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PLASMA WAVE EXPERIMENT
FOR THE ISEE-3 MISSION

by

F. L. Scarf,
Principal Investigator

Semi-Annual Report
(For Period: April 1, 1983 - Sept 30, 1983)

Prepared for
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16. Abstract

The objective of this contract is to provide analysis of data from a scientific instrument designed to study solar wind and plasma wave phenomena on the ISEE-3 Mission.

This report is the 7th Semi-Annual Report, submitted in compliance with Modification 19 to Article XXI of Contract NAS5-20682, entitled, "Plasma Wave Experiment for ISEE-C (Heliocentric) Mission dated 20 November 1974.

The purpose of this report is to summarize the performance of work on the data analysis phase of the contract during the period commencing 1 April 1983 and ending 30 September 1983.

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PREFACE

1. OBJECTIVE

The purpose of this report is to summarize the performance of work for the period 1 April 1983 through 30 Sept 1983, in compliance with Modification 19 to Article XXI of Contract NAS5-20682, entitled "Plasma Wave Experiment for ISEE-C (Heliocentric) Mission" dated 20 November 1974.

The objective of this contract is to provide analysis of data from a scientific instrument designed to study solar wind and plasma wave phenomena on the ISEE-3 Mission.

2. SCOPE OF WORK

Project activities during this past six months have included successful return of data from the instrument, continuing analysis of all data, publication of results, and deposit in National Space Science Data Center of the data.

3. CONCLUSIONS

Not applicable.

4. SUMMARY OF RECOMMENDATIONS

Not applicable.

1.0 INTRODUCTION

The purpose of this report is to summarize the various activities and tasks accomplished on the data analysis phase of the contract during the last six months.

2.0 WORK ACTIVITIES FOR THE SIX-MONTH PERIOD

2.1 Research

During the past six months, several papers have appeared in print, new manuscripts have been completed and submitted for publication, and intensive research on the ISEE-3 tail Measurements has started. In the previous report (Oct 1, 82-Mar 30, 83) we described several pending publications. The paper "Science Return from ISEE-3 Comet Giacobini-Zinner" appeared in Cometary Exploration, Vol 2 (p.225). The paper "The Interplanetary Shock Event of November 11/12 1978-- A Comprehensive Test of Acceleration Theory" appeared in Proceedings of the 18th International Cosmic Ray Conference (p. 131). The paper "Plasma Boundaries and Shocks" appeared in Reviews of Geophysics (21,449, 1983). The paper "Transfer of pulsation-related wave activity across the magnetopause" appeared in Geophysical Research Letters (10, 659, 1983).

The new papers completed during this period include "Plasma Waves in Space" by F. Scarf and "On the Relationship Between Collisionless Shock Structure and Energetic Particle Acceleration" by C. Kennel (to be published in the Porceedings of the Spring College on Radiation in Plasmas, International Centre for Theoretical Physics), and "The Structure of Oblique Laminar Bow Shocks: ISEE 1 and 2" (submitted to J. Geophysics Research) by M. Mellott and E. Greenstadt. Copies of these papers are attached,

During this period, Dr. Kennel and his co-authors worked to restructure the paper formerly entitled "Plasma and Energetic Particle Structure of a Collisionless Quasi-Parallel Shock". This paper is being rewritten in several parts. Another work that is underway is "Report of Working Group 10 on Collisionless Shock Waves in the Solar Terrestrial Environment" (Greenstadt et al) prepared for the Solar-Terrestrial Physics Workshop. Finally, Scarf, Coroniti and Gurnett are now now writing papers on the new ISEE-3 tail data.

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PLASMA WAVES IN SPACE*

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June 1983

*Invited lecture, Spring College on Radiation in Plasmas, International Centre for Theoretical Physics, Trieste, Italy, 24 May - 17 June, 1983 (to be published in the Proceedings).

PLASMA WAVES IN SPACE

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ABSTRACT

During the first ten years of space exploration, spacecraft were generally instrumented to measure properties of the local magnetic field and characteristics of energetic particles, but during the last fifteen years, plasma physics investigations have assumed dominant roles in many space programs. Sensitive, high-resolution plasma probes for analysis of the distribution functions and plasma wave instruments for measurements of electromagnetic and electrostatic wave modes are commonly flown together to provide information on plasma instabilities and wave-particle interactions. Spacecraft with plasma physics payloads have now explored the magnetospheres of Earth, Jupiter, and Saturn; the plasma environment of Venus; and the very-low density interplanetary medium from within the orbit of Mercury to well beyond Saturn's orbit. During the next few years, it will also be possible to study at close range plasma waves and wave-particle interactions that develop near Uranus, Neptune, Comet Giacobini-Zinner, and Comet Halley.

These measurements of solar system plasma processes are of great importance because they provide the only opportunity to acquire <u>in situ</u> data that can be used to test theories developed to explain astrophysical observations. The measurements generally involve parameter ranges that are not accessible in laboratory experiments, and so the space plasma physics programs also serve to extend and validate concepts developed in the laboratory. However, the discipline of space plasma physics has some unique problems. For instance, when local measurements are made from a small platform that moves within the plasma, it is sometimes difficult to separate space and time variations, it is sometimes difficult to distinguish spacecraft interference tones from ambient plasma waves, and it is generally difficult to estimate the wavelengths of the plasma oscillations with certainty. In some areas, however, space plasma physics measurements have natural advantages. For instance, wall effects are not important except at the surfaces of the spacecraft. Plasma physics measurements in space are also unique because, here, the plasma probes are able to measure fine details of the distribution function that are needed to understand how the observed waves are generated. Finally, since many plasma waves in space have characteristic frequencies that occur in the audio range, it is possible to listen directly to the measurements of wave activity in space plasmas.

1. Introduction

At the beginning of the space age, mission planners tacitly made the assumption that the region above the ionosphere is a near-vacuum, populated only by energetic particles trapped in the earth's magnetic field. In the early 60's, the confirmation of the existence of a streaming solar wind showed that the region of influence of the terrestrial magnetic field had to be finite, and the first series of spacecraft to explore the earth's outer magnetosphere therefore carried solar wind plasma probes, as well as instruments to measure characteristics of the magnetic field and the energetic particles trapped in the radiation belts. However, these missions continued to ignore the possibility that plasma physics phenomena are of importance within the magnetosphere.

Subsequent developments conclusively demonstrated the need to start making direct measurements of microscopic plasma processes in space. The strong dissipation and particle acceleration associated with the collisionless bow shock surrounding the magnetosphere clearly could not be explained without invoking localized plasma instabilities and wave-particle interactions. In addition, detailed theoretical analysis showed that the electrons in the earth's radiation belts have characteristics consistent with operation of a gyroresonant plasma instability driven by thermal anisotropies. These advances in the mid-60's convinced mission planners in several space agencies of the need to include sensitive plasma probes and plasma wave instruments in the payloads of spacecraft traversing the terrestrial magnetosphere; somewhat later, plasma physics instruments were also routinely placed on planetary missions.

These spacecraft measurements of plasma processes were designed to provide basic physical understanding of local phenomena (in the magnetospheres of Earth, Jupiter, and Saturn; the plasma environment of Venus; and the interplanetary medium), and in all of the spatial regions explored to date, very important interaction phenomena have been detected. Specifically, it has been discovered that the collisionless plasmas in space generally have non-Maxwellian distribution functions, with characteristics that strongly affect the growth of plasma waves. The detailed measurements of local particle characteristics show that many mechanisms operate to produce a complex variety of non-equilibrium plasma distributions in the earth's ionized environment. Within the magnetosphere thermal anisotropies with $T_{\perp} > T_{\parallel}$ develop because of: (a) inward plasma diffusion and convection with conservation of μ; (b) cyclotron and betatron acceleration effects; and (c) selective pitch angle scattering into the loss cone. The observed magnetospheric distributions with $T_{\parallel} > T_{\perp}$ are probably associated with inward motion and conservation of the longitudinal action invariant, while similar distributions in the solar wind are thought to be connected with conservation of μ, as the interplanetary field strength in the expanding plasma continuously declines. Other thermal anisotropies that are significant with respect to plasma instabilities involve heat flux and higher order moments, and these perturbations can be associated with parallel electric fields, currents, particle beams, and heat conduction.

It has also become clear in recent years that the natural plasmas are locally non-Maxwellian in the sense that there are significant peaks and dips in the energy distributions. These fluctuations arise because: (a) the solar wind and the ionosphere are more or less independent sources of warm and cool magnetospheric plasma; (b) varying gradient drifts selectively remove trapped particles in restricted energy ranges from the magnetosphere and they leave residual quasi-trapped distributions with deep flux ripples; (c) collisionless acceleration processes apparently provide enhanced fluxes at certain energies; and (d) resistive dissipation and heat conduction (and perhaps runaway) contribute to the observed non-thermal tail populations.

The original fairly narrow application of the two-stream instability has also been greatly generalized in recent years. Suprathermal flows are commonly detected within the magnetosphere (i.e., in the polar cusp and in the tail during large substorm events), and it is known that the equivalent electron-proton drift speed in the solar wind and magnetosheath has a significant contribution associated with electron heat conduction. Current-driven instabilities are found to be important at field-merging regions in the magnetosheath, as well as the bow shock, and the field-aligned currents associated with pressure gradients in the magnetosphere, the cusp boundary, and the high latitude ionosphere can involve streaming instabilities.

These solar system measurements of plasma distributions and wave-particle interactions have also proven to be of great value in terms of general plasma physics. In essence, the space observations provide the only way to gain direct information on the characteristics of plasma processes that are commonly invoked by theoreticians who offer explanations of astrophysical measurements. In addition, the space observations are of great importance because they allow the plasma and wave investigations to be conducted with unique and important advantages. The measurements are made from small platforms that move freely within the plasma, and the particle analyzers can measure the distribution functions with very high resolution in velocity, angle, ion mass, etc., while the wave investigators can utilize electric antennas having scale sizes small compared to Debye lengths. Since the space measurements also generally involve parameter ranges that are not accessible in the laboratory, these programs provide important information for all plasma physicists.

In this review, we focus attention on (a) electrostatic instabilities associated with currents, drifts and particle beams, and (b) electromagnetic instabilities associated with thermal anisotropies. Extensive measurements of wave-particle interactions have now been made in the magnetospheres of Earth, Jupiter, and Saturn (Figure 1 shows the relative sizes of these three magnetospheres), in the solar wind from within 0.4 AU (Helios) to beyond 15 AU (Voyager), and in the plasma interaction regions surrounding Venus (Pioneer Venus Orbiter)

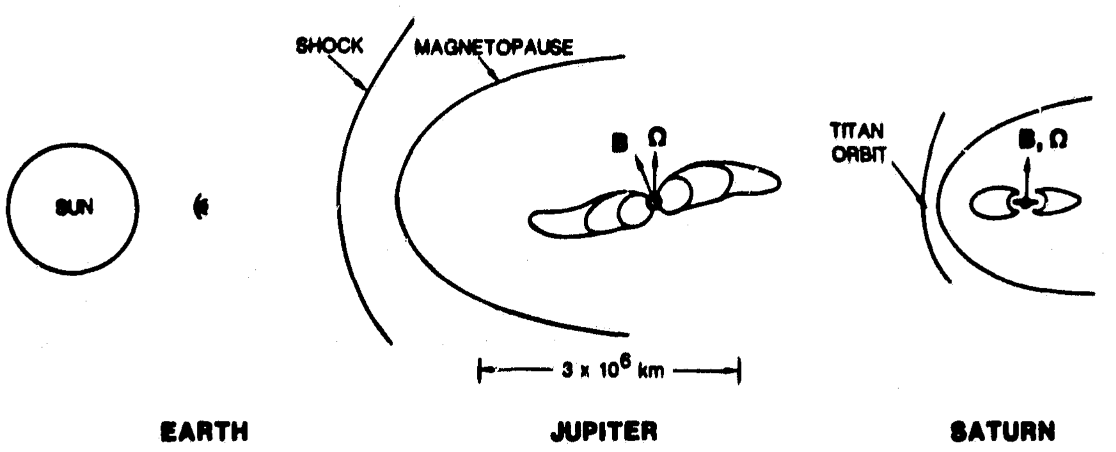

Figure 1. This scale drawing shows how the nominal sizes of the Earth, Jupiter, and Saturn magnetospheres compare with each other and with the solar disk. Only the sunward sections of the magnetospheres are depicted, but the magnetic tails extend very far downstream; instruments on Voyager 2 detected the Jovian tail more than 630 million kiolmeters behind the planet, demonstrating that the tail actually extends beyond the orbit of Saturn.

and Titan (Voyager); we use data from many of these locations to illustrate advances derived from observations of space plasma physics processes.

2. Instabilities Associated with Currents, Drifts, and Beams

From a plasma physics viewpoint, space measurements of strong wave-particle interactions associated with current-driven instabilities are particularly valuable because the significant interactions are highly localized, and the scale lengths are extremely small; magnetic structures and dissipation lengths are on the order of c/f_p^+, c/f_p^- (c is the speed of light, and f_p^-, f_p^+ are the electron and ion plasma frequencies), and wavelengths as small as $2\pi\lambda_D$ (λ_D is the Debye length) play important roles in providing dissipation.[1)] These small scale sizes can, however, be readily studied from spacecraft, since the spacecraft ($\approx$ meters) is very small in comparison with the shock scale sizes (hundreds of meters to kilometers).

The most extensive measurements in space are related to studies of the collisionless bow shock in front of the Earth, and Figure 2 shows some characteristic plasma wave phenomena detected on October 18, 1982, when ISEE-3 crossed the shock surface on its way to start the initial exploration of the Earth's distant magnetic tail. The figure shows the total magnetic field (bottom panel), the magnetic field wave levels in six bandpass channels covering the range 18 Hz to 311 Hz (center panel), and the electric field wave levels in sixteen channels covering the range 18 Hz to 100 kHz (top panel). The shock jump (near 0600) is associated with a peak in the turbulence levels for the E and B components of the plasma waves, but it can be seen that significantly enhanced wave levels persist throughout the downstream magnetosheath. Figure 2 also shows presursor wave activity in the upstream region (the foreshock), and we identify 31 kHz emissions as electron plasma oscillations. The broadbanded mid-frequency (311 Hz to 5.6 kHz) electric field bursts detected between 0200 and 0400 are thought to be short-wavelength Doppler-shifted ion acoustic waves generated by supersonic ions streaming back from the bow shock. These signals are very impulsive, and Figure 2 shows that the peak-to-average ratio is very large (for each channel in Figure 2, the vertical scale corresponds to an amplitude range of 4½ orders of

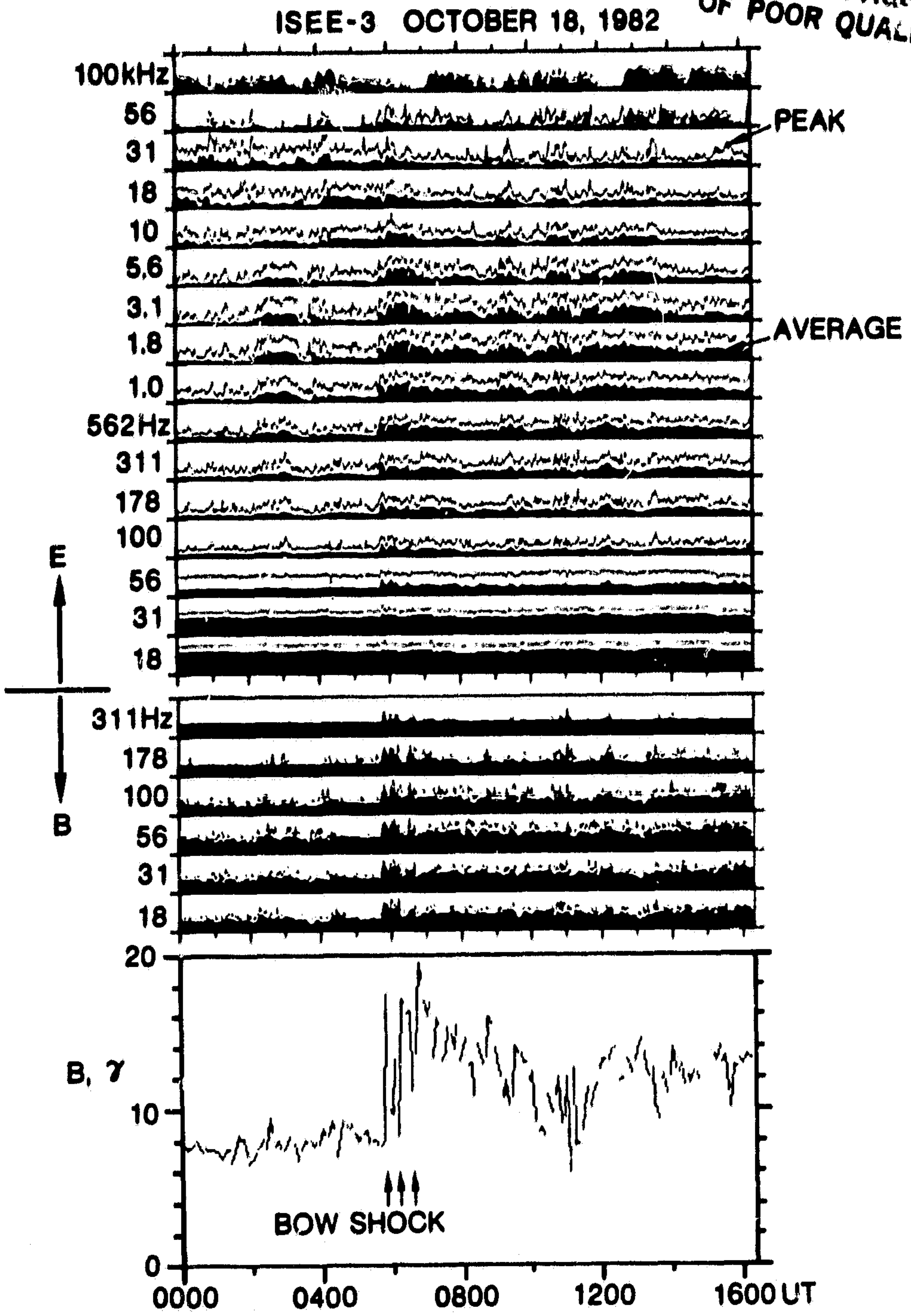

Figure 2. Magnetic field profile (bottom panel) and B and E wave levels (upper panels) measured on October 18, 1982, when ISEE-3 crossed the Earth's bow shock. This figure shows the full range of shock-associated phenomena, including enhanced wave levels within the narrow shock layer (near 0600), upstream electron plasma oscillations and ion acoustic waves, as well as high turbulence levels in the downstream region (magnetosheath).

magnitude).

The low-frequency electromagnetic waves detected at the shock and in the magnetosheath are readily identified as right-hand polarized whistler mode signals. In these regions, the higher-frequency E-field waves are again customarily identified as ion acoustic oscillations, and this suggests that the turbulence peak at the shock jump is associated with an ion sound instability driven by the currents that produce the $\Delta B/\Delta X$. The resulting anomalous resistivity can then, in principle, account for the shock dissipation.[2)]

Although this general concept of the microstructure for a thin collisionless (laminar) shock was put forth at an early stage, detailed investigations of shock processes have continued to occupy the forefront of space plasma physics for more than a decade. The right-hand drawing in Figure 3 contains a sketch that is now thought to represent a "snapshot" of the solar wind-magnetosphere interface region. For a fixed field orientation, the thin quasi-perpendicular shock develops on one side of the magnetosphere, while the other side has thick quasi-parallel shock structures, with an extensive foreshock region that contains suprathermal electrons and ions and enhanced wave levels. This picture was originally constructed using single-point measurements from isolated spacecraft, together with occasional data from multiple spacecraft in the same general region. However, a long-standing problem of great importance involved determination of the shock speed with respect to the spacecraft, so that the actual thickness of the shock layer (and the current) could be evaluated. The left-hand side of Figure 3 shows how the problem was recently solved using two spacecraft in nearly the same orbit; ISEE 1 and 2 measurements, such as those plotted here, provided information that allowed space and time variations to be distinguished, so that $\Delta B/\Delta X$ could be evaluated with confidence.[3)]

In recent years, the measurements of plasma physics phenomena have been extended to Venus, Jupiter, and Saturn, and Figure 4 contains characteristic bow-shock turbulence spectra detected on Pioneer Venus, IMP-6, and Voyager 1 and 2. In order to allow spectral shifts to be assessed with respect to the changes in plasma characteristics, the average values for the electron and proton plasma frequencies (f_{pe}, f_{pi}), the electron cyclotron frequency (f_{ce}), and the Buneman [4)]

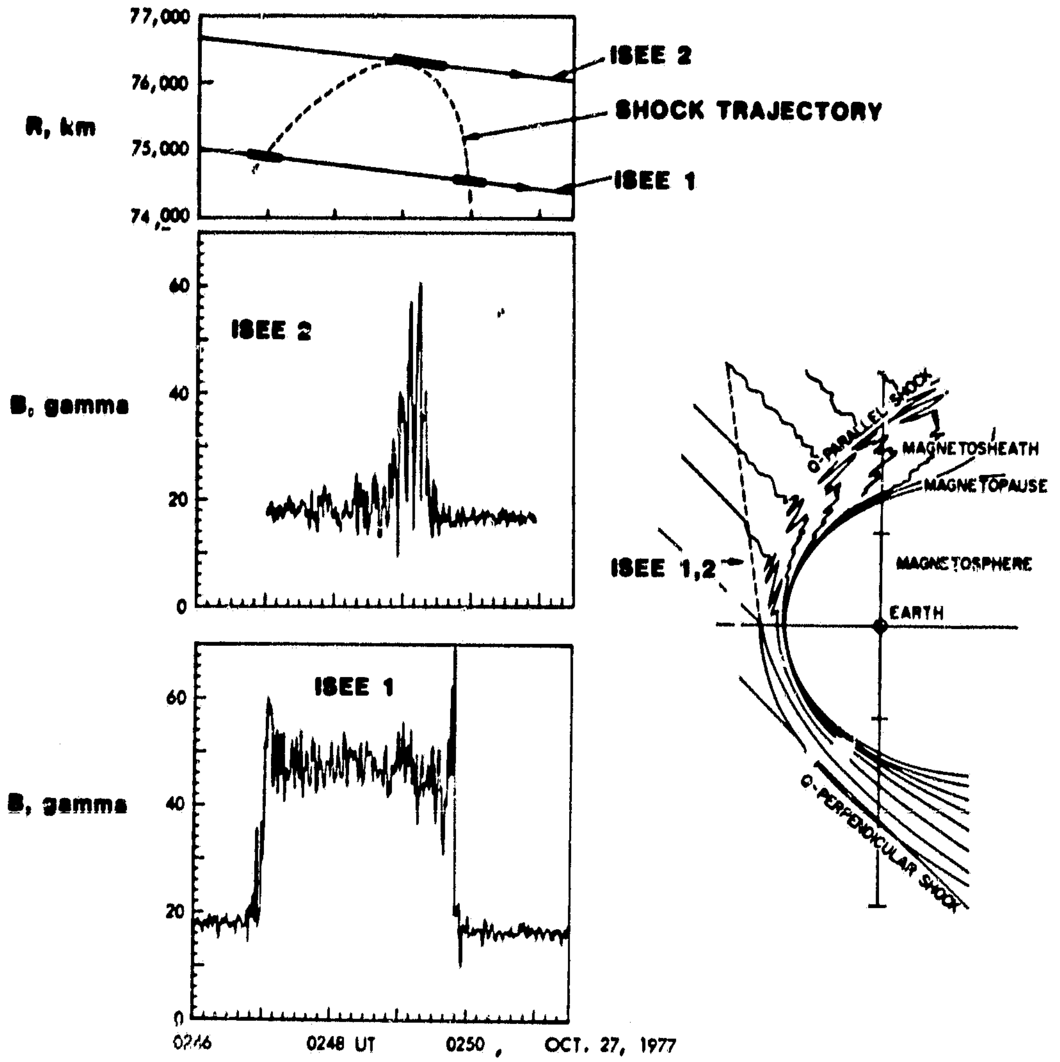

Figure 3. Right side: Conceptual snapshot of the interface between the streaming solar wind and the terrestrial magnetosphere. For any fixed B-field orientation, it is expected that thick quasi-parallel shocks will develop in some regions, while thin quasi-perpendicular shocks will be present in other locations.
Left side: Simultaneous measurements from the ISEE 1 and 2 spacecraft allow space and time variations to be distinguished.

frequency ($f_B = [m_e/m_i]^{\frac{1}{5}} f_{pe}$), 0.7, 1.0, 5.0, and 9.2 AU, are shown at the tops of the individual panels. These measurements suggest very significant changes in spectral shape with changing heliocentric distances. Scarf, Gurnett, and Kurth[5)] attribued the variations to changes in the average Mach number from the range of 5-6 (mean Alfvén Mach number for Earth, Venus) to the range 11-21 (Jupiter and Saturn).

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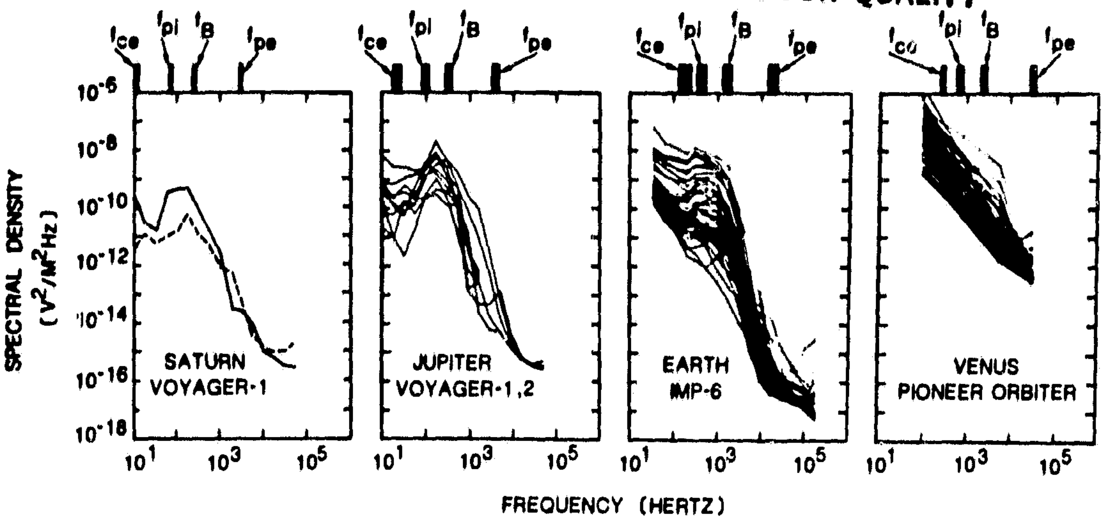

Figure 4. Comparison of bow-shock plasma wave spectra measured at Saturn, Jupiter, Earth, and Venus.

These results are of interest because they suggest that in situ studies in the distant solar system provide direct information on supercritical shock phenomena.

Multi-planet observations also provide very significant information on the variable nature of post-shock plasma conditions. At Earth, it is known that the magnetosheath is characterized by enhanced turbulence (see Figure 1), and these measurements form the basis for certain astrophysical theories of shock-induced particle acceleration involving wave-particle interactions in the pre-shock and the post-shock regions. At Venus, the downstream sheath region is found to be even more turbulent than at Earth. In fact, Figure 5 shows that in a related situation, where Titan's exosphere-ionosphere interacts with the corotating plasma of Saturn's magnetosphere, very intense turbulence levels were detected, although the Mach number was so low that only a slow-mode shock might have developed.[6)]

Since the post-shock turbulence levels at Venus, Earth, and Titan were found to be so high, one could assume that this result is universally true. However, the Voyager 1 and 2 measurements in the magnetosheath regions of Jupiter and Saturn revealed extremely low turbulence levels for $f \geq 10$ Hz. It is possible that with these high Mach number shocks, strong downstream wave activity occurs only for $f \ll f_{ce}$ [Prognoz 8 measurements show enhanced wave levels at the lower hybrid resonance ($f \approx f_{ce}/43$) during crossings of the terres-

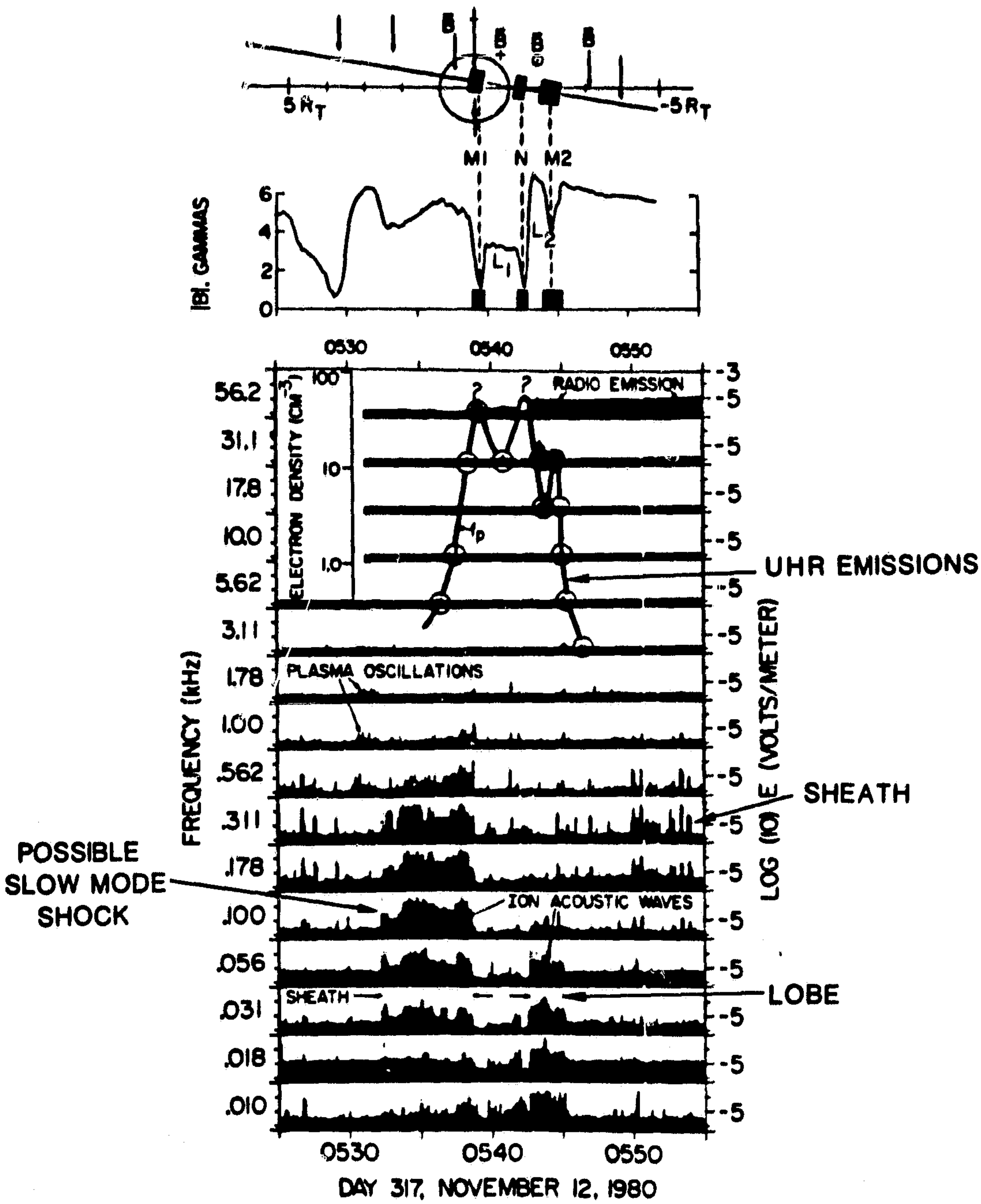

Figure 5. Magnetic field and plasma wave measurements obtained as Voyager 1 passed behind Titan. The high-frequency wave observations yield the electron density profile, and the B-field data show the locations of the magnetotail boundaries (M_1, M_2) and the neutral sheet (N), between the two tail lobes (L_1, L_2). The very intense low-frequency waves are interpreted as ion acoustic oscillations in the sheath and plasma sheet.

trial bow shock; such electrostatic waves, presumably associated with the lower hybrid drift instability, could not have been detected on Voyager]. It is also possible that post-shock flow can be extremely quiescent for some ranges of astrophysical plasma parameters; if this is true, it may be necessary to search for acceleration mechanisms that do not depend on the presence of strong wave-particle interactions downstream from collisionless shocks.

Bow-shock phenomena illustrate the diverse range of plasma waves associated with instabilities driven by currents, plasma beams, suprathermal particles, and heat conduction. However, these instabilities are not uniquely associated with the solar wind-magnetosphere interface region. Field-aligned currents are also of considerable importance within the magnetosphere, and the OGO-5 investigators first described the detection of strong electrostatic turbulence together with field-aligned currents in the polar cusp and on the plasma sheet boundary.[7)]

The plasma turbulence associated with current-driven instabilities produces changes in the distribution functions, and the process can be described in terms of an anomalous or turbulent resistivity. As discussed by several authors, the effective collision frequency, ν_{eff}, is approximately given by[2)]

$$\nu_{eff} \approx \sqrt{2\pi^3}\, f_{pe}\, (\epsilon_o E^2/2N\kappa T_e), \tag{1}$$

and, in principle, the anomalous resistivity can be evaluated directly by measuring the local plasma wave turbulence amplitude and the electron moments. For instance, for a typical terrestrial bow shock, ν_{eff} turns out to be approximately 30-60 collisions per second using Equation (1) with $T_e = 2 \times 10^{5\circ}$ K, and the anomalous conductivity, $\sigma = Ne^2/m\, \nu_{eff}$, can account for the shock dissipation.

Fredricks et al.[7)] first used wave and particle measurements from OGO-5 to argue that during storms anomalous resistivity near the boundaries of the earth's polar cusp allows large-scale parallel electric fields to develop. Other aspects of the high-latitude measurements are consistent with an anomalous resistivity interpretation. In the cusp region, electron spectral plots show a depletion in low-energy population and appearance of suprathermal particles as the spacecraft encounters the current system and its associated turbulence; these changes could be explained by resistive heating associated with the wave particle interactions. It is noteworthy that field-aligned currents and related electrostatic turbulence are also frequently detected above the Venus ionosphere (see Figure 6). This suggests that even in the absence of a permanent planetary magnetic field, microscopic plasma processes that yield anomalous resistivity readily develop; in all of these cases, the dynamical processes cannot be well described in terms of conventional mhd fluid theories, and the plasma physics phenomena actually control the large-scale configuration changes, as well as the local particle distribution functions.

3. Gyroresonant Interactions

The original concept that electromagnetic whistler mode turbulence leads to precipitation of radiation belt particles was developed into a self-consistent theory by Kennel and Petschek[8)]; this was based on use of a natural gyroresonance instability mechanism for the wave growth (amplification associated with trapped particle $T_{\perp} > T_{\parallel}$ pitch-angle distributions) and the concept of turbulent pitch-angle diffusion arising from the local wave-particle interactions. The Kennel and Petschek[8)] theory predicted stable trapping limits and precipitation patterns that agreed well with terrestrial observations, and this pioneering effort has since stimulated an enormous amount of more detailed analytical activity; improved self-consistent theories for electron whistler and ion cyclotron mode turbulence were developed, these ideas were applied to analyze lightning whistler amplification processes, numerical simulation studies were performed, and the basic concepts were used in attempts to explain localized plasmapause phenomena as varied as ring current decay, SAR arc formation, and the development of an energetic electron "slot."

For relativistic electrons, the interaction can be well described in terms of whistler mode waves that propagate parallel to the B-field, with an index of refraction (n) given by

$$n^2 = 1 + \frac{f_p^{\,2}}{f(f_c - f)} \quad . \qquad (2)$$

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The waves resonate with electrons having

$$\frac{v(res)}{c} \approx \frac{f_c - f}{nf} , \qquad (3)$$

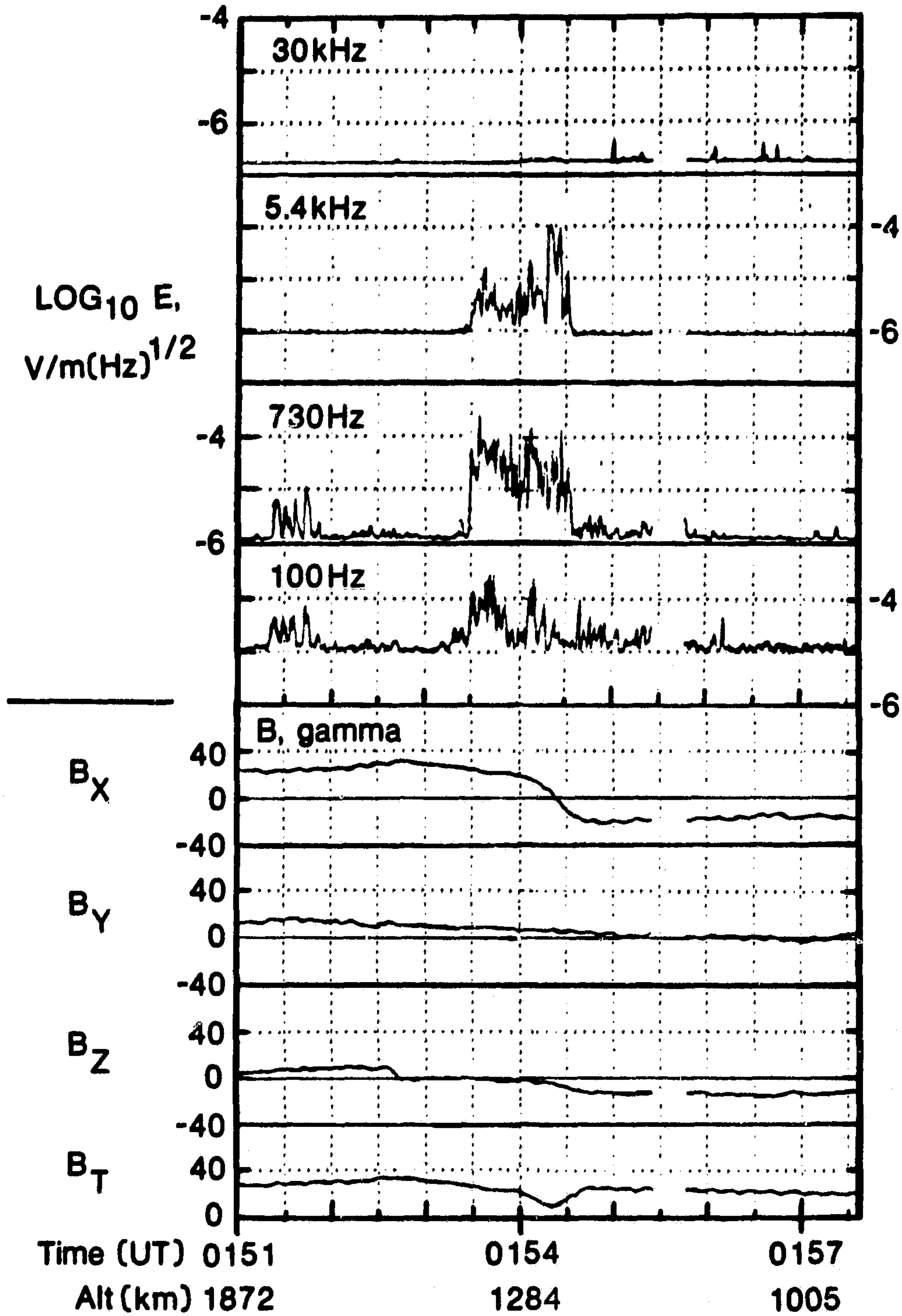

Figure 6. Field-aligned currents and intense electrostatic turbulence detected on August 24, 1981, as the Pioneer Venus Orbiter was inbound on the night side of the planet.

and the resultant diffusion coefficient, $D_{\alpha\alpha}$, is

$$D_{\alpha\alpha} \approx \frac{1}{4}\left[\frac{e}{mc}\, 10^{-5} B'(f)\right]^2 \cdot \frac{f}{f_c + 2f} \; . \qquad (4)$$

Recently, this theory has also been applied to explain radiation belt observations at Jupiter. Figure 7 shows how Voyager detected electromagnetic chorus emissions together with a low-frequency hiss band as the spacecraft moved through the high-density Io plasma torus. Scarf et al.[9] and Thorne and Tsurutani[10] demonstrated that the measured whistler mode turbulence would produce significant losses of radiation belt electrons. Subsequently, Coroniti et al.[11] identified a Jovian chorus structure, and they showed that these waves precipitate

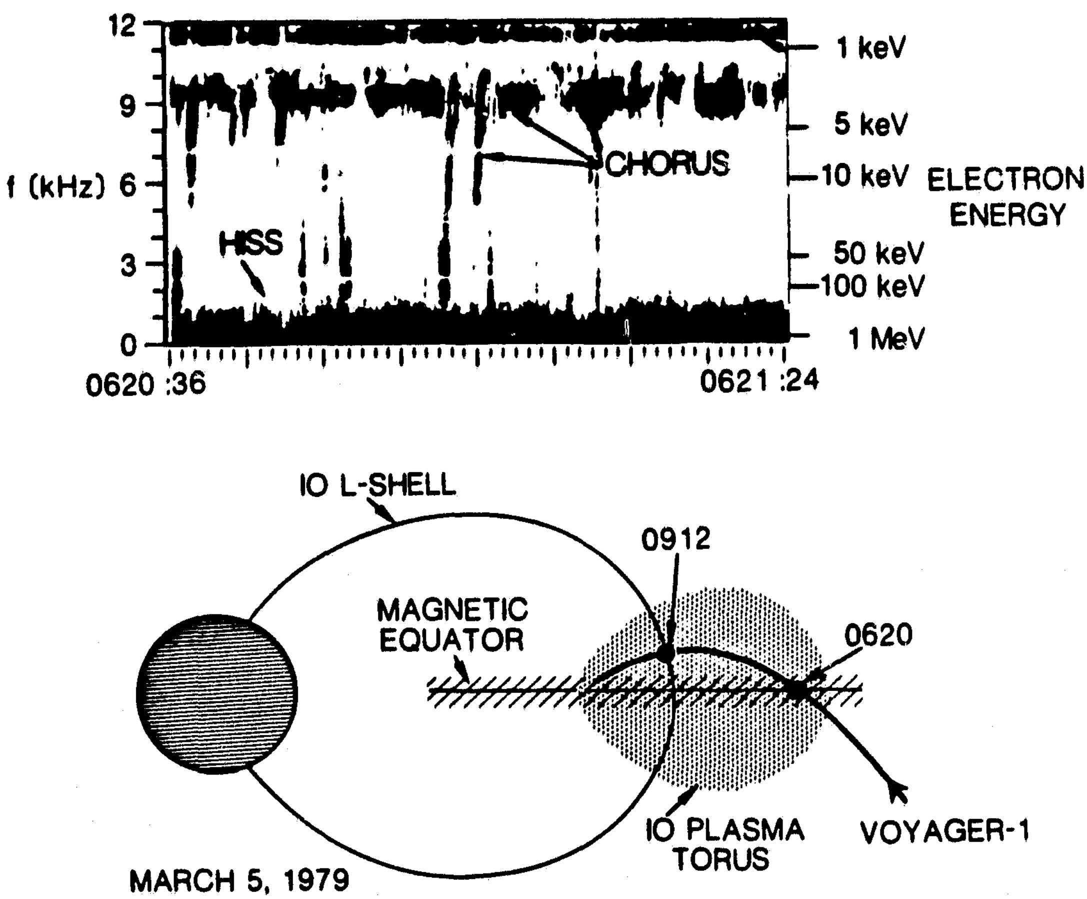

Figure 7. Frequency-time diagram showing chorus and hiss detected as Voyager crossed Jupiter's magnetic equator and entered the Io plasma torus. The resonant electron energies shown on the right side are derived using Equations (2) and (3).

into the atmosphere about 6 ergs/cm^2 sec of electrons with energies on the order of a few keV. Thus, it has been established that at Jupiter pitch-angle diffusion and precipitation associated with whistler mode wave-particle interactions are dynamically important. Chorus was also detected at Saturn, but here the electron fluxes are very low in comparison with the stable trapping limit, and the whistler mode wave-particle interactions have a negligible effect.

The low-frequency hiss band in Figure 7 was originally interpreted in terms of electromagnetic whistler mode turbulence, and Equations (2) and (3) show that such waves would resonate with very energetic electrons. Recently, other interpretations have been considered, and it has been conjectured that these Jovian waves are ion cyclotron modes or even lower hybrid resonance emissions.

Even at Earth, a very significant uncharted area involves ion wave modes and ring current loss mechanisms. Near the terrestrial plasmapause, the local phenomenology of the electromagnetic ion cyclotron instability is unclear, and knowledge about heavy ion electromagnetic modes and positive ion electrostatic modes near the equator is fragmentary (GEOS wave measurements are providing very significant information from one location). The losses of 1-100 keV ions are not well understood, although it appears that auroral protons are on strong diffusion. In future programs, we expect that sensitive equatorial wave measurements will be combined with comprehensive local measurements of particle distribution functions and with simultaneous coordinated information from other spacecraft to yield definitive information about ring current formation and decay processes, the origins of SAR arcs and the proton aurora, the variations with storm effects, and the role of the cold dense plasmasphere in modulating these processes.

4. Electrostatic Cyclotron Harmonics

At Earth, some of the most intense waves with frequencies related to the local electron gyrofrequency, f_{ce}, are the $(n + 1/2)\ f_{ce}$ emissions first discussed by Kennel et al.[12)] Several analyses suggested that these strong emissions (which very frequently have amplitudes as high as 10 millivolts/meter) are substorm related, and Gurnett and Shaw[13)] verified that the modes are electrostatic. The most common observation of this mode is at $f \approx 3\, f_{ce}/2$. These waves were also readily detected at Jupiter and at Saturn. Figure 8 contains Voyager 2 observations centered about the Saturn magnetic equator/ring plane crossing, and the drawing clearly shows intense $3\, f_{ce}/2$ waves, along with upper hybrid resonance emissions.

A definitive analysis of the effects of $(n + 1/2)\, f_{ce}$ emissions on terrestrial magnetospheric particle distributions was carried out by Lyons,[14] who demonstrated that a turbulence amplitude of 1-10 mV/m is sufficient to put electrons with energies of several kilovolts in strong diffusion. Lyons' calculations also verified that 100 mV/m waves would indeed lead to strong diffusion for 100 keV electrons, and showed that some detailed low-altitude (rocket) measurements of 1-20 keV electron energy spectra in the loss cone can be very well explained on the assumption that moderate amplitude (a few mV/m) $3\, f_{ce}/2$ waves produce strong diffusion near the equator. It now seems certain that at Earth the $(n + 1/2)\, f_{ce}$ modes play a very important role in provid-

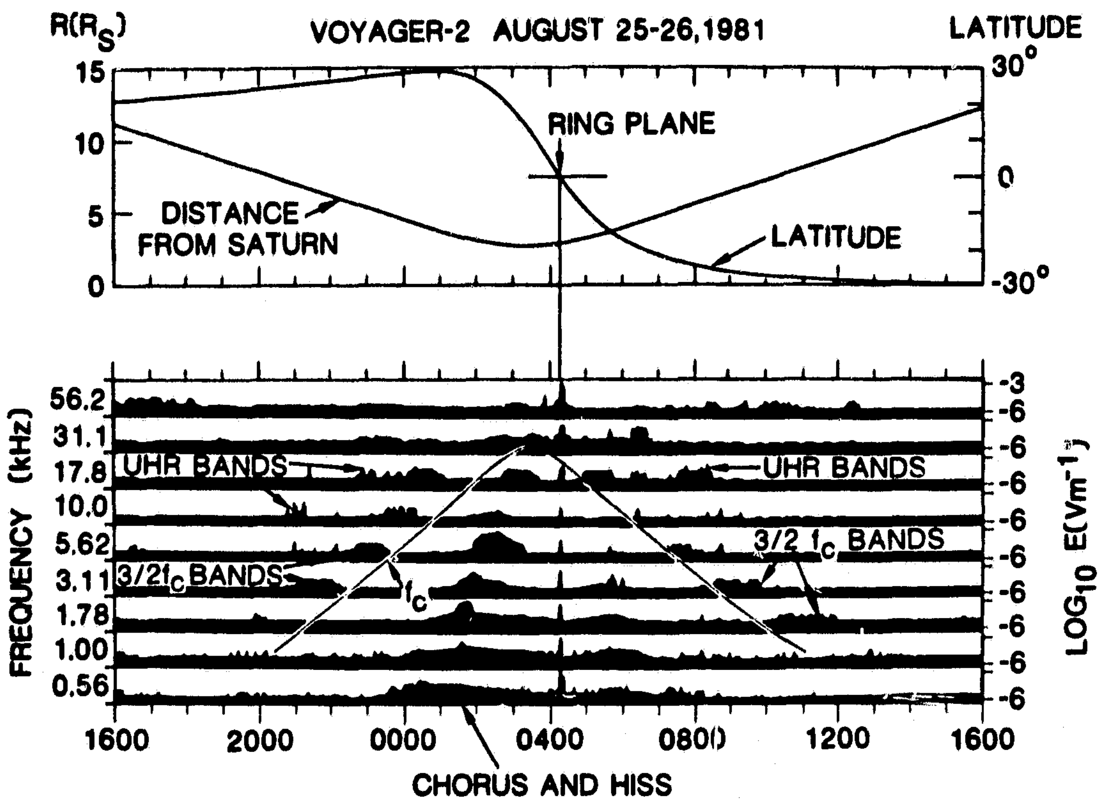

Figure 8. Electromagnetic and electrostatic waves detected in the inner magnetosphere of Saturn, as Voyager 2 crossed the ring plane and magnetic equator.

ing the source of high-latitude electron precipitation fluxes, especially during geomagnetically active periods.

Several theories for the origin of the (n + 1/2) f_{ce} waves have been proposed. The waves commonly grow in regions where cold and hot particles are both present, but Gurnett and Frank[15] reported that the emissions appear to be quenched whenever the density of very low energy thermal plasma exceeds a small fraction (on the order of 5 percent) of the suprathermal plasma density. This suggests that the generation mechanism for these modes involves a hump in the energy distribution as well as a thermal anisotropy. Recently, Kurth et al.[16] showed that intense electrostatic wave activity involving both the (n + 1/2) modes and the upper hybrid resonance is associated with a positive slope in the perpendicular distribution (i.e., for v perpendicular to B). They suggested that strong electrostatic waves can be generated by a wide variety of distribution functions which have a source of free energy and a considerable population of cold electrons. The convective properties of the waves result in large spatial growth rates or a non-convective instability. The waves could heat the cold electrons forming the basis of a nonlinear saturation mechanism. Kurth et al.[16] also noted that anisotropy in the cold electron distribution might actually provide the free energy for the instability.

Magnetospheric measurements of intense electrostatic upper hybrid and (n + 1/2) f_{ce} emissions are of great interest because it appears that some non-linear process allows electromagnetic waves to be generated in those regions where f(UHR) ≈ (n + 1/2) f_{ce}. Thus, the _in situ_ study of these waves and the wave-wave interactions provide unique information on phenomena related to the origin of radio emissions from a magnetized plasma.

5. Discussion

The preceding sections contain brief descriptions of some of the most prominent types of plasma instabilities and wave-particle interactions that have been studied in space. It should be clear that the space environment provides a very important laboratory for the study of general plasma physics. It should also be apparent that only the strongest and most obvious interactions have been analyzed carefully to date. In particular, the study of ion cyclotron plasma waves is quite incomplete, although recent measurements of magnetospheric ions show complex compositions (hydrogen, helium, and oxygen ions at Earth and Venus; hydrogen, sulphur, and oxygen at Jupiter; possibly nitrogen at Saturn; etc.). Thus, there are many cyclotron and hybrid resonances at very low frequencies, and high resolution wave measurements in this spectral region are needed.

The highest resolution wave data from space are transmitted to Earth using wideband amplifiers, and since most of the characteristic frequencies are in the audio band, it is possible to listen directly to these measurements, so that the plasma wave instruments act as "robot ears." The audio link is also frequently extremely useful as a scientific tool. Some of the signals that have been identified with certainty only by listening to the sounds include lightning whistlers (Earth and Jupiter), chorus (Earth, Jupiter, and Saturn), dust impacts (Saturn), and various interference tones.

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