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**Abstract.** During the Spacelab-2 flight, which occurred from July 29, to August 6, 1985, a spacecraft called the Plasma Diagnostics Package (PDP) was released from the shuttle to explore the plasma environment around the shuttle. The plasma wave instrument on the PDP detected a region of intense broadband turbulence around the shuttle at frequencies extending from a few Hz to about 10 kHz. The noise has broadband intensities ranging from 1 to 5 mV/m and was observed at distances of up to 400 m from the shuttle. The highest intensities occurred in the region downstream of the shuttle and along magnetic field lines passing near the shuttle. The intensities also tended to increase during periods of high thruster activity, which provides strong evidence that the noise is caused by an interaction of the ionosphere with gaseous emissions from the shuttle, similar in many respects to the interaction of a comet with the solar wind. Antenna interference patterns observed in the wideband data show that the wavelength of the turbulence is very short, a few meters or less.

### Introduction

In this report we describe plasma wave turbulence observed around the shuttle by a spacecraft called the Plasma Diagnostics Package (PDP) which was released from the shuttle during the Spacelab-2 flight. The PDP was designed and constructed at the University of Iowa and is a reflight of the same spacecraft previously flown on the STS-3 flight [Shawhan et al., 1984a]. On STS-3 the PDP was carried on the remote manipulator arm, which restricted the measurements to about 15 meters from the shuttle. The principal new feature of the Spacelab-2 flight is that the PDP was released from the shuttle, thereby providing measurements at much greater distances. During the free-flight phase of the mission, the shuttle was maneuvered to provide two complete fly-arounds of the PDP at radial distances out to about 400 meters. The fly-arounds provided measurements both upstream and downstream of the shuttle, and along the magnetic field line through the shuttle. In addition to the fly-arounds, a series of maneuvers, called wake transits, were performed to survey the wake region directly downstream of the shuttle.

Included among the various experiments on the PDP was a plasma wave receiver designed to measure electric and magnetic disturbances produced by the motion of the shuttle through the ionosphere. The results presented here are mainly from this instrument. For a description of this and other instruments on the PDP, see Shawhan [1982]. The Spacelab-2 mission, which was launched on July 29, 1985, was flown in a nearly circular low-inclination orbit with a nominal altitude of 325 km and an inclination of 49.5°. The PDP was in free flight for a roughly 6-hour period, from 0010 to 0620 UT on August 1, 1985.

### Observations

An electric field spectrogram showing the plasma wave intensities during the first of the two fly-arounds is shown in the bottom panel of Figure 1. The shuttle position relative to the PDP is given by the x, y, z coordinates at the bottom of each plot. The +z axis is directed downward toward the center of the Earth, the x axis is in the orbital plane with the positive axis in the direction of motion, and the y axis completes the right-handed coordinate system. The electric field spectral density,  $E^2/\Delta f$ , is indicated by the color code, with blue being least intense and red being most intense. The white line labeled  $f_{ce}$  is the electron cyclotron frequency, which is a basic characteristic frequency of the plasma. The points labeled 1 and 2 at the top of the spectrogram indicate magnetic conjunctions, which are times when the shuttle was maneuvered to intercept a magnetic field line through the PDP.

The spectrogram shows two types of noise. At selected times during the flight an electron gun on the shuttle was used to inject a beam of electrons into the ionosphere for purposes of studying beam-plasma interactions. This beam produced the series of whistler-mode emissions identified as "electron beam emissions" in Figure 1. These emissions have been described in a previous series of papers [Gurnett et al., 1986; Bush et al., 1987; Farrell et al., 1988] and will not be discussed further. In addition to the electron beam emissions, a broad band of noise can be seen at frequencies below about  $10^4$  Hz. No comparable type of noise is evident in the magnetic field spectrogram. From the known noise level of the magnetic antenna, the ratio of the electric field energy density to the magnetic field energy density is found to be at least 10 to 100, which is much larger than would be expected for any known electromagnetic mode of propagation. Therefore, the noise is electrostatic. The same type of noise was detected on the STS-3 mission [Shawhan et al., 1984b; 1984c], and is usually referred to as "broadband electrostatic noise."

As can be seen, the broadband electrostatic noise consists of many impulsive short-term variations superimposed on a slowly varying, nearly continuous background. Most of the impulsive variations can be associated with thruster firings. For comparison, the rate of gas ejection from the thrusters averaged over one-minute intervals is shown in the top panel of Figure 1. Major trajectory correction maneuvers, which typically involve gas injection rates of  $10^2$  to  $10^3$  gm/sec over periods of 30 sec or more, almost always produce an intense burst of broadband noise. Examples of such maneuvers occur near the first magnetic conjunction, at 0157 and 0204 UT. In addition to the trajectory correction maneuvers, an almost continuous level of thruster activity occurs in association with minor attitude corrections. These firings, which have durations of about 80 msec and occur at a rate of several per minute, may be responsible for the nearly continuous low level of noise that is present most of the time.

Comparisons of the electric field spectrograms from the two fly-arounds and the wake transits indicate that the intensity varies systematically with the position of the PDP relative to the shuttle. This dependence is illustrated in Figure 2 which shows the x-z projection of the shuttle trajectory relative to the

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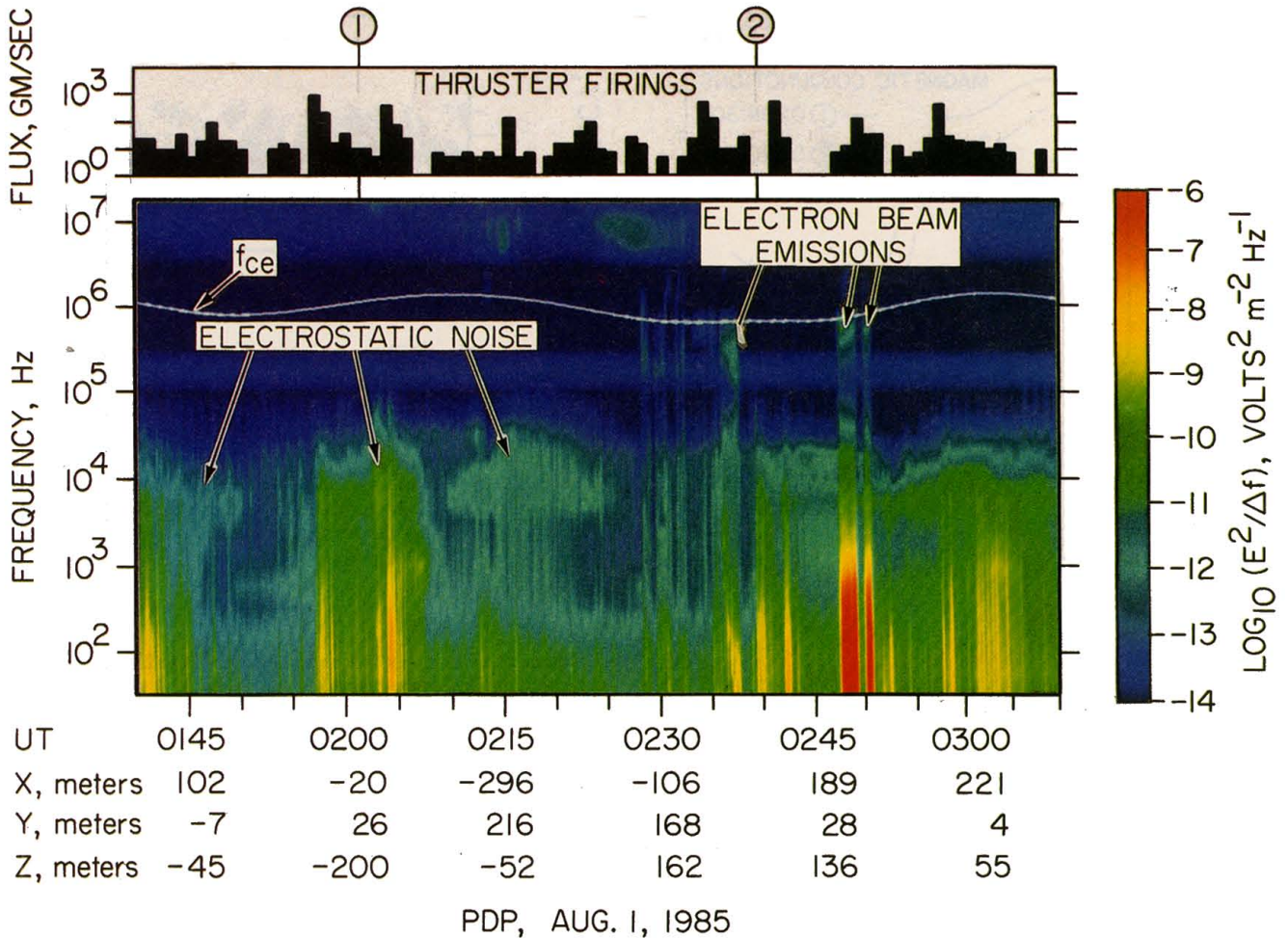


Fig. 1. The bottom panel shows a spectrogram of the electric field intensities observed by the PDP during the first fly-around and the top panel shows the gas flux associated with thruster firings on the shuttle. The broad band of noise below about  $10^4$  Hz is closely associated with the thruster firings and is believed to be caused by an interaction between a cloud of neutral gas around the shuttle and the ionosphere, which is streaming by at  $\sim 8$  km/sec.

PDP. The solid black dots show the regions where the broadband electric field strength, integrated from 35 Hz to 31 kHz, exceeds  $1$  mV/m. As can be seen, the electrostatic noise tends to be strongest and most persistent along the  $+x$  axis, when the PDP is downstream of the shuttle, and weakest along the  $-x$  axis, when the PDP is upstream of the shuttle. The noise is also strong near the four magnetic conjunctions, which are labeled 1 through 4 in Figure 2.

The interpretation of the noise enhancements near the magnetic conjunctions is complicated by the fact that the thruster firing rate tends to be higher in these regions as the shuttle was maneuvered to intercept the magnetic field line through the PDP. Nevertheless, we believe that the intensification in this region is controlled to some degree by the magnetic field geometry. As evidence of this relationship note that thruster firings when the PDP is upstream of the shuttle, for example at 0216 and 0224 UT (see Figure 1), do not have nearly as large an effect as thruster firings near the magnetic conjunction, for example at 0157 and 0204 UT. Also, even when the gas ejection rate is low, for example from 0159 to 0203 UT, the noise level in the magnetic conjunction region is higher than for comparable gas ejection rates when the PDP is upstream of the shuttle.

Representative electric field spectrums of the broadband electrostatic noise are shown in Figure 3. The top panel shows two spectrums selected from near the first and second magnetic

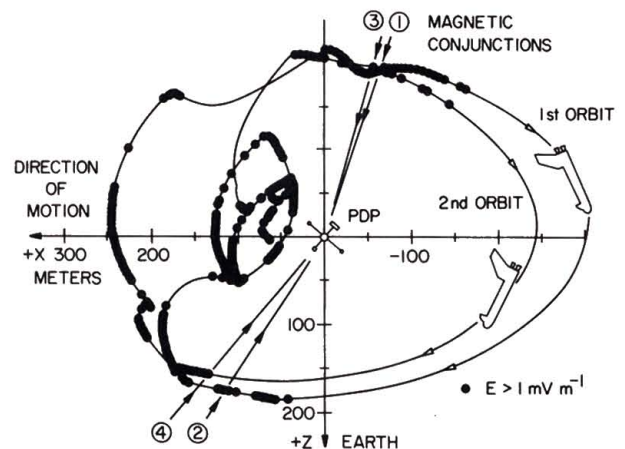


Fig. 2. An orbital plane plot showing the regions (black dots) where the broadband shuttle-induced noise exceeds  $1$  mV/m. The noise is strongest and most persistent in the region downstream of the shuttle and weakest in the region upstream of the shuttle. Strong enhancements also occur near the magnetic conjunctions.

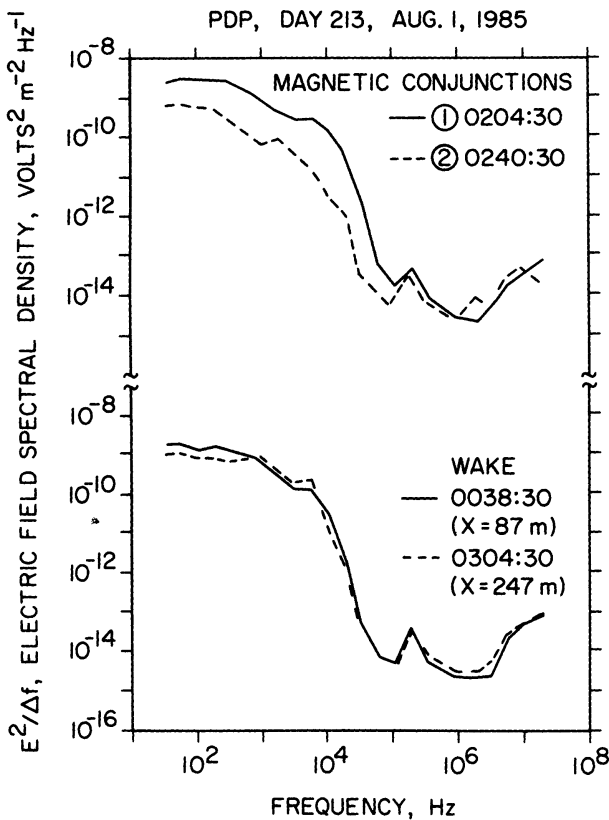


Fig. 3. Selected spectrums of the broadband noise near the first and second magnetic conjunctions, and at two positions in the wake region downstream of the shuttle.

conjunctions, and the bottom panel shows spectrums at two different distances ( $x = 247$  m and  $x = 87$  m) in the wake region directly downstream ( $y \approx 0$ ,  $z \approx 0$ ) of the shuttle. All four spectrums are remarkably similar. Typically, the spectrum is almost flat from 10 Hz to about  $10^4$  Hz, and then drops below the instrument noise level by  $10^5$  Hz. Sometimes a peak can be seen at a frequency of a few kHz, which is near the lower hybrid resonance frequency. This peak can be seen at various times in Figure 1, for example at 0150 and 0255 UT. The broadband electric field strength during the most intense thruster-related events ranges from about 2 to 5 mV/m. The nearly continuous background level in the wake region directly downstream of the shuttle is about 1 to 2 mV/m.

High-resolution wideband spectrograms of the electrostatic noise sometimes show a "fingerprint" pattern that repeats with a period of one-half of the spacecraft rotation period. An example of such a pattern is shown in Figure 4. This type of spin modulation pattern is well known in space plasma wave data and is an antenna pattern effect caused by wavelengths short compared to the antenna length [Temerin, 1979; Fuselier and Gurnett, 1984; Gallagher, 1985]. The nulls occur when the antenna separation projected in the direction of propagation is an integral number of wavelengths. Since the antenna length is only 3.9 meters, the existence of these nulls implies that the wavelengths of the electrostatic noise is substantially less than one meter. For such short wavelengths, the frequency spectrum is almost entirely determined by Doppler shifts. From the nulls in the fingerprint pattern, one can in principle determine the wave frequency in the plasma rest frame. Although a more detailed analysis will be necessary to provide an exact mode identification, our preliminary estimates indicate that the wave frequency in the plasma rest frame is quite low, 500 Hz or less. The fingerprint pattern tends to be most pronounced and easily

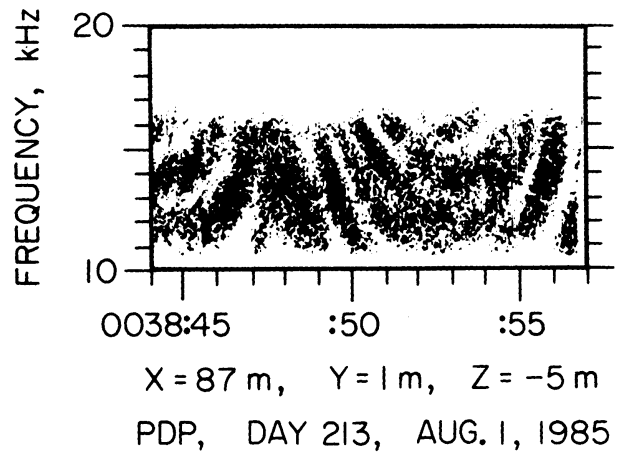


Fig. 4. A high-resolution wideband spectrogram showing "fingerprints" in the broadband noise. This effect is caused by nulls in the antenna pattern as the spacecraft rotates and is indicative of wavelengths shorter than the 3.9 meter length of the electric antenna.

recognized near the upper frequency cutoff ( $\sim 10$  to 20 kHz) and in the region directly downstream of the shuttle.

#### Interpretation

The close correlation between thruster firings and enhancements in the broadband electrostatic noise provides a strong indication that the noise is associated with neutral gas emissions from the shuttle. Previous measurements [Shawhan et al., 1984b; 1984c; Pickett et al., 1985] have shown that the shuttle is surrounded by a neutral gas cloud with pressures as much as  $10^2$  to  $10^3$  above ambient. This gas cloud originates from a variety of transient and steady-state sources including thruster firings, water dumps, outgassing of water absorbed in the tiles, and leaks from pressurized compartments on the shuttle. The fact that the electrostatic noise displays both an impulsive component as well as a nearly steady component simply reflects the complex time variability of these various sources.

Since a neutral atom does not interact with an electric field, some mechanism is needed to generate the noise. This mechanism is believed to be charge exchange between the shuttle gas cloud and the surrounding ionosphere. Studies of the plasma distribution around the shuttle by Paterson and Frank [1987] and Frank et al. [1988] show that the shuttle is surrounded by an energized distribution of  $H_2O^+$  ions and other heavy ions. These ions are believed to be produced by charge exchange between the shuttle gas cloud, which is primarily  $H_2O$  and ionospheric  $O^+$  ions, which are streaming by at  $\sim 8$  km/s. Once ionized, the newly born  $H_2O^+$  ions are immediately accelerated by the  $\vec{V} \times \vec{B}$  electric field and carried downstream, more or less as illustrated in Figure 5.

The pick-up process causes two effects that could possibly account for the intense electrostatic noise observed around the shuttle. First, since the newly born ions are moving with respect to the ionosphere, these ions produce a beam or ring-like velocity distribution that should be highly unstable [Krall and Trivelpiece, 1973; Papadopoulos, 1984]. Second, the pick-up process produces both perpendicular and parallel currents,  $J_{\perp}$  and  $J_{\parallel}$ , which ultimately must close in the ionosphere via an Alfvén wave, more or less as shown in Figure 5. If the current density exceeds a critical value, then current-driven electrostatic waves could be excited, similar to the processes that are believed to occur in the auroral zone [Kindel and Kennel, 1971]. Just which mechanism provides the free-energy



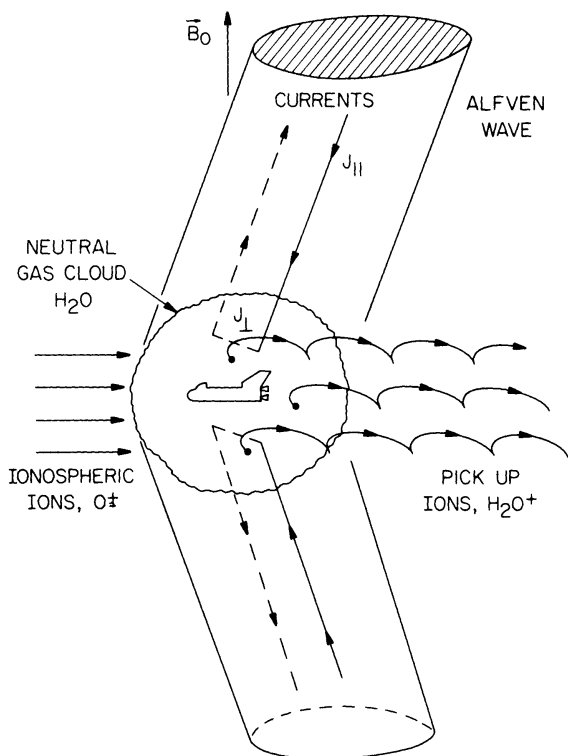


Fig. 5. Charge exchange interactions with ionospheric ions are believed to partially ionize the neutral gas cloud around the shuttle, thereby producing pick-up ions which are accelerated and carried downstream by the convection electric field. The pick-up ions produce a highly unstable ion distribution which is believed to be responsible for the intense electrostatic noise observed downstream of the shuttle.

source for generating the intense electrostatic noise around the shuttle remains to be established. The unstable ion distributions associated with the pick-up ions appears to be the best possibility, since current-driven instabilities usually have a rather high threshold. However, the enhanced noise intensities near the magnetic conjunctions suggest that field-aligned currents may play some role. Although the main energization of the pick-up ions comes from acceleration by the  $\vec{V} \times \vec{B}$  electric field, the electrostatic turbulence may play an important role in thermalizing these ion distributions.

In comparing these results with other measurements, it is interesting to note the very close similarity between the noise observed near the shuttle and the electrostatic noise observed near the AMPTE artificial comet [Gurnett et al., 1985; 1986] and the comets Giacobini-Zinner [Scarf et al., 1986], and Halley [Grard, 1986]. Since charge exchange and ion pick-up are believed to be one of the dominant processes in the interaction of a comet with the solar wind, it appears that the interaction of the shuttle with the ionosphere may have a close similarity to the plasma processes occurring near a comet.

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#### References

Bush, R. I., G. D. Reeves, P. M. Banks, T. Neubert, P. R. Williamson, W. J. Raitt, and D. A. Gurnett, Electromagnetic fields from pulsed electron beam experiments in space: Spacelab-2 results, *Geophys. Res. Lett.*, **14**, 1015-1018, 1987.

- Farrell, W. M., D. A. Gurnett, P. M. Banks, R. I. Bush, and W. J. Raitt, An analysis of whistler mode radiation from the Spacelab 2 electron beam, *J. Geophys. Res.*, **93**, 153-161, 1988.
- Frank, L. A., W. R. Paterson, P. M. Banks, R. I. Bush, and W. J. Raitt, Plasma observations in the vicinity of the shuttle, 1988 National Radio Science Meeting, Boulder, Colorado, Jan. 5-8, 1988.
- Fuselier, S. A., and D. A. Gurnett, Short wavelength ion waves upstream of the earth's bow shock, *J. Geophys. Res.*, **89**, 91-103, 1984.
- Gallagher, D. L., Short-wavelength electrostatic waves in the earth's magnetosheath, *J. Geophys. Res.*, **90**, 1435-1448, 1985.
- Grard, R., A. Pedersen, J.-G. Trotignon, C. Beghin, M. Mogilevsky, Y. Mikhailov, O. Molchanov, and V. F. Formisano, Observations of waves and plasmas in the environment of comet Halley, *Nature*, **321**, 290-291, 1986.
- Gurnett, D. A., R. R. Anderson, B. Häusler, G. Haerendel, O. H. Bauer, R. A. Treumann, H. C. Koons, R. H. Holzworth, and H. Lühr, Plasma waves associated with the AMPTE artificial comet, *Geophys. Res. Lett.*, **12**, 851-854, 1985.
- Gurnett, D. A., W. S. Kurth, J. T. Steinberg, P. M. Banks, R. I. Bush, and W. J. Raitt, Whistler-mode radiation from the Spacelab-2 electron beam, *Geophys. Res. Lett.*, **13**, 225-228, 1986.
- Gurnett, D. A., T. Z. Ma, R. R. Anderson, O. H. Bauer, G. Haerendel, B. Häusler, G. Paschmann, R. A. Treumann, H. C. Koons, R. Holzworth, and H. Lühr, Analysis and interpretation of shock-like electrostatic noise observed during the AMPTE solar wind lithium releases, *J. Geophys. Res.*, **91**, 1301-1310, 1986.
- Kindel, J. M., and C. F. Kennel, Topside current instabilities, *J. Geophys. Res.*, **76**, 3055-3078, 1971.
- Krall, N., and A. W. Trivelpiece, *Principles of Plasma Physics*, McGraw-Hill, N. York, 473, 1973.
- Papadopoulos, K., On the shuttle glow (the plasma alternative), *Radio Science*, **19**, 571-577, 1984.
- Paterson, W. R., and L. A. Frank, Observations and modeling of ion pickup in the vicinity of the orbiter, *EOS*, **68**, 1399, 1987.
- Pickett, J. S., G. B. Murphy, W. S. Kurth, C. K. Goertz, and S. D. Shawhan, Effects of chemical releases by the STS-3 orbiter in the ionosphere, *J. Geophys. Res.*, **90**, 3487-3497, 1985.
- Scarf, F. L., F. V. Coroniti, C. F. Kennel, D. A. Gurnett, W.-H. Ip, and E. J. Smith, Plasma wave observations at comet Giacobini-Zinner, *Science*, **232**, 377-381, 1986.
- Shawhan, S. D., Description of the plasma diagnostics package (PDP) for the OSS-1 shuttle mission and JSC chamber test in conjunction with the fast pulse electron gun (FPEG), *Artificial Particle Beams in Space Plasma Studies*, ed. B. Grandel, Plenum, N. York, 419-430, 1982.
- Shawhan, S. D., G. B. Murphy, P. M. Banks, P. R. Williamson, and W. J. Raitt, Wave emissions from dc and modulated electron beams on STS-3, *Radio Science*, **19**, 471-486, 1984a.
- Shawhan, S. D., G. B. Murphy, and J. S. Pickett, Plasma Diagnostics Package initial assessment of the shuttle orbiter plasma environment, *J. Spacecraft and Rockets*, **21**, 387-391, 1984b.
- Shawhan, S. D., G. B. Murphy, and D. L. Fortna, Measurements of electromagnetic interference on OV102 Columbia using the Plasma Diagnostics Package, *J. Spacecraft and Rockets*, **21**, 392-397, 1984c.
- Temerin, M., Doppler shift effects on double-probe-measured electric field power spectra, *J. Geophys. Res.*, **84**, 5929-5934, 1979.

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