Electron Flux 10^9 - 10^{14} Electrons/cm^2 Sec
- AC ELECTRIC AND ELECTROSTATIC WAVE ANALYZERS
  - Spectra with a Frequency Range of 30 Hz to 800 MHz
  - Electric Field Strength at S-Band, 2.2 GHz
- DC ELECTROSTATIC DOUBLE PROBE WITH SPHERICAL SENSORS
  - Electric Fields in one axis from 4 mV/m to 4 V/m
- DC TRIAXIAL FLUXGATE MAGNETOMETER
  - Magnetic Fields from 12 Milligauss to 1.5 Gauss
- LANGMUIR PROBE
  - Thermal Electron Densities between 10^3 and 10^7 cm^{-3}
  - Density Irregularities with Frequencies of .5 Hz to 178 kHz
- RETARDING POTENTIAL ANALYZER/DIFFERENTIAL ION FLUX PROBE
  - Ion Number Density from 10^2 to 10^7 cm^{-3}
  - Energy Distribution Function below 6 eV
  - Directed Ion Velocities up to 15 km/sec
- ION MASS SPECTROMETER
  - Mass Ranges of 1 to 64 Atomic Mass Units
  - Ion Densities from 20 to 2 X 10^7 Ions cm^{-3}
- PRESSURE GAUGE
  - Ambient Pressure from 10^{-3} to 10^{-7} Torr

effects. The attitude of the Orbiter for all of the PDP data presented here is referred to as Nose-To-Sun (NTS) with a 2x orb rate roll (see Figure 1). This attitude results in a cyclic ram/wake cycle for instruments in the payload bay such that maximum ram occurs around ascending node and maximum wake at descending node.

Effects of the Space Shuttle Orbiter on the ionospheric plasma will be discussed in two parts. The first is induced contamination which will be treated only briefly and the second are effects induced by the vehicle's size, velocity and electrical properties.

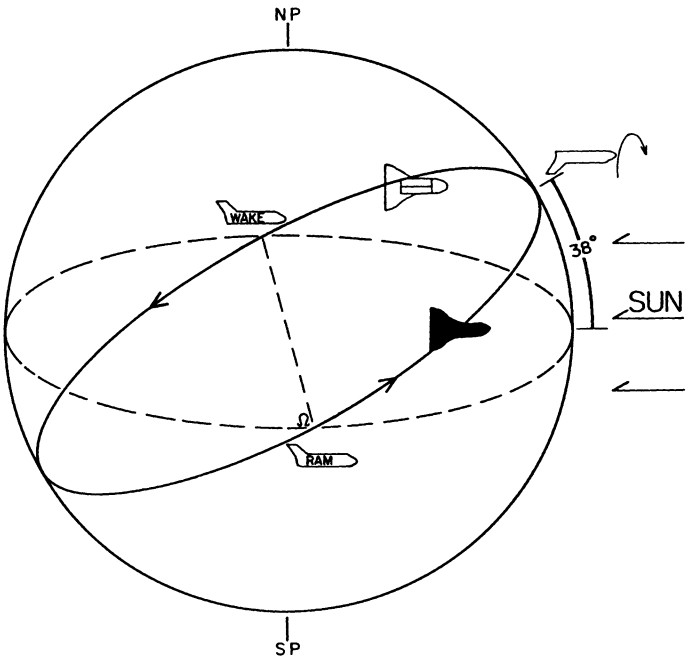

Figure 1. STS-3 Orbit Attitude

2. INTERACTION VIA CONTAMINATION

Electromagnetically, the Orbiter is relatively clean. Shawhan and Murphy (Ref. 4) indicated that both transmitters and unintentional interference are well below Interface Control Document specs. The predominant noise turned out to be the ubiquitous broad band electrostatic noise which will be discussed in the next section.

The principle form of modification via contamination takes the form of chemical releases. These chemicals; water, nitrogen, hydrogen and traces of other heavier molecules, enter the ionosphere as a result of Orbiter outgassing, thruster firings, and water dumps. In a discussion of the pressure environment, Shawhan and Murphy (Ref. 5) pointed to high payload bay outgassing rates that bring neutral pressure to 4 x 10^{-5} torr when the doors are closed in orbit. The gas cloud did not decrease significantly as the mission progressed evidenced by enhanced pressures when the payload bay was turned "Top-To-Sun" on the sixth day of the mission.

A Bennett Ion Mass Spectrometer utilizing retarding potentials was capable of separating the ambient ionospheric ions from those released by the Orbiter. Results reported by Grebowsky et al (Ref. 6) indicate that the expected O^+ ion is predominant, but that there is a significant amount of H_2O^+, NO^+ and CO_2^+. Narcisi et al (Ref. 7) on a subsequent shuttle flight, confirm the presence of high concentrations of H_2O^+ and noted that at times over one-half of the ambient O^+ has been converted to H_2O^+ by a reaction with water vapor in the Orbiter vicinity.

This molecular contamination is accentuated by thruster operation. The dominant neutral species released by the N_2O_4/hydrazine attitude control thrusters is H_2O (32% mole fraction), N_2 (31%) and H_2 (17%). These neutrals act to deplete the surrounding plasma by means of recombination reactions. Narcisi et al, reported an order of magnitude decrease in ambient O^+ density when thrusters are fired. In a detailed report summarizing the observed effects of thrusters on the local plasma Murphy et al (Ref. 8) pointed to plasma turbulence, momentary increases in pressure and electron density as well as enhancement of broadband electrostatic noise that were associated with thruster events. Abrupt shifts in spacecraft potential were also noted with the admonition that events were extremely variable and depended on Orbiter orientation as well as the location of the thruster with respect to the sensor.

3. INTERACTIONS RESULTING FROM VEHICLE MOTION

3.1 The Plasma Wake

As can be seen in Table 1, the size and speed of the Orbiter enables it to produce a significant plasma wake. Several investigators have measured ion and electron energies and densities in this wake. Raitt and Siskind (Ref. 9) reported four orders of magnitude decreases in the electron density in the near wake and noted elevated temperatures of > 4000°K. They had difficulty in getting reliable temperature measurements because of the severe plasma turbulence present near the Orbiter which had not been seen on small spacecraft. Data reduction for the PDP Langmuir Probe is still in a preliminary state, but comparisons with Raitt's data (Ref. 9) from the VCAP investigation has provided a cross calibration point and qualitative agreement is good. Figure 2 shows the measured electron density as a function of attack angle from the PDP data. An angle of 0° corresponds to ram condition (payload bay pointing into velocity vector) and 180° is wake condition. Since these data have an absolute scale that is uncertain by a factor of 2 to 5, they are primarily noteworthy in that the 4 orders of magnitude depletions are also evident. Measurements made by the PDP on the RMS arm at distances 5 to 10 meters from the payload bay show depletions which are narrower in spatial extent and of only 2 to 3 orders of magnitude. Since maximum ram occurs at approximately sunrise and maximum wake at sunset, the correction for day/night density differences is unnecessary to first order.

Stone et al (Ref. 10) reported differential ion flow measurements made with the PDP while on the RMS. Ion streams up to 40° from the angle of attack and with 10% of the full ram current density were observed. These secondary streams had not been previously observed and are as yet unexplained.

4. VEHICLE CHARGING AND ASSOCIATED ELECTRIC FIELDS

Several experimentors have measured vehicle potential at F2 region altitudes and low inclination orbits. Shawhan and Murphy (Ref. 5) measured the potential of two spherical floating probes with respect to the Orbiter chassis and reported potentials of several volts with no electron gun operation. Murphy et al (Ref. 8) observed a dramatic shift in this vehicle potential accompanied by rapid changes in the electric field when thrusters fire.

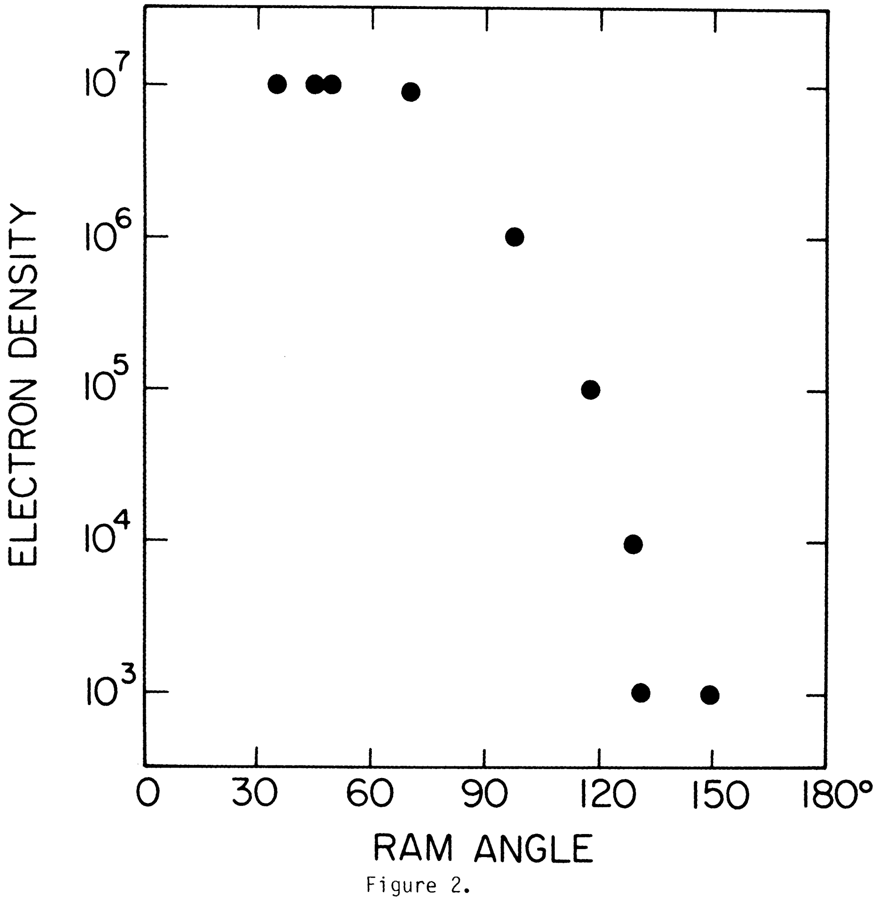

Figure 2.

Both Raitt and Siskind (Ref. 9) and Shawhan and Murphy (Ref. 5) reported the potentials measured by their plasma probes are consistent with $V \times B \cdot L$ charging effects where L is the distance between the main engine nozzles (the principle exposed conducting surface) and the probes. Any passive charging due to energetic electrons or similar sources appeared to be negligible and was a minor perturbation to the overall $V \times B$ effect.

5. OPTICAL EMISSIONS

One of the surprises of the STS-3, was the discovery by Banks et al (Ref. 11) of the presence of a glow near the ram surface of the vehicle. This glow, which may be due to a chemical reaction near the surface of the vehicle, has a brightness of 10K Rayleighs or greater. The precise brightness depends on the wavelength of the emission. This glow is not entirely unprecedented and has been reported from Atmospheric Explorer (AE) observations at low altitude. Yee and Abreu (Ref. 12) in a detailed study attributed the AE results to an interaction of atomic oxygen with the vehicle surface.

Papadopoulos (Ref. 13) speculated that the shuttle glow was a critical ionization phenomena and proposed a series of measurements to determine if the shuttle behaves like an artificial comet.

PDP observations on STS-3 indicated a surface pressure enhancement on the ram side of the vehicle as great as a factor of 200 over ambient (Ref. 5). These enhanced pressures would be consistent with chemical interaction on or near the vehicle surface since they are 2 to 5 times greater than pressure enhancements in the normal supersonic shock front.

Recent flights of hand-held spectrometers should lead to confirmation of the Yee and Abreu, or Papadopoulos explanation or perhaps to a new theory. The glow seems most pronounced at lower altitudes and Banks et al (Ref. 11) also report that the glow is enhanced during and for a brief period following thruster operations.

6. ELECTROSTATIC NOISE

The most intense emission observed at any frequency by the PDP plasma wave receivers has been called Broadband Orbiter Generated Electro Static (BOGES) noise. The characteristics of this noise as briefly reported by Shawhan and Murphy (Ref. 4) are summarized in Table 3. The Table has been divided into two columns designated "above and "below" the presumed Lower Hybrid Resonance (LHR) frequency. The marked difference in degree of polarization of these electrostatic waves is illustrated in Figure 3. Note the sharp peaks in emissions above LHR at oblique angles to the magnetic field. The lower frequency waves show virtually no polarization. These observations were made while the PDP was being maneuvered on the RMS arm and were well out of the payload bay. At no time did the RMS move the PDP far enough from the Orbiter to see a noticeable decrease in the intensity of this noise. Figure 4 illustrates that BOGES noise is relatively intense anytime the PDP is out of the deep wake and the small variations seen are believed to be local geometry effects not related to the plasma density as measured at the PDP. Note also the data in Figure 4 indicate that high frequencies disappear first and reappear last as the PDP passes through the wake condition. This is generally true for all cases although there is considerable variability from orbit to orbit on the details. For example, if spectrograms like Figure 4 taken 12 hours apart are compared, there are considerable differences in the details of the behavior close to maximum wake. The only difference in these cases is the magnetic field direction at that point in the orbit which infers that the generation or propagation of these waves depends on the magnetic field between the source of the emission and the detector. Another characteristic of this noise is that it is well correlated with $\Delta N/N$ turbulence as measured with the PDP Langmuir Probe. Peak $\Delta N/N$ values of 1-3% are observed when the noise is most intense. This turbulence and associated noise is increased by thruster operations and water dumps.

Waves of a similar nature near and below the LHR frequency have been reported by Koskinen et al (Ref. 14) on the Swedish S29 Barium-GEOS Sounding Rocket.

Table 3

1. Broadband: approximately 30 Hz to 200 kHz with 50 to 70 dB variation over orbit
2. Peak spectral density occurs at 100-300 Hz and is approximately 80 dB $\mu V/M/(Hz)^{1/2}$
3. Well correlated with plasma turbulence as measured by $\Delta N/N$ spectrum
4. Has distinctly different character above and below LHR

Below LHR:	Above LHR:
- Noise present for virtually whole orbit but modulated by attitude and B-field orientation of orbiter	- Evidence of increasing polarization at higher frequencies
- No evidence of significant polarization	- Peak intensities occur when E-field sensor axis is 30-45 degrees from B-field alignment
- Seems to disappear completely only when PDP is in orbiter wake	- E-field intensity as high as .01 V/m at 100 kHz observed
- Primarily electrostatic	

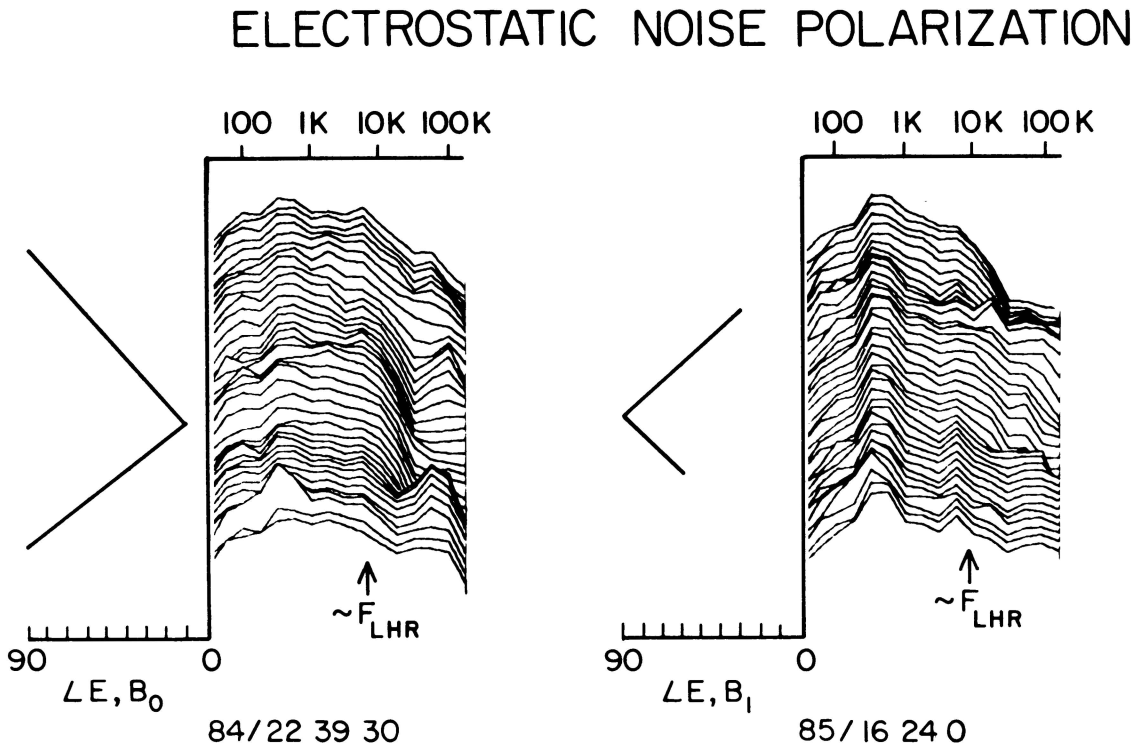

Figure 3

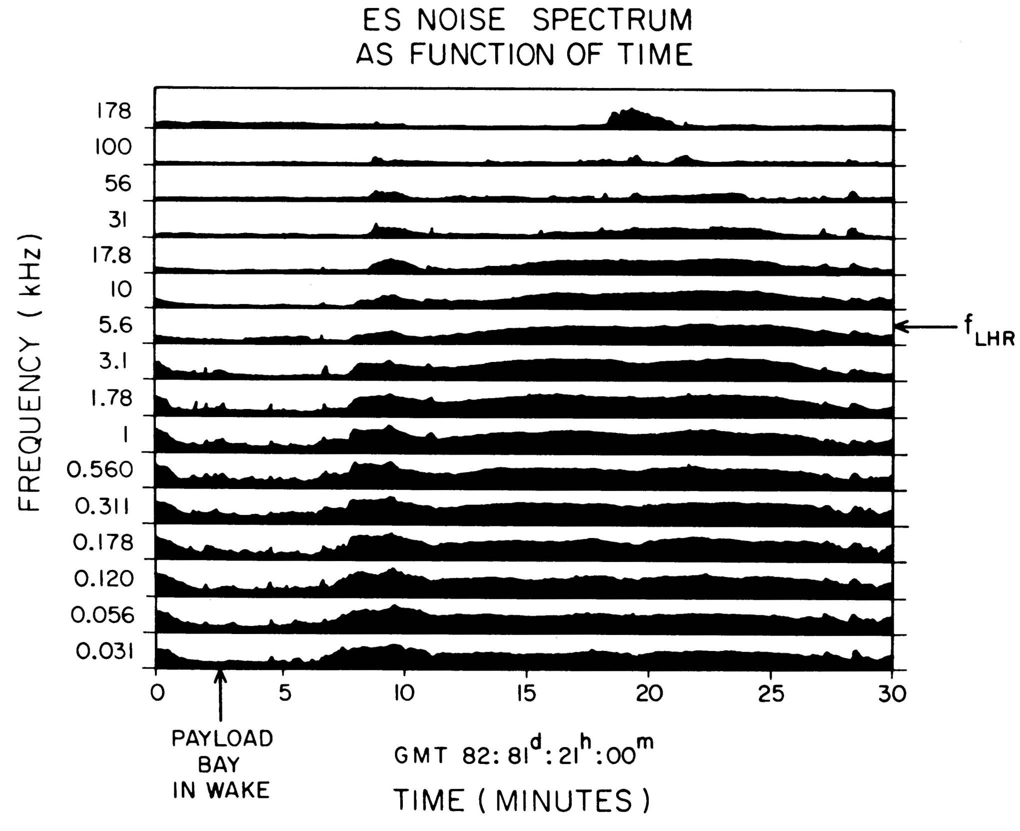

Figure 4

Several explanations are available (Ref. 14) for the phenomenon observed on this and other rocket flights, but they do not adequately explain all characteristics of the BOGES noise observed on the STS Orbiter. Kintner et al (Ref. 15) described ion acoustic noise during a chemical release which they attributed to ion-ion streaming between Cs$^+$ and ambient ions. Considering the observation of ion streams by Stone (Ref. 10) this may be a candidate for explaining the Shuttle induced noise. It is important to note that neither of these observations have a spectrum quite like the BOGES noise observed on STS-3. Much theoretical work is being done at present dealing with this problem. Papadopoulos (Ref. 16) is working to explain the noise spectrum by a critical ionization velocity phenomena driven by plasma instabilities. Initial agreement looks good and results will soon be published. Parrish et al (Ref. 17) have taken another approach seeking to use strong turbulence theory to produce hydrodynamic or ion acoustic waves. Present observational data may not be sufficient to choose the correct theory but additional experimentation on Spacelab-2 should lead to a better understanding of this phenomena.

7. SUMMARY

The flight of the Shuttle Orbiter through the ionosphere has proved to be an intersting plasma physics experiment. Discovery of the vehicle glow, secondary ion streams, BOGES noise and other associated phenomena are leading to an increased understanding of the F2 ionospheric physics and chemistry. The flights of Spacelab-1 (1983) and Spacelab-2 (1985) carry plasma diagnostics as well as electron and ion guns to stimulate plasma interactions and study Orbiter charging. Further theoretical work on the instabilities creating BOGES noise and the physics of the Orbiter wake will provide further guidance for the experiments on these missions and ultimately for a Space Plasma Lab mission in the 1987 time frame.

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