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Data Reduction and Analysis of Pioneer Venus Orbital Ion Mass Spectrometer

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Over the duration of NASA Grant NAG 2-566, the Pioneer-Venus Orbiter Ion Mass Spectrometer (OIMS) Team at Rice University has comprised eight different people. This includes Paul Cloutier, principal investigator, six students/postdocs (Brian Stewart, Mark Matney, Leonard Kramer, Shannon Walker, Gary Hoogeveen and Colin Law) and Harry Taylor working under subcontract. It should be noted that all six students were able to complete and successfully defend their Ph.D. theses while working under this PVO grant. Over the eight years of this grant, these individuals each made significant contributions to a better understanding of the PVO OIMS data and the solar wind interaction at Venus. In addition to production work on OIMS data for the NSSDC archives (submissions have been completed) research was done on a variety of topics concerning both the dayside ionosphere and the nightside ionosphere. With a common theme of refining the already successful flow/field interaction model, the research carried out at Rice investigated some of the remaining Venus puzzles in the specific topics listed below:

Dayside Ionosphere of Venus

1. Wave-Particle Mechanisms at the Ionopause
   - (a) Missing Pressure in the Venus Ionosphere
   - (b) Model of Superthermal Ion Behavior in the Venus Ionosphere
2. Structure and Dynamics of the Venus Ionopause and Ionosphere
   - (a) Venus Ionopause Formation
   - (b) Magnetic Signatures and Structure in the Dayside Venus Ionosphere
3. Flows and Fields in the Venus Ionosphere
   - (a) Refinement of the Flow/Field Models of the Ionosphere
   - (b) Venus Flow/Field Model: Comparative Applications for other Solar System Bodies

Nightside Ionosphere of Venus

1. Structure and Dynamics of Ion Troughs
   - (a) Instabilities and Electric Field Noise in Venus Nightside Ion Troughs

Summaries of these research topics along with associated Abstracts and related References from publications by Rice researchers are on the following pages. In addition Dr. Shannon Walker has written an in depth review or her research as a more detailed examination into the work performed at Rice under NAG 2-566. This supplement can be found attached at the end of this report.

Dr. Cloutier wishes to acknowledge the past and present students named above for their contributions to the generation of this final report.

I. Dayside Ionosphere of Venus.

1. Wave-Particle Mechanisms at the Ionopause.

The ionopause of Venus, defined as the sharp decrease in planetary thermal ion density which marks the boundary between the planetary ionosphere and high-speed post-shock solar wind flow around the planet, is a boundary layer in which several interesting physical phenomena are observed. One effect observed by several different instruments, is the presence of superthermal ions in the vicinity of the ionopause, occasionally extending upward into the post-shock solar wind. These ions, which are of planetary origin, are apparently energized to at least several tens of eV's by some mechanism occurring over a small distance near the ionopause. They form a distinctly different population from the thermal ions of the ionosphere and from the keV energy "pick-up" ions energized by the solar wind **V×B** electric field. The largest concentration of these superthermal ions occurs in the vicinity of the inbound ionopause, with a small concentration seen both inbound and outbound at altitudes above the ionopause. Also apparent in this data is the existence of electric field noise in both the 100 Hertz and 730 Hertz channels of the Orbiter Electric Field Detector (OEFD) in the region of highest superthermal concentration.

This coincidence of electric field noise and superthermal ions, seen repeatedly on the majority of orbits, is strong evidence of a wave-particle interaction, presumably due to a plasma instability, as the energization mechanism for the superthermals. However, due to the limitations on the electric field band widths and the inability of any of the PVO instruments to uniquely determine concentration and energy spectrum of the superthermals, the details of the energy generation and the role of the superthermals in the dynamics of the solar wind interaction remain uncertain. Under PVO funding provided we have examined both the possible effects of the superthermal population on the dynamics of the ionosphere and the mechanisms governing the distribution of superthermals within the ionosphere. We have found that pressure balance between the solar wind and the ionosphere of Venus requires the existence of a "missing pressure" component below the ionopause which may carry as much as 30% of the total solar wind pressure within the ionosphere.

1a. Missing Pressure in the Venus Ionosphere

[P. A. Cloutier, Brian Stewart, and Harry Taylor]

An investigation of total momentum transfer from solar wind to the ionosphere of Venus found that a substantial fraction of the measured solar wind pressure (up to ~30%) is "missing" just below the ionopause when the total of magnetic pressure, thermal ion pressure, and electron pressure is calculated. This missing pressure was found to be dependent on solar wind pressure. Results of this investigation are contained in the Ph.D. dissertation at Rice by Dr. Brian Stewart, and are the subject of a GRL paper published in 1992.

Associated ABSTRACT: *Cloutier et. al., GRL 1992.*

Data obtained by various instruments on the Pioneer-Venus spacecraft were used to study the conservation of momentum flux from the solar wind through the dayside ionopause into the thermal Venus ionosphere. A consistent pressure deficit was found below the ionopause, with a strong dependence on solar wind pressure. Independent of solar wind pressure, the pressure deficit was found to decrease with decreasing altitude below the ionopause. Measurements of this pressure deficit (missing pressure) are presented as a function of altitude for various solar wind condition. The identity of the missing pressure component and the correlation with solar wind pressure are discussed.

Related REFERENCES:

Stewart, B. K., A Modified Flow/Field Model of the Solar Wind Interaction with Mars, Ph.D. Thesis, Department of Space Physics & Astronomy, Rice University, 1991.

Cloutier, P. A., B. K. Stewart and H. A. Taylor, Jr., Missing pressure in the dayside ionosphere of Venus, *Geophys. Res Lett.*, 19, 1431-1434, 1992.

Cloutier, P. A., B. K. Stewart and H. A. Taylor, Jr., Reply to 'Comment on "Missing pressure in the dayside ionosphere of Venus" by C. T. Russell,' *Geophys. Res Lett.*, 20, 2153-2154, 1993.

1b. Model of Super-Thermal Ion Behavior in the Venus Ionosphere :

[P. A. Cloutier, Leonard Kramer, and Harry Taylor]

After the discovery of the "missing pressure" described above, research focused on the search for the source of the missing pressure on superthermal ions in the energy range 10–100 eV. This focus was suggested by the many previous detections of superthermal ions by the OIMS and ONMS instruments near the ionopause and within the upper (thermal) ionosphere. The rapid increase in thermal ions below the ionopause can effectively "mask" the instrument response to a small number of superthermals. However, since direct particle collisions are relatively unimportant at the ionopause altitude shown, there are reasons to believe that superthermals may retain most of their energy until they penetrate to much lower altitudes where interaction with neutrals becomes important.

We have completed a model of superthermal ion behavior to determine whether they are possible carriers of this missing pressure. We are able to match the missing pressure profiles by assuming a concentration of superthermals which is roughly 1-2% of the thermal ion concentrations just below the ionopause, and allowing these superthermals to be scattered with a scattering scale length of 10 km or less. Such a scale length is in agreement with theoretical predictions for a lower-hybrid instability producing the wave-particle interactions. However, because of the lack of any direct measurements of concentration or energy spectra, we have been unable to uniquely determine the characteristics of the superthermal population. We also found that charge exchange of superthermal O^+ with atmospheric neutrals will result in a planet-wide loss of atomic oxygen which may be important to the evolution of the Venus atmosphere over geological times. The results of the calculation of superthermal ion behavior are contained in the Rice Ph.D. and M.S. theses by Leonard Kramer, and published in a paper in JGR..

Associated ABSTRACT: *Kramer, et. al., JGR 1993.*

A model is presented which simulates the behavior of superthermal ions previously reported in the dayside ionosphere of Venus. The model considers effects of **E**×**B** and gradient drifts, charge exchange and collisions with the ambient neutral atmosphere and the possible effects of a wave-particle (anomalous) scattering process. Results indicate that scattering processes are required if superthermal ions are the explanation for the observed "missing pressure" component in the dayside Venus ionosphere. The scattering length required to match the "missing pressure" distribution is similar to the scale length previously predicted for growth of a lower hybrid beam instability.

Related REFERENCES:

Kramer, Leonard, Model of Superthermal Ions in the Postshock Flow Field at Venus, M. S. Thesis, Department of Space Physics & Astronomy, Rice University, Aug 1991.

Kramer, L., Model of Superthermal Ions in the Dayside Venus Ionosphere, Ph. D. thesis, Department of Space Physics & Astronomy, Rice University, Feb 1993.

Kramer, L., P. A. Cloutier and H. A. Taylor, Jr., Model of superthermal ions in the Venus ionosphere, *J. Geophys. Res.*, 98, 3645-3658, 1993.

2. Structure and Dynamics of the Venus Ionopause and Ionosphere.

The ionopause of Venus defines the boundary between thermal ions of planetary origin and the post-shock solar wind. It marks a tangential shear in horizontal plasma velocity, but also allows vertical transport of the post-shock interplanetary magnetic field into the ionosphere by downward convection and diffusion. At present, no comprehensive model of ionopause formation and dynamics exists which can predict ionopause morphology and altitude as a function of solar wind conditions, and attempts to relate ionopause altitude to solar wind pressure have shown much larger variability than expected from simple pressure balance arguments.

In addition we have explored the structure of the magnetic field draped around the dayside of the planet. Models of the dayside solar wind interaction at Venus have generally been restricted to a one or two dimensional calculation, varying parameter and result magnitudes with altitude. In doing so, very successful results have been obtained that reproduce the field and plasma profiles observed by the Pioneer Venus Orbiter. There is however a great variety in the orientation of the magnetic and electric field orientations within the dayside ionosphere that seem to be unnecessary factors in a successful model. We have explored the high-resolution PVO data in depth to try and resolve these questions and to determine boundary conditions for possible three-dimensional extensions of the flow/field model of the interaction put forward by this research group at Rice.

2a. Venus Ionopause Formation

[P. A. Cloutier and Mark Matney]

A simple explanation of the Venus ionopause is that it is the boundary which separates high-speed flow around the planet from the much lower-speed flow within the ionosphere. However, attempts to relate ionopause altitude to solar wind pressure have shown much larger variability than expected from simple pressure balance arguments, and at present there exists no simple predictive model of ionopause height and structure. A model of ionopause formation has been developed which starts with a specified flow pattern behind the Venus bow shock and which allows variation of various parameters describing the interaction of the post-shock flow with the Venus ionosphere and neutral atmosphere. Results from this model are able to demonstrate how ionopause height and structure vary in response to variations in a number of parameters, and the model is able to reproduce ionopause position and structure reasonably well for low-altitude ionopauses (<350 km altitude). The model does not seem to be able to reproduce high-altitude ionopause position and structure under conditions of low solar wind pressure, however. Our present results indicate that whereas low ionopauses apparently are controlled by local ionospheric and atmospheric interactions, other mechanisms determining the global post-shock flow pattern around the planet may be most important in determining the position and structure of the high-altitude ionopauses.

We plan to investigate these mechanisms further in the hope of producing a prediction model for ionopause formation and dynamics.

Associated ABSTRACT: *Matney, Ph.D. Thesis, 1992.*

A model is presented that simulates the physics of the Venus mantle plasma. A modified magnetohydrodynamic (MHD) fluid picture is assumed where the post-shock solar wind plasma is mass-loaded by photo-ionizations and other atomic interactions with exospheric neutral atoms. By assuming Newtonian pressure profiles and draped magnetic field geometry in the mantle, the three-dimensional steady-state flow problem is reduced to a one-dimensional calculation along the stagnation (subsolar) flow line. In addition, the validity of the model assumptions and question about the plasma thermodynamics are addressed. When the resulting model is run using various solar wind conditions, the computed magnetic field features correspond with those measured by the Pioneer Venus spacecraft. The model reproduces the observed region of sharp ion density gradients, known as the ionopause, that separates the mantle plasma from the denser ionospheric plasma below. The straightforward application of the model reproduces the shape and location of the low-altitude ionopause cases well, but for solar wind conditions that correlate with high-altitude ionopauses, the computed ionopauses tend to be lower than those observed. The addition of anomalous heating terms to the model, however, raises the computed ionopause to locations consistent with the medium altitude cases. The inability of the model to adequately describe the high altitude cases may indicate that they are transient events and thus cannot be simulated in steady state. While the source of the anomalous heating is not specified, the presence of hyperthermal ions of plasma-wave interactions are suggested as possible heating mechanisms.

Related REFERENCES:

Matney, M. J., The Formation of the Venus Ionopause Interaction Between the Mantle Region and the Solar Wind, M.S. thesis, Department of Space Physics & Astronomy, Rice University, April 1990.

Matney, M. J., Model of Venus Ionopause Formation, Ph. D. thesis, Department of Space Physics & Astronomy, Rice University, Jan 1992.

2b. Magnetic Signatures and Structure in the Dayside Venus Ionosphere

[P. A. Cloutier and Colin Law]

Since the beginning of the Pioneer Venus program, there have been several unanswered questions related to the solar wind interaction with Venus. The first has to do with the day-to-night flow of ionospheric plasma. The flow of plasma around the planet appears to be radial and nearly axisymmetric from the subflow point regardless of the interplanetary magnetic field direction external to the Venus obstacle. Mechanical forces acting on the plasma in the vicinity of the terminator are usually large compared with magnetic forces. Using this assumption, the antisolar plasma flow has been accurately modeled even while neglecting any magnetic field terms. These numerical models using an unmagnetized ionosphere reproduced the observed horizontal plasma flows and attributed them solely to the horizontal plasma pressure gradient associated with the decrease in plasma density from the dayside to the nightside. Though these models are not good at describing the flow at low solar zenith angles, the good agreement with the measured global flow velocities is puzzling because the rate of mass transport should also depend on electrodynamic parameters. The general steady state momentum equation for flow in the ionosphere can be written

$$\nabla \cdot \left[\rho \bar{\upsilon}\bar{\upsilon} + \underline{\underline{P}} + \frac{B^2}{2\mu_0}\underline{\underline{1}} - \frac{\bar{B}\bar{B}}{\mu_0} \right] = \rho \bar{g} - \rho \bar{\upsilon} \nu_{in} - \left(\sum_i m_i l_i \right) \bar{\upsilon}$$

where ρ is the average ion mass density, $\bar{\upsilon}$ is the plasma flow velocity, $\bar{B}$ is the local magnetic field, $\underline{\underline{P}}$ is the plasma pressure tensor, $\bar{g}$ is the local gravitational acceleration, ν_{in} is the ion-neutral collision frequency, and the last term is loss due to recombination and charge exchange which is usually very small compared to the collisional term over the relevant altitude range. Observationally, the magnetic pressure terms are never zero over the entire ionospheric altitude range, and in fact can be of the same magnitude as the plasma pressure terms, making them hardly negligible when the ionosphere is sufficiently magnetized (a typical ionospheric β is around 1). Yet the day to night flow is explained very well by only considering the plasma pressure gradient.

Another question concerns the presence of a large horizontal velocity shear at the ionopause. The magnetosheath flow is of the order of 100 km/s from the jump conditions at the Venus bow shock, assuming a typical solar wind velocity of 400 km/s. Plasma flow velocities then must drop to below 10 km/s (escape speed for Venus) over the distance scale of the ionopause (typically 30 to 100 km) if an ionosphere is going to exist. Over the distance of a few ion scale heights the horizontal velocity drops by a factor of 10 or more, but the magnetic field magnitude is nearly constant through this sharp transition. While it might be expected that something significant must happen to the field magnitude as it crosses through the shear, data indicate that this is not generally true. In fact, observations of the high resolution magnetic field data have shown a field rotation (described in the next section) in the shear region which violates the standard picture employed in the past of a two-dimensional field whose direction is fixed above and through the ionopause boundary.

We have observed a local horizontal magnetic field rotation (no substantial vertical field components nor vertical field rotations occur in this region) at the ionopause of Venus that alters the standard picture of a draped magnetic field flowing around and over the planet. These field rotations coincide with the scale of the ionopause thickness and can be explained by the mass loading of the magnetosheath field lines as they come in contact with the relatively stationary ionospheric plasma. The velocity shear at the ionopause boundary distorts the field lines until they become aligned with the axisymmetric day to night ionospheric plasma flow ("weathervaning"), enabling the plasma to flow across the terminator along magnetic field lines. Close to the magnetic noon meridian, magnetic diffusion should always merge oppositely directed field lines, so that the field along that meridian may have a substantial component parallel to the magnetic equator. Thus we expect the "weathervaning" effect to break down along that meridian. Numerical models of the antisolar plasma flow using an unmagnetized ionosphere have reproduced the observed horizontal plasma flows and attributed them solely to the horizontal plasma pressure gradient from day to night. This research provides the answer as to why in this highly magnetized ionosphere, the electrodynamic terms can be ignored when calculating the plasma flow.

Statistics taken over many orbits allow us to use the magnetic field as a diagnostic to pinpoint the location of the ionopause. Using the magnetic field from a single orbit to locate the ionopause can be misleading, however, since the presence of superthermal ions above the thermal ionosphere can also affect the magnetic field orientation. Only with sufficient statistics can ionopause locations be determined if no ion data exists to cross correlate with the magnetic field.

The solar wind interaction with Mars is less well understood than that of Venus. If the Mars scenario can be treated like that at Venus, one would expect a steady state penetration of IMF throughout the ionosphere of Mars, regardless of the fluctuating solar wind conditions. There are many similarities between the two planets that justify this comparison including ionospheric constituents, ion density and temperature profiles, exobase height, and a bow shock standoff distance that is insensitive to changes in the solar wind pressure (indicative of an ionospheric interaction). Future work will involve applying the research done on Venus to Mars. This research, which establishes the magnetic field as a diagnostic for the location and scale of the ionopause at Venus, may allow a spacecraft magnetometer to be used to probe the structure and boundaries of the ionosphere of Mars in the absence of direct ion measurements. This would have had direct applications to the Mars Observer project and will hopefully play a role in future low cost Mars missions such as Mars Surveyor.

Associated ABSTRACT: *Law, Ph.D. Thesis, 1995.*

The solar wind interaction with the non-magnetic Venerean ionospheric obstacle is unique. Ionospheric models of this interaction have primarily been in two dimensions that do not allow for changes in the orientation of the solar wind magnetic field near the obstacle. Analysis of high resolution magnetic field data from the Pioneer Venus Orbiter spacecraft has revealed field rotations

that are observed to occur in conjunction with the dayside ionopause. These rotations are a result of the velocity shear at the ionopause and indicate the alignment of the magnetic field with the radial day to night flow of ionospheric plasma. A new configuration of the dayside magnetic field draping has been derived from these results. In addition, a new current system to account for this changing field orientation has been determined and is discussed in relation to current systems derived from previous models. These new aspects of the dayside solar wind interaction at Venus can be applied to other similar solar system objects. Assuming Mars also represents a non-magnetic obstacle to the flow, as past experimental observations indicate, the field diagnostics discovered here make it possible to probe the structure of the Martian ionosphere using magnetometer data in the absence of ion mass spectrometer data. These results will play a major role in predictive modeling and data analysis for future Mars missions.

Related REFERENCES:

Law, C. C., Observations of Magnetic Signatures and Structure in the Dayside Ionosphere of Venus, M. S. Thesis, Department of Space Physics & Astronomy, Rice University, 1994.

Law, C. C., Currents and Magnetic Field Structures in the Dayside Solar Wind Interaction with Venus and Mars, Ph.D. Thesis, Department of Space Physics & Astronomy, Rice University, Dec 1995.

Law, C. C. and P. A. Cloutier, Observations at magnetic structure at the dayside ionopause of Venus, *J. Geophys. Res.*, 100, 23973-23981, 1995.

3a. Flows and Fields in the Venus Ionosphere

[P. A. Cloutier, Brian Stewart, Leonard Kramer, Gary Hoogeveen and Colin Law]

Previous attempts to model the dynamics of the solar wind-Venus interaction within the ionosphere of Venus (Cloutier et al., 1987) produced a result that implied an additional energy source was required above the energy available from magnetic fields and thermal ion and electron pressures in order to obtain a self-consistent solution to the flows and fields within the Venus ionosphere. Discovery of the "missing pressure" described previously led us to recalculate the flow field with the observed "missing pressure" profiles included as a particle pressure. This inclusion of missing pressure was found to provide exactly the right correction to the flow equations to remove the requirement of any additional energy sources, indicating that the missing pressure was a necessary and significant part of the solar wind interaction. These results are also described in the Ph.D. dissertation at Rice by Dr. Brian Stewart, and will be the subject of a paper now in preparation for publication. We plan to continue the development of the flow/field model of the Venus ionosphere with inclusion of the measured "missing pressure" profiles for various local times and solar wind conditions in an attempt to further match observed ion and magnetic field profiles obtained by PVO.

Associated ABSTRACT: *Stewart, Ph.D. Thesis, 1992.*

A modified steady-state flow/field model is applied to the direct interaction of the solar wind with the Martian ionosphere. The original flow/field model (Cloutier et al., 1987) is a one -dimensional, self-consistent derivation of differentials in vertical velocity, magnetic field, and ion densities from the coupled MHD equations. While successful in reproducing features of Venus and of Mars (Stewart, 1989), the flow/field model required an independently specified heating term (Q). The requirement of this term implies the presence of an energy source not accounted for in conventional calculations. This source was previously simulated with the inclusion of Q, but an unrecognized momentum or pressure term may also provide the coupling with the solar wind without the need of the free parameter Q. An in-depth analysis of Pioneer Venus data in relation to the total conservation of momentum of the system led to the discovery that the total momentum was in most cases not entirely accounted for, and that this "missing" term was correlated with solar wind dynamic pressure. By including this missing pressure, a new set of differential equations, which were also extended to include horizontal velocity terms, was derived. Extrapolation of the missing pressure to Mars gave results that faithfully reproduced the ionospheric features associated with previous flow/field models while maintaining agreement with Viking 1 and 2 observations. Finally, we suggest that the source of $P_{missing}$ could be a population of superthermal particles within the ionosphere. The missing pressures in the Viking simulations are consistent with measured superthermal pressures at Mars.

Related REFERENCES:

Cloutier, P. A., H. A. Taylor, Jr. and J. E. McGary, "Steady-State flow/field model of solar wind interaction with Venus: Global implications of local effects," *J. Geophys. Res.*, **92**, 7289-7307, 1987.

Stewart, B. K., A Steady State Flow/Field Model of Solar Wind Interaction with Mars, M.S. Thesis, Department of Space Physics & Astronomy, Rice University, May 1989.

Stewart, B. K., A Modified Flow/Field Model of the Solar Wind Interaction with Mars, Ph.D. Thesis, Department of Space Physics & Astronomy, Rice University, 1991.

Hoogeveen, G. W., Flow/Field Model of a Hot Magnetized Plasma Interacting with a Cold Neutral Atmosphere, M. S. Thesis, Department of Space Physics & Astronomy, Rice University, Dec 1992.

3b. Venus Flow/Field Model: Comparative Applications for other Solar System Bodies

[P. A. Cloutier and Gary Hoogeveen]

The similarity between the Triton-Neptune magnetosphere interaction with the Venus-solar wind interaction prompted us to use some of the formalism developed during the Pioneer Venus mission on the Triton ionosphere problem. As shown in Cloutier et al. [1987] the direct solar wind access to the Venus ionosphere, due to the lack of a Venusian magnetic field, results in some unique characteristics in the Venus ionosphere. For instance, the interaction produces a more shallow ion density profile than is the case at the Earth, as well as convecting the solar wind magnetic field into the ionosphere. Similarly-unique phenomena were observed at Neptune's unmagnetized moon, Triton. Radio occultation experiments on the Voyager 2 spacecraft found a large and robust ionosphere at Triton. As was the case at the unmagnetized planet, Venus, Triton's ionosphere possessed an unusual ion density altitude profile. Further, Neptune's magnetic field, although unmeasured, was postulated to exist within Triton's ionosphere. Its existence was needed to help explain the ion density profiles.

We began with the flow field model developed for the Venus ionosphere [Cloutier et al., 1987]. This model assumed the magnetic field lines were draped around the planet and modeled the plasma interaction in a pseudo-2D cylindrical coordinate system. The magnetic field was assumed to be 1-D, and the velocity was 2-D with the horizontal component constrained. The conservation of mass, momentum, and energy equations were numerically solved using a Runge-Kutta algorithm. The model was constrained by various Voyager 2 results, such as electron density and temperature altitude profiles.

We found that the detailed characteristics of Triton's ionosphere, as observed by Voyager 2, can be explained within the framework of our model. The interaction between Neptune's magnetosphere and Triton's neutral atmosphere produces the large ionosphere, mainly due to unmagnetized electron precipitation, and the suppressed ion density profiles. Finally, our model describes in detail the transfer of pressure, or momentum, from the flowing magnetospheric plasma to Triton. This is marked by magnetic pressure at 1000 km, the nominal top of the ionosphere, being transferred down to the neutral atmosphere through ion-neutral collisions. At an altitude of ~650 km the magnetic field has gone to zero and transferred all its momentum to the neutrals. Below this point, the precipitating magnetospheric electrons are unmagnetized, thereby flowing directly into the neutral atmosphere, and through multiple interactions, produce the peak in the ionosphere near 350 km altitude.

Associated ABSTRACT: *Hoogeveen, Ph.D. Thesis, 1994.*

Solar wind interactions with planets that possess neither an intrinsic magnetic field nor a significant ionosphere have not been well studied. We have constructed a model to simulate the interaction between a hot magnetized plasma and a planet containing only a neutral atmosphere. Examination of the boundary conditions that yield a physically valid solution shows that the interaction is similar to the solar wind interaction with Venus. We show that most (97%) of the incident flow is deflected around the atmosphere, and the small fraction that enters interacts in such a way as to transfer the flowing momentum through the neutral atmosphere to the planetary body. This demonstrates that the true barrier to a flowing plasma, such as the solar wind, is neither its ionosphere nor its intrinsic magnetic field, but rather the planetary body itself.

Related REFERENCES:

Hoogeveen, G. W., Flow/Field Model of a Hot Magnetized Plasma Interacting with a Cold Neutral Atmosphere, M. S. Thesis, Department of Space Physics & Astronomy, Rice University, Dec 1992.

Hoogeveen, G. W. and P. A. Cloutier, The Triton-Neptune plasma interaction, *J. Geophys. Res.*, 101, 19-29, 1996.

The Nightside Ionosphere of Venus

1. Structure and Dynamics of Ion Troughs

On the nightside of Venus, within a few hours of local time on either side of midnight, the nightside ionosphere frequently exhibits spatial regions in which ionospheric concentrations are depleted by up to several orders of magnitude as compared to horizontally adjacent regions. These regions are called ion troughs and typically exhibit strong magnetic fields with large vertical components, and magnetic pressures within the trough very close to balance with external plasma pressure outside the trough. This balance is a strong indication that these ion troughs are stable spatial structures, although repeated passes trough the nightside shows that these structures may form or disappear on time scales less than 24 hours. Also found in the data are bursts of 100 Hz electric field noise coincident with the ion troughs, thought to be the signature of lightning bursts in the atmosphere of Venus.

Analysis of ion concentrations within troughs from the OIMS data base indicates departures from chemical equilibrium which are strong indications that rapid vertical transport of ionization or rapid production must be occurring within ion troughs. Moreover, the presence of superthermal ions detected by the OIMS and very hot electrons detected by OETP in conjunction with electric field noise point to troughs as a possible location of wave-particle interaction processes. However, current knowledge of the formation and dynamics of ion troughs is limited, and no model exists which explains in detail the development and evolution of ion troughs. We used the Pioneer-Venus high-resolution database for OIMS, OETP and OEFD to study the structure and dynamics of ion troughs with the goal of developing a model which describes the dynamics and evolution of ion troughs and the physical processes which occur in the troughs, especially those related to instabilities which might produce superthermal particles and electric field noise. Work done under this PVO grant includes the detection of electron density fluctuations associated with electrostatic waves near 100 Hz and analysis of the lower-hybrid drift wave instability leading to 100 Hz electric field noise detected in troughs. However, the energetic particle populations and vertical flows inferred from chemistry remain largely unexplained.

1a. Instabilities and Electric Field Noise in Venus Nightside Ion Troughs

[P. A. Cloutier, Shannon Walker, and Harry Taylor]

The study of 100-Hz electric field transients previously described above as being an indication of whistler waves produced by lightning at Venus, and have found that 90% of these transients occur in regions of ion troughs unstable to the lower hybrid drift wave, with the remaining 10% correlated with ionospheric structure. These results are contained in the M.S. thesis at Rice by Shannon Walker, and will be reported in a paper now in preparation for publication. The observation of the lower-hybrid instability with electric field transients in ion troughs is shown in Figure 8. As previously stated, the events which are found in the region marked "stable" are associated with ionospheric structures, and are therefore unlikely to have been produced by Venus "lightning". We propose to study such events, which do not necessarily result from the lower-hybrid drift wave instability, in order to find possible explanations for their correlation with ionospheric structure.

Associated ABSTRACT: *Walker, Ph. D. Thesis 1993*

The Pioneer Venus Orbiter Electric Field Detector (OEFD) detected numerous impulsive electric field events in its 100 Hz channel when in nightside ionospheric troughs. What the source of the signals is has been under debate for over 10 years. Some researchers claim that lightning is generating whistler waves which are then being detected, while other researchers have supported the view that the signals are caused by a local generation of a plasma instability due to the conditions inside the troughs. We believe that the evidence collected by the PVO clearly disproves a lightning source and, in fact, points to an electrostatic wave as being the producer of the transients. We studied several wave modes in an effort to determine the source of the signals. We looked at the two-stream instability, the ion-acoustic instability, the gentle-bump instability, the lower-hybrid-drift instability and the Alfvén wave mode.

We found that not one of the wave modes studied could account for all of the signals. It would appear that there is not a large enough current within the troughs to support the two-stream instability. While the ion-acoustic instability may well be present within some troughs, the conditions needed to produce 100 Hz waves may not be universal trough conditions. Thus, this wave mode is not a likely generator of all the signals. The gentle-bump instability cannot produce 100 Hz waves and any Alfvén waves will be damped.

The lower-hybrid-drift-instability seems to be the most likely candidate of the wave modes studied for producing the transient signals. The frequencies of the lower-hybrid-waves, however, appear to be too low to be detected by the OEFD. We believe that either the frequencies that we calculated are too small due to factors not taken into account, or there is a cascade of energy from the lower-hybrid waves to waves with frequencies that can be detected by the OEFD, or there is a combination of the two.

NOTE: Dr. Walker has provided a more detailed supplement to this section which is included at the end of the report.

Related REFERENCES:

Cloutier, P. A. and H. A. Taylor, Jr., "Telemetry interference incorrectly interpreted as evidence for lightning and present-day volcanism at Venus," *Geophys. Res. Lett.*, 15, No. 7, 729-732, July, 1988.

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Cloutier, P. A., with K. K. Mahajan, H. G. Mayr and L. H. Brace, "On the lower altitude limit of the Venusian ionopause," *Geophys. Res. Letters*, 16, No. 7, 759-762, July 1989.

Cloutier, P. A., with H. A. Taylor, Jr., "Is Venus a Living Planet?," *Solar System Research* 24, 1, (1990), pp. 29-39.

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SUPPLEMENT

The Source of Impulsive 100 Hz Electric Field Signals Detected in the Nightside Ionosphere of Venus

Dr. Shannon Walker

The Pioneer Venus Orbiter Electric Field Detector (PVO OEFD) detected numerous impulsive electric field events in its 100 Hz channel when on the nightside of Venus. What the source of the signals is has been under considerable debate. Some researchers theorize that lightning is generating whistler waves which are being detected, while other researchers have supported the view that the signals are caused by a local generation of a plasma instability in the ionosphere. The author believes that the evidence collected by the PVO clearly disproves a lightning source and, in fact, points to an electrostatic wave as being the producer of the transients. Several wave modes were studied in an effort to determine the source of the signals. The electrostatic wave modes examined were the two-stream instability, the ion-acoustic instability, the gentle-bump instability, and the lower-hybrid-drift instability. Two electromagnetic wave modes were examined, whistler waves and Alfvén waves.

A primary consideration in attempting to relate the 100 Hz impulsive electric field events to lightning is whether lightning is expected to occur on Venus. One possible source of lightning has been conjectured to be volcanoes [*Scarf and Russell*, 1983]. Because certain terrestrial volcanoes are known to produce lightning discharges, it was assumed that comparable Venusian volcanoes would do the same. The type of volcano that produces lightning on Earth erupts with a large, violent explosion with lots of gas and dust in the plume. It is by no means the average type of volcanic eruption on Earth. It seems obvious that explosions would work best in low pressures. The extreme pressures found on the surface of Venus (90+ atmospheres) would tend to inhibit explosive volcanism. The regions that Scarf and Russell originally claimed were the areas where volcanic eruptions were taking place, the highland areas of Phoebe and Beta Regio and the Alta region on the eastern edge of Aphrodite Terra, are indeed believed to be regions of recent, if not current, volcanic activity. But, the type of volcanoes that are believed to be there are shield volcanoes [*McGill et al.*, 1983; *Eberhart*, 1990] which vent lava in a continuous, rather than explosive, process. In addition, there is no evidence of dust in the lower atmosphere [*Esposito et al.*, 1983]. Dust would be expected if there where great numbers of large volcanic eruptions.

The second, and most obvious, source of lightning would be the clouds of Venus. This explanation, however, has several problems. The main cloud deck on Venus is approximately 45 km above the surface [*Esposito et al.*, 1983]. It would seem that at such a great distance above the planet, cloud-to-ground lightning would be a virtual impossibility. Of course, cloud-to-cloud lightning might still exist. But can Venus' clouds produce lightning? On Earth, cloud electrification requires strong updrafts to separate the smaller charged particles from the larger ones, which are controlled by gravity. There is no evidence to suggest that such processes are occurring in the clouds of Venus [*Knollenberg et al.*, 1980; *Esposito et al.*, 1983].

The type of particles within the Venusian clouds also present problems to generating lightning. The Venus cloud particles are composed of small droplets of sulfuric acid. Such particles are not likely to become charged, much less separated in space, to produce discharges. The particles in terrestrial clouds which produce lightning are of a different composition, one which obviously supports charging. The terrestrial particles are also larger than those in the Venusian clouds, which lends to the charge separation. If there are comparable particles in the clouds on Venus, they have escaped detection. It seems unlikely that a certain type of particle would have been missed due to the number of direct cloud measurements made [*Knollenberg et al.*, 1980; *Esposito et al.*, 1983]. In short, lightning activity seems incompatible with the observed properties of the Venusian clouds.

Of course, the definitive test of whether or not there is lightning would be an optical sighting of a flash. There have been four optical searches made for lightning on the nightside which have returned negative results. Two of these have used the star tracker on the PVO to detect flashes [*Borucki et al.*, 1981; 1991] and the other two, on the Soviet VEGA balloons, have used an optical sensor designed to detect lightning [*Sagdeev et al.*, 1986a; 1986b]. These experiments covered the regions claimed by Scarf and Russell to be the sources of copious lightning and found no evidence of it. If large amounts of lightning were being produced in volcanic plumes or in the clouds, these experiments should have seen some flashes.

There are several reasons why a local ionospheric plasma instability should be considered as the source of the impulsive 100 Hz signals. The most notable reason is that the 100 Hz transients are associated with ion troughs rather than geographical areas [*Taylor et al.*., 1985; *Taylor et al.*, 1986; *Taylor and Cloutier*, 1986; *Taylor et al.*, 1987]. They found that the onset and duration of the 100 Hz events were closely correlated with the onset and duration of troughs. Taylor et al. also investigated the distribution of events in altitude. The peak number of events, normalized to time spend at each altitude by the PVO, occurred at around 170 km. The frequency of the events decreased sharply below 170 km, which is inconsistent with a sub-ionospheric source.

Ion troughs are large areas of plasma depletion which are found on the nightside of Venus. The decrease in plasma density is accompanied by a radial, or nearly radial, enhanced magnetic field. There are many feature of troughs that would lend themselves to generating plasma instabilities. Some of the characteristics of troughs which have been detected are as follows [*Brace et al.*, 1980; 1982; *Luhmann et al.*, 1982]. The plasma density within the troughs tends to be at least an order of magnitude less than the surrounding ionosphere. The troughs tend to be more depleted of plasma at higher altitudes with the lower boundary of the troughs being generally

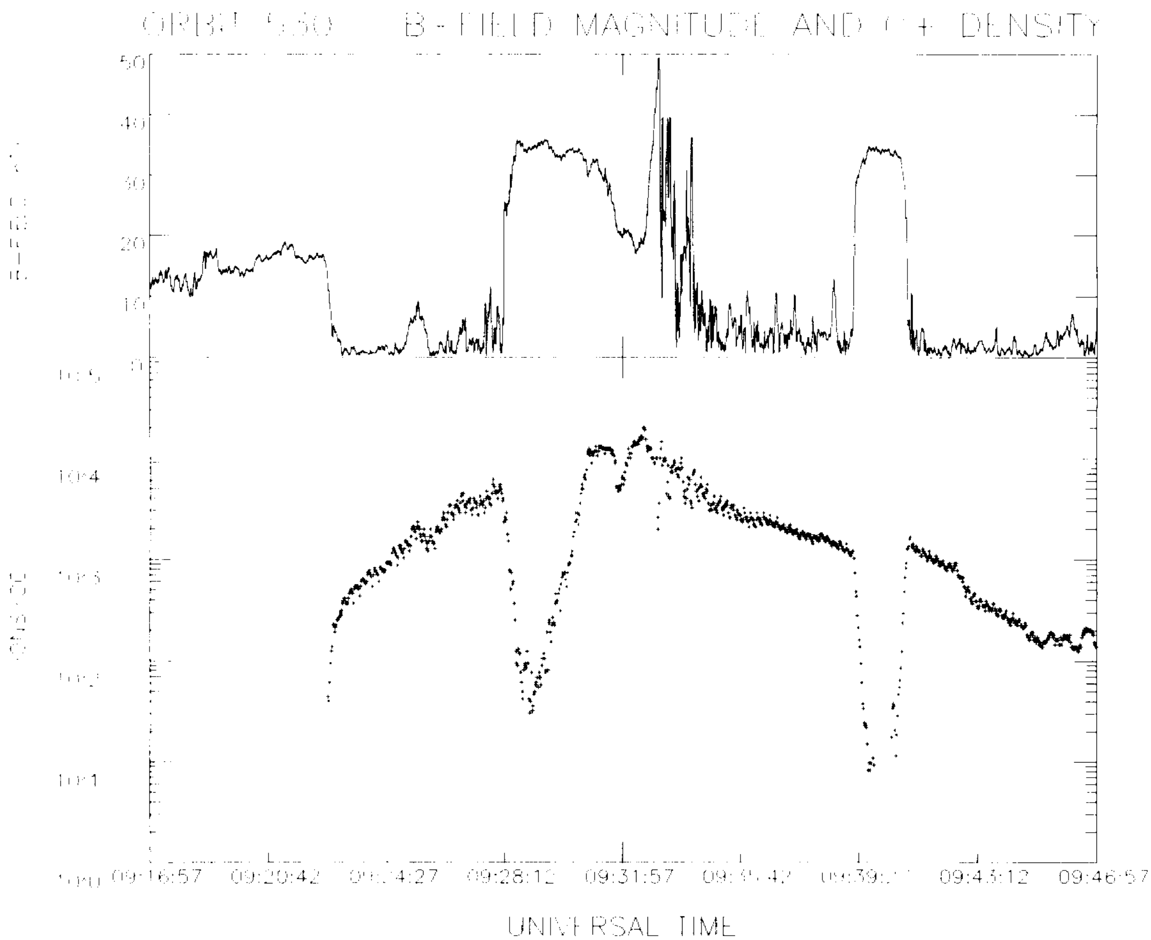

Figure 1 A plot of O+ density versus time. This orbit has two ion troughs. Periapsis is in the center of the plot.

around 200 km. The magnetic field within a trough is strong and steady and has a sharp gradient at the edge. At the lower altitudes the magnetic field turns from being vertical to being horizontal. An example of ion troughs is shown in Figure 1.

There appears to be a dual temperature profile within troughs, resulting in a bi-Maxwellian distribution. Near the edges of the troughs the electron temperatures are generally cooler than the surrounding ionosphere, on the order of 2000 K, while in the severely depleted regions the temperatures are on the order of 15000 K or greater. The number of hot electrons is much less than the number of cooler electrons, so there is probably a high temperature component superposed on the high energy tail of the cooler distribution.

Within the troughs we often see that the ratio of light ions (H^+, He^+) to heavy ions (O^+, O_2^+) is increased as compared to the ionosphere outside troughs. There is some recent evidence to suggest that there are flows of plasma parallel to the magnetic field within the troughs [*Hartle and Grebowsky*, 1990; *Kasprzak and Niemann*, 1992]. It is estimated that the flow speeds increase with altitude, and the light ions flow faster than the heavy ones. Kasprzak and Niemann calculated a minimum flow speed of 3 km/s for O^+, but were unable to determine a flow direction. From plasma theory, these ionospheric troughs should be ideal for generating plasma instabilities as they are not in thermodynamic equilibrium.

In order to identify wave modes as likely candidates for the source of the electric field activity, one must consider both wave generation and wave propagation. Whistler waves are transverse electromagnetic waves which propagate along the background magnetic field of a plasma. For propagation to occur the frequency of whistler waves must generally be between the ion cyclotron frequency f_{ci} and the electron cyclotron frequency f_{ce}, where the cyclotron frequency of species s is given by $f_{cs} = \frac{|q|B}{2\pi m_s}$. The magnetic field strength of the nightside Venusian ionosphere is such that generally only the 100 Hz channel of the OEFD will be able to detect waves, as it is usually the only channel that lies below f_{ce}. Although, occasionally when the magnetic field strength is large, the 730 Hz channel will be able to detect whistlers. Thus, any whistler waves detected will be low frequency, long wavelength waves.

While it is true that the plasma conditions inside troughs will permit low frequency whistler waves to propagate, a point that is often overlooked is the ability of whistler waves to penetrate into the ionosphere. The lower edge of a trough, as stated above, is characterized by a horizontal rather than a vertical magnetic field. In addition, the plasma density returns to the "normal" nightside ionospheric plasma density profile, which can be 10^5 particles per cubic centimeter or more. The large densities would quickly attenuate whistler waves [*Huba and Rowland*, 1992] and the magnetic field profile would not lend itself to picking up whistler waves from a source within the lower atmosphere.

There has been evidence discovered of small scale plasma density perturbations which are often coincident with the OEFD measurements of wave activity [*Grebowsky et al.*, 1991]. This information comes from the Orbiter Electron Temperature Probe (OETP). Grebowsky et al. determined that a great number of the plasma density perturbations occurred simultaneously with bursts of 100 Hz OEFD signals. Grebowsky et al. concluded that the fact that plasma density fluctuations occurred at the same time as 100 Hz transients was evidence of local electrostatic plasma wave generation. Lightning produced whistler waves, being electromagnetic waves, are also non-compressional and, therefore, cannot induce the density fluctuations seen by the OETP.

Electrostatic waves can produce density fluctuations. Electrostatic waves are created when there is a charge imbalance in a neutral plasma. The charge imbalance creates an electric field which then accelerates the charged particles thereby creating oscillations. It is well known from plasma theory that electrostatic waves can be induced by particles streaming parallel to a background magnetic field or from sharp density gradients. These are the conditions found in ion troughs and, therefore, it would be expected that electrostatic waves would exist within troughs.

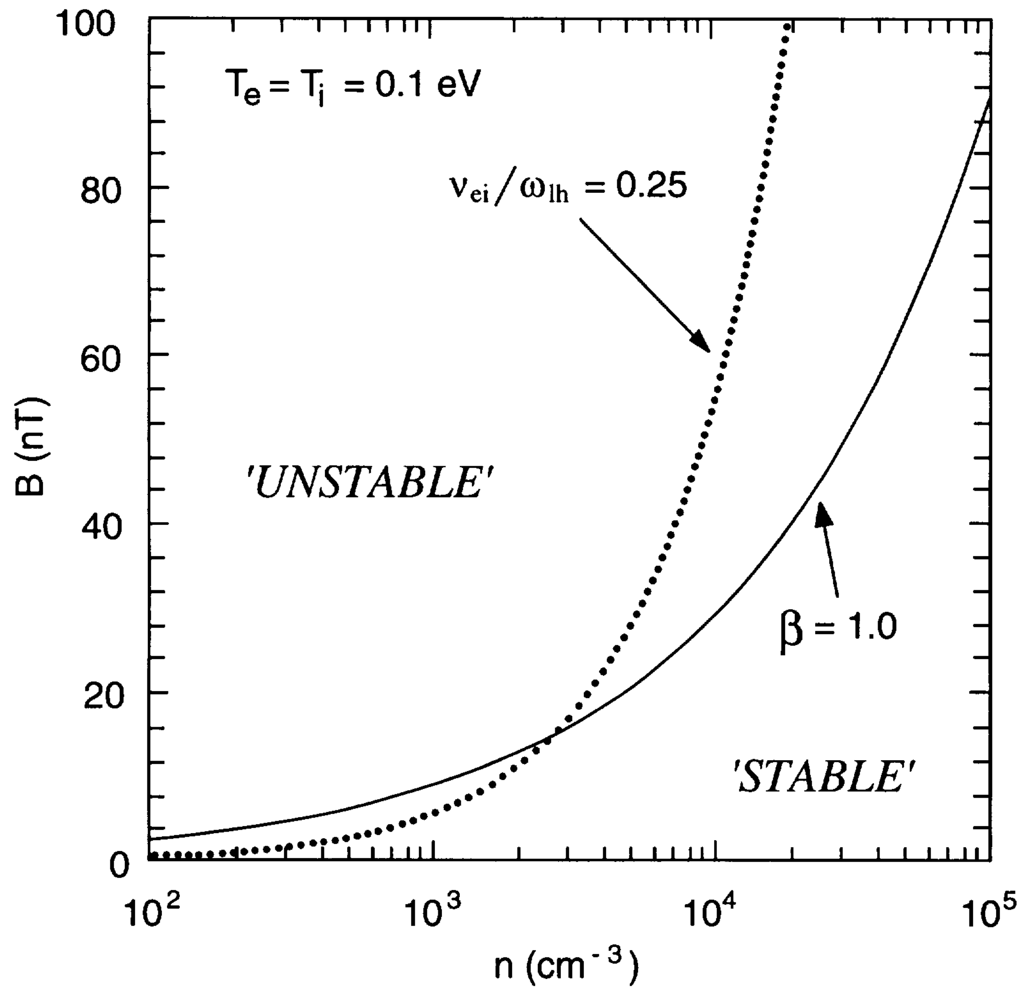

Figure 2 Plot of constant values of beta equals 1.0 and electron-ion collision frequency/lower hybrid frequency equals 0.25. Electron temperature is assumed to be equal to the ion temperature which is placed at 0.1 eV. The region marked "unstable" has beta less than 1 and the frequency ratio less than 0.25. The "stable" region is where beta is greater than 1 and the frequency ratio is greater than 0.25. The regions are indicative of where the lower-hybrid-drift instability will be unstable [*Huba*, 1991].

Researchers first studied the lower-hybrid-drift instability in an effort to determine the possibility that this particular electrostatic drift mode is the source of these electron density irregularities and the 100-Hz-only signals [*Huba*, 1992; *Huba and Grebowsky*, 1992]. There are several reasons why the lower-hybrid-drift instability is a likely choice as the generator of the 100 Hz signals. The lower-hybrid-drift wave mode propagates perpendicularly to the background magnetic field. It has a relatively short wavelength and the frequency of the wave can likely be Doppler shifted to be approximately 100 Hz. Also, it is most unstable in low-β plasmas, where β is the plasma thermal pressure divided by the magnetic pressure. Ion troughs are low-β regions. There are several ways to excite lower hybrid waves. These mechanisms include loss cone plasma distributions, pressure gradients, and cross-field currents. Huba estimated that a density gradient scale length of less than or equal to 20 km would excite the lower hybrid mode. The free energy for wave generation comes from the diamagnetic current associated with density gradients. Finally, the lower-hybrid-drift wave mode can produce plasma density as well as electric field fluctuations.

Huba [1992] developed a rule-of-thumb for determining whether or not the lower-hybrid-drift wave mode could be expected for a given plasma configuration. This guide is shown in Figure 2. If the observed plasma densities plotted against the magnetic field data cluster in the unstable region of the plot, in the $\beta < 1$ region, then correspondingly observed electric field and density fluctuations are most likely due to the lower-hybrid-drift instability. Conversely, if the data cluster in the stable region, then the waves are due to some other source mechanism, either another type of plasma instability or perhaps lightning.

Application of PVO data to the lower-hybrid-drift postulation was done using four separate data sets, the Walker data set and the Scarf and Russell data set [*Walker*, 1992], the Strangeway data set and the Grebowsky data set [*Walker*, 1993]. The Walker data set is ionospheric data taken at the time of 100-Hz-only signals detected within a number of well-defined troughs. It should be

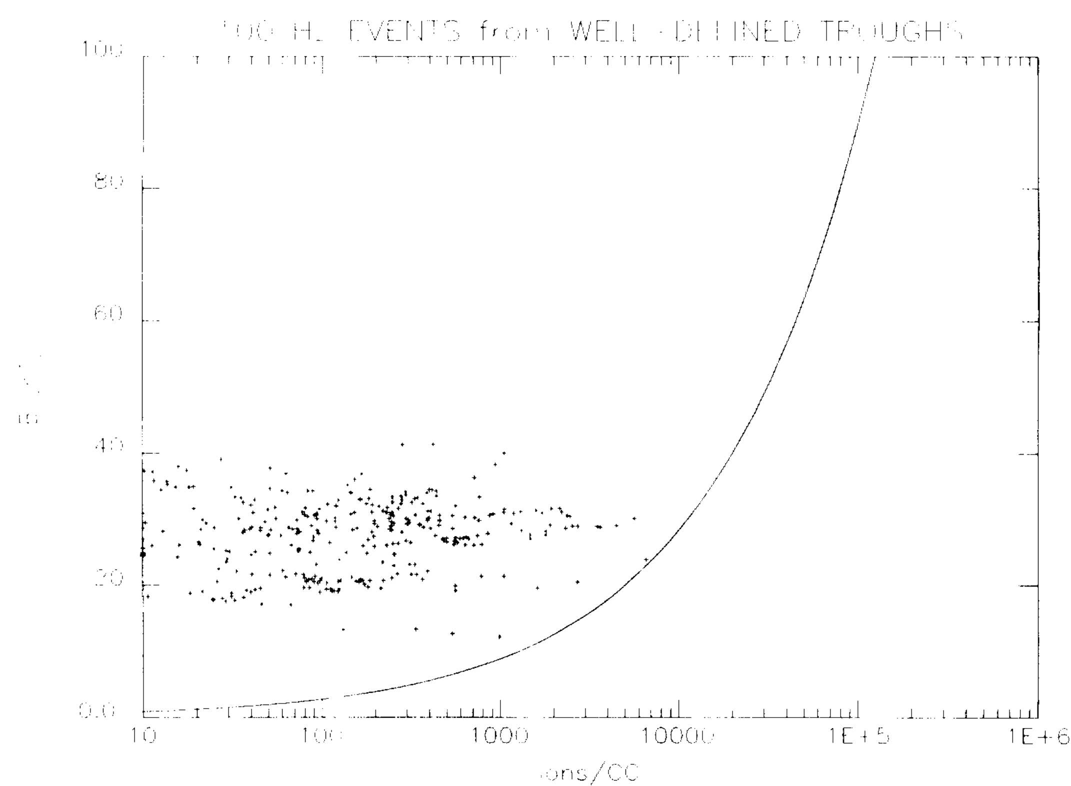

Figure 3 O^+ density versus magnetic field strength for 100 Hz events within well defined ion troughs (332 points, 24 orbits). All events lie within the unstable region [*Walker*, 1992].

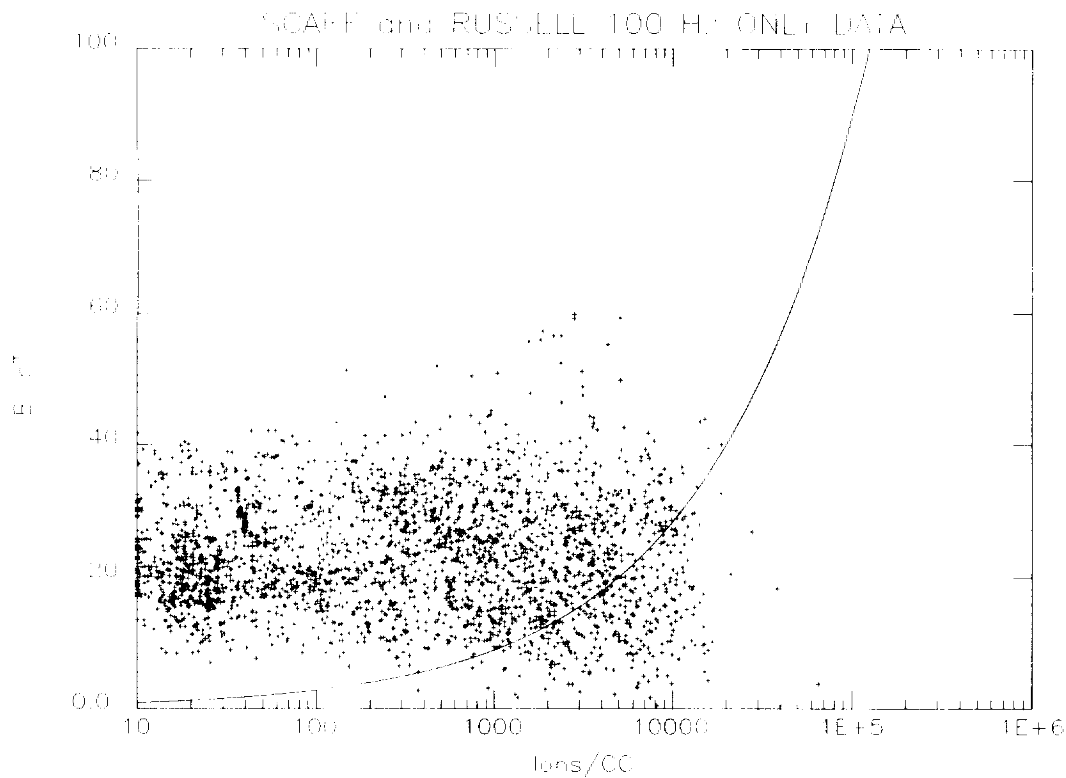

Figure 4 O^+ density versus magnetic field strength for 100 Hz events identified by Scarf and Russell on Orbits 1 - 1895 (3027 points, 266 orbits) [*Walker*, 1992].

noted that there were no well-defined troughs discovered by Walker that did not have 100 Hz events within the trough. The results which were found are as follows: the Walker data, consisting of 332 impulsive events from 24 different orbits, were found to be entirely within the $\beta < 1$ unstable region of the Huba rule-of-thumb plot. These results are shown in Figure 3.

The Scarf and Russell data set of 100 Hz transients from the first 1895 orbits yielded different results as shown in Figure 4. Approximately 10 percent of the Scarf and Russell 3027 events were found to lie outside in the $\beta > 1$ stable region. Upon further investigation it was found that almost all of these stable events (299 out of 312 events) occurred when the magnetic field was fluctuating. The remaining events, save 2, occurred when the ion density was fluctuating.

The Strangeway data set [*Strangeway*, 1992] differs from the previous two in that different criteria were used in determining what was a 100 Hz "burst." Instead of trying to denote each peak of the electric field signature as a burst as was done in the other two data sets, the Strangeway data is based upon the decay time of the OEFD instrument [*Ho et al.*, 1991]. Because many of the impulse signatures decay at a rate that is slower than the decay time of the OEFD, Strangeway and associates have assigned more than one burst for each peak where this occurs. While the overall location of the bursts is often the same as the Scarf and Russell bursts, there are many more data

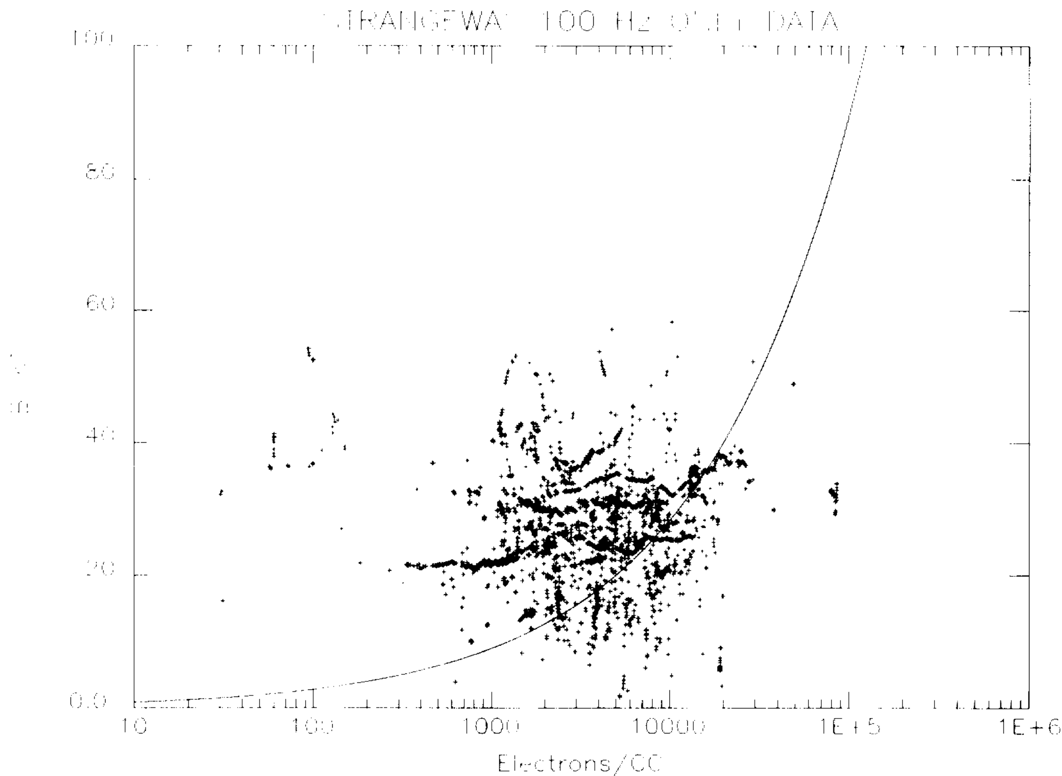

Figure 5 O^+ density versus magnetic field strength for 100 Hz events identified by Strangeway (2999 points, 121 orbits).

points. The Strangeway data contains 2999 points from 121 orbits. Performing the same analyses on this data yields similar results, as shown in Figure 5.

The Grebowsky OETP data [*Grebowsky*, 1992], when put to the Huba rule-of-thumb test, performs no differently from the other data sets, although all of its data points lie in the unstable region. Grebowsky and co-workers found 55 examples of density fluctuations within ion troughs in 28 different orbits. The corresponding figure of the plasma conditions is shown in Figure 6.

The results of the Huba criteria test were quite encouraging. It was expected that when the lower-hybrid frequency of the plasma was calculated for each data point it would match the electric field measurements. The results from these calculations were quite surprising. The average lower-hybrid frequency, given by $\omega_{lh}^2 = \omega_{ce} * \omega_{ci}$, for all the data points is on the order of 24-28 Hz [*Walker*, 1993]. These frequencies are much too low to be detectable by the 100 Hz channel of the OEFD. In fact, the calculated lower-hybrid frequencies cannot even be Doppler shifted into the 100 Hz channel.

The results of the lower-hybrid frequency calculations led to other instabilities being investigated [*Walker*, 1993]. The two-stream instability was looked at due to the evidence that ions are flowing within the troughs. It was shown that the two-steam instability could produce a

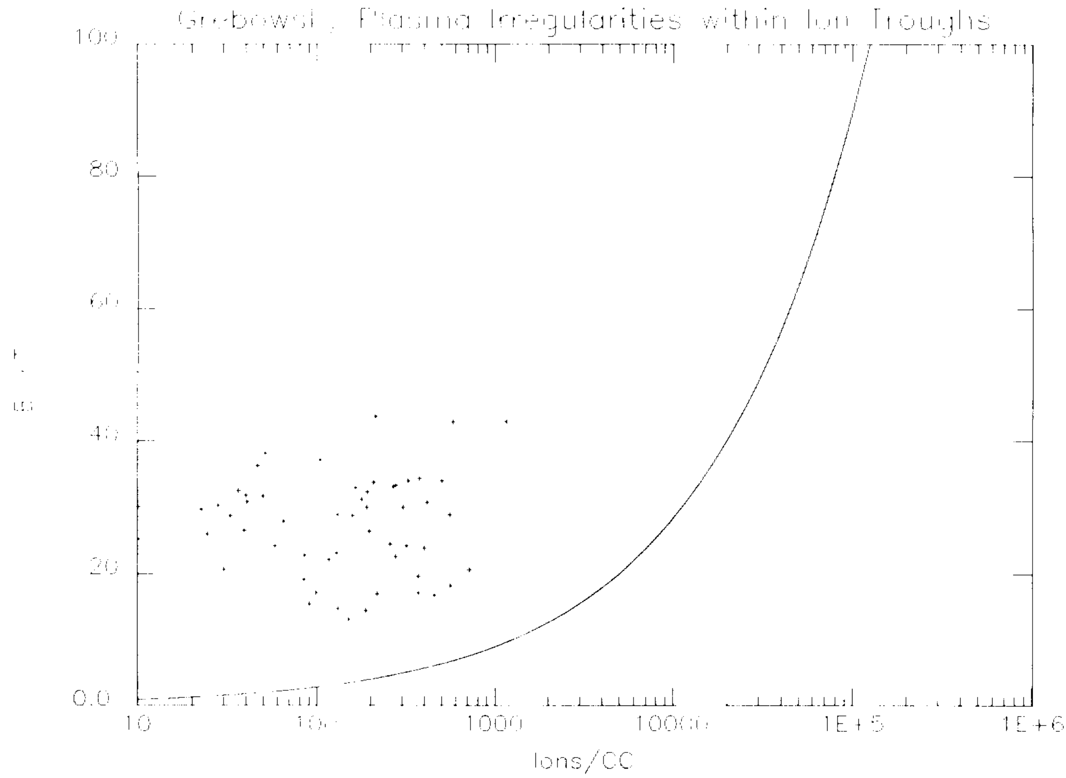

Figure 6 O^+ density versus magnetic field strength for plasma density fluctuations within O+ ion troughs identified by Grebowsky (55 points, 28 orbits).

weakly growing wave with a frequency of approximately 100 Hz for a wide range of trough parameters: a plasma density from 100 to 1000 particles/cc and a relative velocity between ions and electrons from 10 - 10,000 m/s. In fact, as long as $|\mathbf{k} \cdot \mathbf{u}|$ is less than the electron plasma frequency, where **k** is the wave number and **u** is the drift velocity of the ions with respect to the electrons, the two-stream instability will have growing waves.

The ion-acoustic instability was examined because ion-acoustic waves are electrostatic low frequency oscillations. It was determined that ion-acoustic waves with a frequency of 100 Hz could exist, but the plasma parameters needed for the waves to occur were narrowly defined. The gentle-bump instability was chosen because of the high temperature component seen in the electron temperature profile. The lowest frequency wave that the gentle-bump instability can produce is has a frequency equal to the electron plasma frequency. For typical trough conditions, the electron plasma frequency is on the order of 5.6×10^5 rad/s. This frequency is several orders of magnitude above the desired frequency of 100 Hz. Alfvén waves, an electromagnetic wave, was shown to be weakly damped at 100 Hz. While this wave mode may be promising, it should be remembered that electromagnetic waves cannot produce the plasma density fluctuations measured by the OETP.

Not one of the wave modes studied could account for all of the signals. It would appear from the steady magnetic field inside of the troughs that there is not a large enough current to support the two-stream instability. While the ion-acoustic instability may well be present within some troughs, the conditions needed to produce 100 Hz waves may not be universal trough conditions. Thus, this wave mode is not a likely generator of all the signals. The gentle-bump instability cannot produce 100 Hz waves and any Alfvén waves will be damped.

The author believes that the lower-hybrid instability shows the most promise of the waves we studied as the 100 Hz signals' source. However, the problem with the lower-hybrid-drift instability is the frequency of the waves would seemingly be too small to be detected by the OEFD. The lower-hybrid frequencies and subsequent Doppler shifted frequencies which we calculated lie far below the lower limit of the OEFD. There may be one or more conditions which we did not take into account that may contribute to these low frequencies. The lower-hybrid frequencies may be higher than calculated because a different ion population may be with the troughs than the one assumed. The Doppler shift may be greater than calculated because of the strong flows of plasma which have been detected or due to a plasma temperature other than the one assumed. Finally, it is plausible that processes similar to those observed on Earth are occurring on Venus. This would imply that the waves that are being detected are not the lower-hybrid waves, per se, but waves that are being generated because of the lower-hybrid waves [*Scannapieco and Ossakow*, 1976; *Huba and Ossakow*, 1979; *Kelley et al.*, 1982a; 1982b; *Drake et al.*, 1983; 1984]. A cascade of energy from the lower-hybrid waves is supporting shorter wavelength waves whose frequencies are such that they are detectable by the OEFD.

Although, in the course of this research, the source of the 100 Hz impulsive signals was not definitively located, the scope of the problem has certainly been narrowed. It is clear that the signals are not from whistler waves originating in the lower atmosphere. Further investigation may show that the lower-hybrid-drift instability is involved in generating the waves. Or, there is always the possibility that there is another instability at work which has not yet been discovered.

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