Current Status of IMS Plasma Wave Research

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Much progress has been made in plasma wave research as a result of the International Magnetospheric Study (IMS) in all areas from ground-based studies to multiple-satellite observations. Studies in all the areas have contributed to better understandings of the propagation and generation of magnetospheric plasma waves and the impact the waves have on other magnetospheric phenomena. Plasma wave measurements have been used as both local and remote sensing determinations of plasma parameters. The role of plasma waves at the various magnetospheric boundaries has been extensively studied using the IMS sources. Plasma wave observations during the IMS have tested many existing theories and led to the foundation of many new theories. Several suggestions for future directions of plasma wave research are offered.

1. INTRODUCTION

The purpose of this paper is to review the status of magnetospheric plasma wave science as a result of the International Magnetospheric Study (IMS). The charge to the authors has been not only to assess where we have come with the IMS work, but also to identify where we should go using the IMS data resources and in planning future projects. During the IMS Assessment Symposium, the authors were encouraged to stress the importance of the IMS on the research we were reporting on. With regard to all magnetospheric science research, four areas of IMS influence seem to dominate: the existence of the spacecraft and the data, cooperation, workshops, and theoretical support.

1.1. The Existence of the Spacecraft and the Data

The presence of an international effort certainly has supported the development and completion of the numerous magnetospheric science spacecraft launched during the IMS, for example, GEOS, ISEE, EXOS B, etc. The international cooperative effort has supported the extension of the operating lifetimes of some of the older pre-IMS spacecraft and has helped stress the importance of tracking and data analysis funding for all spacecraft involved in the IMS.

1.2. Cooperation

The IMS has stimulated cooperation both among countries and among scientists, and among the latter the IMS has stimulated interdisciplinary cooperation. It should be pointed out that the international and interdisciplinary cooperation did not evolve with complete perfection, but that the cooperation that has been promoted by the IMS is definitely a step in the right direction. In addition to getting scientists from various countries and various science disciplines working on common efforts, the IMS has promoted the dissemination of the scientific results to a broader spectrum of scientists.

1.3. Workshops

The Coordinated Data Analysis Workshops and other workshops in support of the IMS effort have focused the scientists' attention on specialized topics which might not have been done in a timely or efficient manner otherwise. The workshop formats have promoted the cooperative efforts mentioned in item 1.2.

1.4. Theoretical Support

The workshops and other programs resulting from the IMS have encouraged the active participation of theoreticians in attacking and understanding the critical problems in magnetospheric physics. Especially at the workshops, the theoreticians and experimentalists have worked hand in hand examining the data and formulating techniques to test various hypotheses.

While item 1.1 has assured us of an abundance of data to work with, the last three items have been very important in understanding the data and have laid the groundwork to facilitate widespread cooperative efforts to analyze and interpret the data. These four influences together are thus probably the most important results of the IMS. I will now review topic by topic important progress that has been made in the specific area of space plasma wave research as a result of the IMS.

This review will concentrate on research that has been carried out in direct support of the IMS and on research topics whose importance to the IMS community has been emphasized by the various IMS workshops and correlated study efforts. A more general review of all magnetospheric plasma wave research through 1978 can be found in the work of Shawhan [1979a, b].

2. GROUND-BASED VLF OBSERVATIONS

During the IMS, experiments involving ground-based VLF observations of both natural and controlled whistler mode signals have made important contributions in measuring the characteristics of the plasma waves and their modes of propagation, as diagnostic tools to determine the characteristics of the space and plasma through which the waves have travelled, and in studying wave-particle and wave-wave interactions.

Prior to the IMS, much progress had already been made in magnetospheric VLF wave diagnostics using dispersion techniques. However, many important questions remained about the propagation path, especially concerning the properties and dynamics of the ducts, the manner of duct excitation, and the propagation between the duct endpoints and the lower boundary of the ionosphere. Additional complications in answering the questions arose because the plasma...
waves usually travelled on multiple paths. To help unscramble the pieces of the problem, researchers at Stanford University developed a tracking receiver/direction finder (TR/DF) as a part of the IMS developmental efforts [Carpenter, 1980]. Data from the TR/DF have shown unexpectedly that the directional properties of signals transmitted from Siple, Antarctica, and received at the conjugate station in Roberval, Quebec, Canada, were stable for only minutes at a time. Carpenter [1980] attributes the rapid large shifts in the directions to the possible switching on and off of the whistler propagation ducts due to structure in the drifting interacting particles in the region of space through which the signals propagate. A slow movement in the bearing of stronger signals on the time scale of about 30 min is believed to be associated with quiet day convection. Small-scale fluctuations on a time scale of minutes are attributed possibly to temporal modulation of propagation conditions between the ends of the magnetospheric ducts and the lower boundary of the ionosphere. Thus much new information is being learned about plasma wave propagation using instruments developed especially for the IMS. Obvious future research using the IMS data base will involve examining the particle data from the various IMS spacecraft that are in the interaction region when the rapid large shifts occur in the reception direction.

Studies of the nonlinear mechanisms of wave growth and wave-wave interactions performed using Siple Station and its conjugate, Roberval, Quebec, Canada, have been reviewed by Helliwell [1979]. Three classes of wave-wave interactions (i.e., triggering, suppression, and entrainment) were identified and interpreted in terms of a cyclotron resonance interaction model. A new type of triggered emission called a 'band-limited impulse' which often appears at the end of an amplified signal was described and explained.

In a study of how harmonic radiation from electrical transmission lines triggers strong emissions in the magnetosphere, Park and Chang [1978] reported on a transmitter simulation of power line radiation effects in the magnetosphere. Using the Siple Station VLF transmitter, they were able to simulate many important features of power-line-induced emissions, including their frequency dependence, rapid amplitude variations, and spectral forms. They found that power line effects can be simulated by radiating as little as 0.5 W at a given frequency and that the magnetosphere can generate sidebands at frequencies up to 25 Hz away from the transmitter frequency. In another study involving Siple Station, Helliwell et al. [1980a] found that the minimum power threshold for the growth and triggering of coherent VLF signals in the magnetosphere was 1 W.

In a wave-particle interaction study using naturally occurring VLF signals, Helliwell et al. [1980b] found a one-to-one correlation at \( L \approx 4 \) between bursts of VLF noise and optical emissions at \( \lambda 4278 \). The optical emissions were believed to be produced by electrons scattered into the loss cone over Siple by triggered emissions produced by waves propagating away from the equator after reflection in the ionosphere over Siple. A reduction in intensities of VLF hiss and \( \lambda 4278 \) emissions immediately following each discrete event was believed due to a temporary depletion of particles near the loss cone. Helliwell et al. [1980b] include a list of many desired follow-up studies suggested by this investigation.

A study to determine the location of microburst source regions has been carried out by Rosenberg et al. [1981] using balloon-borne VLF receivers and X-ray detectors over Roberval, Quebec, Canada, and ground VLF receivers at the conjugate site at Siple Station, Antarctica. They reported detailed correlations between electron microbursts precipitated in one hemisphere and chorus elements of rising frequency recorded at the conjugate point. The observations were consistent with near-equatorial cyclotron resonance interactions occurring outside the plasmasphere. The Rosenberg et al. [1981] results suggest that microburst generation regions are located near the equator on subauroral field lines but may extend to higher magnetic latitudes on auroral field lines.

Simultaneous measurements of ionospheric and magnetospheric electric fields in the outer plasmasphere were made during the IMS using the incoherent scatter radar at Millstone Hill and whistler data from Siple, Antarctica [Gonzales et al., 1980]. Excellent correlation has been obtained using the two techniques: the east-west magnetospheric field inferred from whistlers agrees well with east-west fields measured by the incoherent scatter radar at about the \( L \) shell of the whistler data when appropriate scaling laws for the altitude difference are taken into account. Good agreement on the occurrence of the westward excursion of the east-west field during a substorm has been observed.

3. COORDINATED GROUND-BASED AND SATELLITE OBSERVATIONS

During the IMS, much plasma wave research has been based on coordinated ground-based and satellite observations of both naturally occurring plasma wave emissions and signals from man-made VLF transmitters.

For the first time, data on magnetospheric equatorial electron density from multiple whistler paths have been compared with in situ satellite measurements of electron density along near-equatorial orbits [Carpenter et al., 1981]. The whistler data were recorded at Siple and Palmer, Antarctica, and the in situ electron density measurements were made using the University of Iowa plasma wave experiment on ISEE 1. The data were obtained mostly in the range \( 3 < L < 5.2 \) and represent the nightside under quiet to moderately disturbed magnetic conditions. Excellent agreement between the two techniques has been found. The results support the assumption that the electron density distribution along the high-altitude part of field lines in the outer plasmasphere can be described by a diffusive equilibrium model. The data also showed for the three cases studied that densities within the observed whistler ducts differed by less than 30% from the mean or interduct level and that in the range \( 3 < L < 5.2 \) there were no significant east-west density gradients within about 15° of the ground station's longitude.

In order to study ground-satellite relationships with respect to particle precipitation and wave propagation, a French mobile geophysical observatory was instrumented with VLF equipment which had similar band-pass and sampling rate characteristics to the VLF experiment on GEOS. Cornilleau-Wehrlin et al. [1978b] reported on the simultaneous measurements of VLF waves observed by the mobile station at Husafell, Iceland, and by GEO 1 in the conjugate equatorial region. Frequently abrupt changes in the observed VLF intensities occurred simultaneously at the satellite and at the ground, indicating that at these times there were no strong variations in ionospheric absorption. At times the VLF fluctuations observed at GEO 1 were associated with high-energy electron fluctuations, and at
other times they were associated with fluctuations of the cold plasma density. However, Cornilleau-Wehrlin et al. [1978b] point out that other parameters, including ULF waves and the ionospheric reflection coefficient, can also affect the generation of the VLF emissions. Further studies of the coordinated ground-based and satellite observations to understand better the VLF emission generation process and its relationship to the ULF waves, ionospheric properties, and local plasma parameters are in progress.

Madden et al. [1978] reported on coordinated ELF/VLF observations made at ground sites in Iceland and Norway and wave and energetic particle observations made on GEOS 1. Using direction-finding receivers at the ground sites, they showed that whistler mode risers have well-defined exit points from the ionosphere. A comparison of VLF signals observed on the ground and at the satellite showed that sometimes the same signals were observed at both locations while at other times higher-frequency portions of the spectrum observed at the spacecraft would be absent in the ground records. Madden et al. [1978] suggested this could be due to the higher-frequency signals having wave normals that caused them to reflect in the ionosphere. Energetic particle measurements made on GEOS simultaneously to the observation of VLF emissions showed that the electron distribution function was appropriate for the operation of the electron cyclotron instability. Madden et al. [1978] urged that GEOS 1 and ISEE 1 and 2 be used with similar coordinated ground station observations to study various interesting VLF signals.

Another important aspect of IMS-related plasma wave research has been the conduction of controlled VLF wave injection experiments involving the ISEE 1 spacecraft; the VLF transmitter at Siple Station, Antarctica, and various navigation transmitters; and the VLF receiving site at Roberval, Quebec, Canada. Bell et al. [1980, 1981] have reviewed the results of this research. They found that the ground transmitter signals in the VLF range, propagating in the nunducted mode, are observed continuously over large regions of the plasmasphere and magnetosphere. Within these regions the transmitter signals can interact strongly with energetic electrons to produce VLF emissions under much more general conditions than previously thought possible. Bell et al. [1980, 1981] found that VLF emissions triggered by nunducted waves possess spectral characteristics different from those of emissions triggered by ducted signals. The nunducted emissions observed by satellite usually consisted of intense multiemission noise bursts of large bandwidth, and the maximum time rate of change of frequency of the individual emissions in these noise bursts is often as much as 3 times higher than that of emissions triggered by ducted waves. Bell et al. [1980, 1981] also found that the emissions triggered by nunducted waves were regularly observed as low as \( L = 2 \), while those triggered by ducted waves are not generally observed below \( L = 3 \). They pointed out this could be due to few ground stations below \( L = 3 \), the difficulties ground stations have in observing ducted emissions if the duct endpoints are not near the ground stations, or because the nunducted waves interact with a different class of energetic electrons. The nunducted waves can have a large wave normal angle which means they will interact with more energetic electrons than those required for ducted waves. Bell et al. [1980] surmised that it is conceivable during geomagnetically disturbed times that the pitch angle distribution of the higher-energy electrons might be more favorable for the emission generation process.

Cornilleau-Wehrlin et al. [1978c] and Ungstrup et al. [1978] studied the reception of ground transmitter signals on board GEOS 1. Cornilleau-Wehrlin et al. [1978c] reported several large enhancements in the observed \( B/E \) ratio as GEOS passed over the powerful Jim Creek ground transmitter. The enhancements were attributed to GEOS 1 passing through ionization ducts. Ungstrup et al. [1978] reported that Omega transmitter signals observed on GEOS 1 showed large fluctuations in amplitude and \( B/E \) ratio on time scales of the order of tenths of a second. The observed time delays of the signals varied considerably over periods of minutes, and the duration of the received pulses were often longer than the duration of the transmitted pulses. Ungstrup et al. [1978] compared ray-tracing calculations to the observations and concluded that the observed waves were ducted.

EXOS B has also been used in conjunction with ground transmitters to study wave propagation, wave-particle interactions, and local plasma parameters. Kimura et al. [1981, 1982] reported on experiments using EXOS B and the Siple Station transmitter. A positive correlation was found between detected Siple signals and the observed energetic electron flux. Strong Siple signals were observed when the electrons with energies from 300 eV to 3 keV had a strong pitch angle anisotropy. A sudden cessation of the Siple signal occurred coincidentally with the disappearance of the strong pitch angle anisotropy. These observations indicate the Siple signal was being amplified by the energetic electrons. During the summer 1979 and winter 1979–1980 campaign, artificially stimulated emissions associated with the Siple transmission were only observed on five consecutive geomagnetically quiet days following a strong magnetic storm. The observations of the triggered emissions occurred at the equatorial region or in the northern hemisphere. When artificially stimulated emissions were observed, the energetic electron fluxes were usually larger than on those passes when no triggering was observed, but the simultaneously observed pitch angle distributions were usually almost isotropic. However, high fluxes of electrons were also observed on passes where no triggering occurred. Further studies are under way to determine what factors control the triggering.

Doppler shift measurements of the 22.3-kHz NWC ground transmitter signal observed by the DPL instrument on EXOS B have been used to search for ionization ducts in the magnetosphere [Kimura and Hashimoto, 1981]. Preliminary results indicated that the signals observed were mostly unducted. Antenna capacitance measurements by the DPL instrument have been used to detect plasmapause crossings. Measurements of the magnetospheric electron temperature by the DPL instrument have not yet been accomplished but are being pursued.

Since both the GEOS and the EXOS B ground transmitter observations are preliminary and based on only a few passes, the questions of ducts (When? Where? How many?) require more extensive analysis of the data sets.

4. Satellite Observations

During the IMS, plasma wave research using satellite data has covered a wide range of subjects, from studying individual phenomena to studying the plasma wave characteristics in a given magnetospheric region or boundary. Much of the research had been started using data from the pre-IMS
spacecraft. As we will see, the new instrumentation launched during the IMS and the concerted cooperative effort by many groups to study and understand specific problems in magnetospheric physics have fostered many advances in plasma wave research. I will now review the satellite plasma wave observations that have received much attention during the IMS.

4.1. Magnetospheric Electrostatic Emissions

Much progress has been made during the IMS in studying magnetospheric electrostatic emissions using pre-IMS spacecraft. Anderson and Maeda [1977] using S3-A data showed that enhancements of electrostatic emissions above the electron gyrofrequency in the outer magnetosphere were associated with increases in ~1-keV electrons. Hubbard and Birmingham [1978], using IMP 6 plasma wave and magnetometer data, developed a classification scheme for banded electrostatic waves observed between harmonics of the electron gyrofrequency in the earth's outer magnetosphere. The four classes were (1) low '3/2,' or '3/2'; (2) multiple (n + 1); (3) diffuse; and (4) f ~ f_UHR narrow band (f_UHR is the electron plasma frequency). Hubbard et al. [1979] carried out a synoptic study of the plasma wave, magnetometer, and plasma data from IMP 6 for times when the banded electrostatic waves were observed. They studied the spatial and temporal occurrence of the waves and the correlation with geomagnetic activity, and they examined the associations between the observations of waves of different classes and the relative portions of hot and cold electrons present. Hubbard et al. [1979] found that the cold to hot ratio varied in accordance with the Hubbard and Birmingham [1978] predictions which modeled the emissions as arising unstably from a hot loss cone distribution existing simultaneously with a cold isotropic electron component.

Kurth et al. [1979a], using IMP 6 and Haswkeye 1 data, undertook a comprehensive study of intense electrostatic waves near f_UHR, the upper hybrid resonance frequency. They found that these waves are among the most intense waves observed in the earth's magnetosphere with electric field strengths of 1-20 mV m^-1. A detailed study of more than 140 cases showed that the intense electrostatic noise occurred just beyond the plasmapause at all local times and from 0° to 55° magnetic latitude. The electric field vector of the waves was polarized perpendicular to the geomagnetic field. The frequency of the most intense waves usually corresponded to an (n + 1/2) f_UHR harmonic (f_UHR is the electron gyrofrequency) near f_UHR. A simultaneous study of the plasma measurements showed that the occurrence of the intense electrostatic waves was not strongly controlled by the intensities of 1- to 20-keV electrons but that specific details of the hot electron distribution functions were directly related to the wave turbulence. Strong pitch angle anisotropies peaking at α ~ 90° were present for all events at less than about 10° magnetic latitude. For a few events the hot distribution function showed two sources of free energy: a temperature anisotropy and a loss cone distribution. One event showed that a bump on tail in V_e might contribute free energy. Kurth et al. [1979a] also gave evidence that the intense electrostatic waves might be a source of nonthermal continuum radiation.

The new instrumentation launched during the IMS has vastly aided the study of electrostatic waves in the magnetosphere. Much new information has been gained from the sweep frequency receivers on the plasma wave instruments on GEOS [Christiansen et al., 1978a], ISEE 1 [Gurnett et al., 1979a], and EXOS B [Morioka et al., 1981], because of the excellent frequency resolution of the receivers. The active sounders on GEOS, ISEE 1, and EXOS B have contributed significantly to the understanding of the natural emissions by identifying the many resonant frequencies [Christiansen et al., 1978a, b; Harvey et al., 1979; Oya et al., 1981].

Using GEOS 1 data, Christiansen et al. [1978a, b] identified and classified many naturally occurring electrostatic emissions in the magnetosphere. Christiansen et al. [1978b] studied naturally occurring emissions at the f_p resonances. They concluded these waves, occurring in the electron cyclotron harmonic mode, are radiated incoherently by suprathermal electrons. Wrenn et al. [1979], using GEOS 2 data, studied the plasma parameters associated with strong f_p emissions. They found the strong wave generation at f_p^- corresponded to times of high-anisotropy index in the 50- to 500-eV electrons combined with an absence of dense cold plasma. Gough et al. [1979] found, using GEOS 1 data, that enhanced upper hybrid resonance emissions with f_p^- features were tightly confined to the equator. They also found a strong correlation between the spectral density of electron harmonic waves and the anisotropy index for warm electrons with energies below 500 eV. They suggest the pancake distributions observed are a result of the wave-particle interaction which generates the waves.

Rönnmark et al. [1978] using GEOS 1 data and Kurth et al. [1979b] using ISEE 1 data compared the experimental plasma and plasma wave data with current linear instability theory for electrostatic multicyclotron emissions, also referred to as banded electron cyclotron harmonics. The theory of multicyclotron harmonic instabilities has been explored by Hubbard and Birmingham [1978], Ashour-Abdalla and Kennel [1978a, b], Rönnmark et al. [1978], Ashour-Abdalla et al. [1979a, b], and Curtis and Wu [1979]. Both Rönnmark et al. [1978] and Kurth et al. [1979b] used analytic models of the electron distribution which consisted of a hot electron distribution with a weak loss cone free energy source and a cold electron distribution. Both groups found good qualitative agreement between the shape of the measured spectra and frequencies where the theory predicts growth. However, many problems still exist and much work needs to be done before good quantitative agreement can be found. Kurth et al. [1979b] found that the loss cone in the hot electrons is not always evident. Especially important is the need for good low-energy electron distribution measurements. The propagation and saturation characteristics of the waves must be determined before actual levels can be calculated. A wealth of GEOS, ISEE, and EXOS B data are available to provide input for these efforts.

4.2. Magnetospheric Electromagnetic Plasma Waves

Magnetospheric electromagnetic plasma waves and the wave-particle interactions in which they are involved have received much attention during the IMS. Using S3-A data, Anderson and Maeda [1977] showed that during geomagnetically disturbed times, VLF chorus emissions are associated with enhanced levels of low-energy (1-10 keV) electrons which penetrate into the dusk-midnight sector of the magnetosphere from the geomagnetic tail and then drift eastward outside the plasmasphere. Further studies of the plasma...
waves and wave-particle interactions have been advanced by the IMS spacecraft GEOS, EXOS B, and ISEE. GEOS 1 provided a nearly continuous survey of VLF waves in the magnetosphere, and examples of the data obtained and the capabilities of the plasma wave experiment have been reviewed by Cornilleau-Wehrlin et al. [1978a]. They have shown that hiss and chorus occur simultaneously most of the time, although one or the other frequently dominates the spectrum. By using the coherence function between the electric and magnetic antennas [Lefeuvre and Parrot, 1979], the GEOS experimenters have been able to program the automatic recognition of hiss and chorus. With this capability, Cornilleau-Wehrlin et al. [1978a] have been able to study the occurrence pattern of hiss and chorus with less ambiguity than previously possible. Their present studies suggest that some kind of VLF turbulence must be present before strong chorus emission events can occur. Cornilleau-Wehrlin et al. [1978a] showed that VLF hiss amplitude was correlated with increased cold plasma density in detached plasma regions. Cornilleau-Wehrlin et al. [1978b] showed that a suddenly varying hiss amplitude can also be associated with a variation in the particle distribution function. Lefeuvre et al. [1981] determined the electromagnetic wave distribution function for VLF waves observed on GEOS 1. They found that the wave energy of the natural VLF emissions is generally concentrated within two wave packets whose wave normals are approximately in the same off-meridian plane and oriented in the same way relative to the direction of the earth’s magnetic field. More research is planned using GEOS and ISEE data to determine how the wave characteristics, such as the spectra, polarization, and wave normal directions, may differ depending on whether the cold plasma density or the energetic particle distribution functions change.

The plasma wave instrumentation on EXOS B and examples of electromagnetic plasma waves observed have been reviewed by Matsumoto et al. [1981a]. Typical VLF waves observed in the magnetosphere included band-limited hiss and associated chorus with a missing band in the center frequency, whistler echo trains, discrete emissions triggered by whistlers, bistable or multistable band-limited hiss, natural discrete emissions well correlated with fluxes of energetic electrons, and sharply defined discrete emissions possibly indicating power line harmonic radiation. In a correlated study between VLF plasma waves and energetic electrons simultaneously observed on EXOS B, Matsumoto et al. [1981b] showed that band-limited hiss and discrete VLF emissions below the local cyclotron frequency were well correlated with 1- to 10-keV electrons. Future EXOS B research includes an extensive comparative analysis of high-time-resolution VLF plasma wave and energetic particle data.

4.3. Continuum Radiation

During the IMS, continuum radiation has been investigated using data from ISEE 1, ISEE 3, and GEOS 1. Hoang et al. [1980] studied the low-frequency continuum observed in the solar wind by ISEE 3 and concluded that it is generated by local thermal electrostatic plasma waves and not by electromagnetic waves. They believe the low-frequency continuum radiation is of local origin because (1) they observe it as longitudinal plasma waves which do not propagate to large distances, (2) they do not observe it to be spin modulated, (3) the intensity variations they observe follow within a few seconds local electron density and temperature changes, and (4) for similar ambient conditions the observed intensity is about the same at ISEE 3 (R = 1.5 x 10^6 km) as at IMP 8 (R = 2 x 10^6 km). Hoang et al. [1980] reinterpret many previous low-frequency continuum observations as supporting their findings. They concluded that radio measurements made on an electric antenna operating near the local plasma frequency could provide information on the electron distribution function, electron density, and solar wind velocity.

Jones [1980] studied terrestrial nonthermal continuum radiation (which he labeled terrestrial myriametric radiation [TMR]) using GEOS 1 data and reported that it is beamed away from the geomagnetic equator. Direction-finding measurements from GEOS 1 supported previous IMP 6 findings [Gurnett and Shaw, 1973] that the sources for TMR are located on the dayside plasmapause and on the morning magnetosheath. Jones [1980] using data from GEOS 1 close to the apparent source region proposed that intense electrostatic upper hybrid resonance waves coupling to L-O waves through the Z mode are the source of TMR.

Escaping nonthermal continuum radiation has also been investigated by Kurth et al. [1981] using ISEE 1 data. They showed that the higher-frequency escaping component of continuum radiation has spectral features quite different from the lower-frequency trapped component. The escaping component consists of numerous narrow band emissions which drift slowly in frequency with time. Kurth et al. [1981] present evidence of a direct connection between intense electrostatic emissions near the upper hybrid resonance frequency and the escaping continuum radiation. Kurth et al. [1981] found little or no evidence of the beaming of the continuum radiation away from the magnetic equator as predicted by Jones [1980]. Further study and analysis of the GEOS and ISEE data sets will be required to resolve this controversy.

4.4. Auroral Kilometric Radiation

Much research has been done on auroral kilometric radiation (AKR) during the IMS using data from pre-IMS spacecraft. I will review these efforts first.

Using Hawkeye 1 plasma wave data, Gurnett and Green [1978] found that at low altitudes AKR appears to have a low-frequency cutoff at the local electron gyrofrequency which could indicate that AKR is propagating in the R-X mode. Benson and Calvert [1979] and Calvert [1981a] using topside sounder data from ISIS 1 found that AKR seems to be generated in the extraordinary mode just above the local cutoff frequency and emanates nearly perpendicular to the magnetic field. Polarization measurements of AKR made by the Voyager spacecraft [Kaiser et al., 1978] also indicate that AKR is apparently emitted primarily in the extraordinary mode. Benson and Calvert [1979] found that AKR occurs within local depletions of electron density. James [1980], using ISIS 1 data, found that in the generation region the AKR wave vectors make angles of about 60° to 90° with respect to the local magnetic field. He also found that f_e was much less than f_g in what was believed to be the generation region. Calvert [1981b], using Hawkeye 1 plasma wave data, detailed the character of the auroral plasma cavity. Direct observations of inverted V electron precipitations associated with AKR have been made by Green et al.
for AKR by Benson [1975] and Jones [1977]: precipitating proposed for Jovian decametric radiation by Oya [1971] and auroral energetic particles excite electrostatic waves near the upper hybrid resonance frequency which then escape as L-O electromagnetic radiation after travelling through a slightly inhomogeneous plasma. The characteristics of the spectral behavior and the fine structure of AKR have also been studied by Morioaka et al. [1981] using plasma wave data from JIKIKEN (EXOS B). Their conclusions on the source motion and size were similar to those of Gurnett et al. [1979a] and Gurnett and Anderson [1981]. Morioaka et al. [1981] also found that the altitude of the source region was about 6000 to 7000 km during quiet times but extended from 2500 km to 12,000 km during storms.

Recently, Anderson et al. [1982b] have reported observations of proton cyclotron harmonic bands in the high-frequency AKR wideband spectra. A theory of AKR developed by Grabbe et al. [1980] based on the nonlinear interaction between electromagnetic waves and coherent electrostatic ion cyclotron waves could explain such observations. In other AKR research, Calvert [1981c], using data from ISEE 1, ISEE 3, and IMP 8, found that AKR could apparently be stimulated by Type III solar radio bursts.

Although much has been learned about AKR during the IMS, a single definitive theory of generation and propagation that encompasses the various characteristics observed has not been universally accepted. More detailed studies of the AKR, the plasma and the energetic particle population in the source region and throughout the magnetosphere will be required before any specific AKR theory prevails. The advice and support of the theoreticians in using the existing observations and data to test the theories will help AKR research progress in a timely manner.

4.5. Auroral Zone Plasma Waves

During the IMS, the most extensive studies of auroral zone plasma waves have been made using data from the S3-3 satellite. A review of auroral zone plasma wave observations and their association with low-altitude auroral particle acceleration has been done by Mozer et al. [1980]. The major new results from S3-3 involve waves within and near shocks and ion cyclotron waves. Mozer et al. [1980] give evidence that VLF saucers are created by electrostatic shocks. They show that the point of creation of saucers is coincident with the observation of electrostatic shocks. Within electrostatic shocks, lower hybrid resonance waves with amplitudes exceeding 120 mV m\(^{-1}\) have been observed. These waves are as intense as any previously reported waves within the magnetosphere. Mozer et al. [1980] obtained wavelength measurements for the lower hybrid waves in the range of 15 to 37 m which are comparable to the thermal ion gyroradius.

Mozer et al. [1977] showed that electrostatic ion cyclotron wave turbulence was observed associated with paired electrostatic shocks. Kintner et al. [1978] examined in more detail electrostatic hydrogen cyclotron waves detected near 1 R\(_E\) altitude in the polar magnetosphere. By comparing the observed wave properties with the theoretical dispersion relation and the linear instability theory for current-driven ion cyclotron waves, they determined that the plasma was more than 90% hydrogen, that \(T_e\) was about 3.5 eV, and that \(T_i/T_e\) was \(\sim 1\). The strongest wave events were associated with large (\(\sim 120\) mV m\(^{-1}\)) dc electric fields. The observation of electrostatic hydrogen cyclotron waves in the absence of clear shock structures was found to be consistent with a lower threshold for ion cyclotron waves than for shocks or double layers. Kintner et al. [1979] compared observations
of upstreaming energetic ions and electrostatic hydrogen cyclotron waves and found they coincided in more than 90% of the cases studied. Also, both electrostatic hydrogen cyclotron waves and upstreaming ions greater than 500 eV had a lower boundary in their altitude distribution near 5000 km. Kintner et al. [1979] gave evidence that the electrostatic hydrogen cyclotron waves are heating the ions and also that the upstreaming ions could be the source of free energy driving the waves. Drifting thermal electrons were also considered as a possible source of free energy for the waves.

Another auroral zone plasma wave phenomenon observed by S3-3 is zero-frequency turbulence, which has been studied in detail by Temerin [1978]. From resonance fingerprints observed in spectrograms obtained from double-probe electric field measurements, Temerin [1978] was able to determine the polarization, frequency, and wavelength of the waves. He found that in the rest frame of the plasma the frequency was approximately zero, the wavelengths were as short as 5 m, and the electric field was polarized in a plane normal to the magnetic field.

4.6. Plasma Waves in the Magnetosheath and Near the Magnetopause

Rodriguez [1979], using plasma wave data from IMP 6, studied electrostatic waves in the earth’s magnetosheath. He found that three components of electrostatic turbulence were almost continuously present: (1) a high-frequency component above 30 kHz peaking at the electron plasma frequency, (2) a low-frequency component with a broad intensity maximum below the ion plasma frequency, and (3) a component between the ion and electron plasma frequencies. He found that the low-frequency component was associated with the bow shock and suggested that the ion heating which begins at the bow shock continues downstream into the magnetosheath. Electrostatic waves below 1 kHz were found to be polarized along the magnetic field direction, which is consistent with the polarization observed at the bow shock. The intermediate and high-frequency components were found to be unrelated to the bow shock. The plasma wave noise was found to decrease away from the subsolar magnetosheath. Observations of intense electrostatic bursts correlated with magnetic field gradients, and fluctuations suggested the presence of strong current systems such as those occurring at the magnetopause.

Further characterization of plasma waves in the magnetosheath has been advanced by the high-time and high-frequency resolution and multiple-antenna capabilities of the ISEE 1 and 2 spacecraft. Anderson et al. [1982a] report four types of plasma wave emissions being characteristic of the nominal magnetosheath: (1) a very low frequency continuum, (2) short-wavelength spikes that extend in frequency up to 100 kHz, (3) electrostatic ‘festoon-shaped’ emissions below about 2 kHz, and (4) electromagnetic ‘lion roars.’ Comparing magnetic field, plasma, and plasma wave data, Tsurutani et al. [1982] found that the ‘lion roars’ occur in high β regions of the magnetosheath, i.e., when the magnetic field is depressed and the electron number density is enhanced. Anderson et al. [1982a] found that the ‘festoon-shaped’ emissions occurred in the low β regions of the magnetosheath.

Plasma waves at the magnetopause were first investigated by Gurnett et al. [1979b]. They reported strong electric and magnetic fields near the magnetopause extending over a large frequency range. The electric field spectrum extended from a few hertz to over 100 kHz, and the magnetic field spectrum extended from a few hertz to about 1 kHz. The maximum intensities were observed in the magnetopause current layer and the plasma boundary layer. Similar intense broadband spectra were also observed in flux transfer events and inclusions of boundary layer plasma in the magnetosphere. Occasionally, narrow band electrostatic emissions near the electron plasma frequency were also observed near the magnetopause. For frequencies of less than 1 kHz the electric fields were found to be oriented perpendicular to the local magnetic field, and the wavelengths were found to be greater than 215 m. They determined that even below the electron gyrofrequency, a substantial component of electrostatic waves was present.

Tsurutani et al. [1981] studied wave-particle interactions at the magnetopause using ISEE 1 and 2 data. They found a strong correlation between the intense broadband plasma waves and 1- to 6-keV electrons and protons. The mean intensity of electromagnetic waves observed at the magnetopause was found to meet or exceed the level required for strong diffusion scattering of 1- to 10-keV electrons and protons. The mean intensity of the electrostatic waves was near the strong diffusion limit. They concluded that wave-particle interactions resulting from the observed waves at the magnetopause would make a substantial contribution to the dayside auroral precipitation. Further studies are in progress examining the relationship between the electrostatic waves and electrons with energies below 1 keV.

4.7. Plasma Waves at the Bow Shock

The study of the earth’s bow shock and plasma waves at the bow shock has been advanced considerably by the spacecraft pair ISEE 1 and 2. The two spacecraft travelling near each other can be and have been used to separate space and time effects. Gurnett et al. [1979a], Harvey et al. [1979], and Greenstadt et al. [1980] have shown that a variety of plasma waves can identify the bow shock. When the electron number density increases at the shock, a corresponding increase in the electron plasma oscillation frequency is observed. At or just outside a quasi-perpendicular shock, intense low-frequency plasma wave turbulence, most likely consisting of both whistler mode waves and Doppler-shifted ion acoustic waves, is observed. Gurnett et al. [1979a], by comparing electric field spectral densities (the long electric antennas are 215 m tip to tip to ISEE 1 and 30 m tip to tip on ISEE 2), found that below 2 kHz the wavelengths exceeded 215 m but above 2 kHz the wavelengths were less than 215 m. Greenstadt et al. [1980] found that the plasma waves from 400 Hz to 3 kHz peaked just outside the bow shock simultaneously with the observation of reflected ions. Low-frequency noise around 10 Hz peaked just inside the shock coincident with the abrupt increase in ion heating. Greenstadt et al. [1981], in a study of whistler mode propagation near a bow shock, found that a staggered whistler foot was typical, i.e., whistler mode waves of frequency 15–30 Hz were observed farther upstream than either higher- or lower-frequency whistler mode waves. They suggested that whistler mode waves may play a significant role in the transition from quasi-perpendicular to quasi-parallel structure. Much research is in progress correlating the high-time-resolution wave, field, plasma, and energetic particle data acquired from many ISEE 1 and 2 bow shock crossings in an attempt
to understand better the processes taking place at the bow shock.

4.8. Plasma Wave Observations Upstream of the Earth’s Bow Shock

During the IMS, investigations of plasma waves in the upstream solar wind associated with the earth’s bow shock have primarily focused on four types: ion acoustic waves, electron plasma oscillations, whistler mode waves, and 2f_p\textsuperscript{-} emissions.

Using wavelength measurements from IMP 6, Gurnett and Frank [1978] identified the bursty electrostatic turbulence in the solar wind between the ion and electron plasma frequencies as short-wavelength ion acoustic waves which are generated at or below the ion plasma frequency and Doppler-shifted upward in frequency by the motion of the solar wind. By comparing plasma wave and particle data from IMP 6 and 8, Gurnett and Frank [1978] found that over half of the ion acoustic wave turbulence detected in the solar wind near the earth was related to suprathermal protons streaming into the solar wind from the earth’s bow shock. Using ISEE 1 and 2 plasma, electric field, and magnetic field data, Dobrowolny et al. [1980] and Harvey et al. [1981] showed that the ion acoustic wave turbulence was well correlated with low-frequency (<1 Hz) magnetic turbulence. Further work using the ISEE 1 and 2 data sets is planned to distinguish whether the low-frequency magnetic turbulence is of MHD or whistler type. If it is MHD turbulence, Dobrowolny et al. [1980] interpret the association between the MHD waves and the ion acoustic waves in terms of a parametric instability of low-frequency electrostatic ion cyclotron waves. If the turbulence is in the whistler mode, they suggest the association could be explained by whistler waves decaying parametrically into ion acoustic waves.

Anderson et al. [1981] found that both ion acoustic waves and weak whistler mode emissions with frequencies of up to 100 Hz were observed simultaneously with ion beams or dispersed ion populations in the energy range from about 500 eV to more than 45 keV. The whistler mode emission frequencies were typically between 1/4 and 1/2 the electron gyrofrequency. The peak amplitudes of the ion acoustic waves increased with increasing ion flux and at spatial gradients in the energetic ion densities.

Harvey et al. [1981] and Gary [1981] argue that the observed backstreaming protons cannot directly produce the ion acoustic waves. Harvey et al. [1981] conclude that the flux of backstreaming protons is too low to lead to instability of the ion acoustic mode. Gary [1981] claims the observed beam and plasma parameters are not compatible with an ion beam driving an ion acoustic instability, namely, the beam velocity is much larger than the ion thermal velocity and the ion temperature is much larger than the electron temperature. Lemons et al. [1979] found that solar wind electron and ion distribution functions measured simultaneously with intense electrostatic fluctuations were far from the threshold of the ion acoustic heat flux instability. It is quite evident that more detailed studies of the particle distributions and the wave characteristics are required to identify the source of the ion acoustic waves.

Filbert and Kellogg [1979] studied electrostatic noise near the solar wind plasma frequency beyond the earth’s bow shock using IMP 6 plasma wave data. They found that the electron plasma oscillations were present only when the interplanetary magnetic field at the observing point was connected to the bow shock and that the noise amplitude was largest along field lines tangent to the shock. They found these observations to be consistent with a two-stream instability mechanism in which the necessary double-humped distribution was probably produced by a finite time of flight mechanism. The ISEE 1 observation of intense electron plasma oscillations on field lines tangent to the shock was used by Harvey et al. [1981] to test the validity of the Egid et al. [1970] paraboloidal shock model.

Anderson et al. [1981], using ISEE 1 and 2 plasma wave and particle data, showed that the upstream electron plasma oscillations are long-wavelength nearly monochromatic electrostatic waves which are closely correlated with the flux of low-energy electrons, especially in the energy range 200 eV to 1.5 keV. Positive slopes in the parallel electron velocity distributions corresponding to beams coming away from the bow shock were observed coincident with upstream electron plasma oscillations. While the above observations are consistent with the two-stream instability theory, some electron plasma oscillation observations need explanation. The amplitudes of the electron plasma observations were found to be enhanced at gradients in the energetic electron densities. Whistler mode emissions, short-wavelength ion acoustic waves and long-wavelength low-frequency electrostatic emissions were also observed simultaneously with the electron plasma oscillations during most electron flux enhancement events. Anderson et al. [1981] suggested that the simultaneous observation of the low-frequency electrostatic emissions and the ion acoustic waves with the electron plasma oscillations might be due to the parametric decay instability.

Anderson et al. [1981] showed that the whistler mode waves associated with the enhanced ion flux events might be due to either a cyclotron resonance involving the protons or a streaming instability. The electron cyclotron resonance instability might be responsible for whistler mode waves during the electron flux enhancement events, but it is not testable because the resonant energies are far below the particle detectors’ range. Another possible source considered was the electron heat flux instability. More research is required to identify clearly the source of the whistler mode waves.

Narrow band radio emissions generated at twice the local plasma frequency in the vicinity of the earth’s bow shock and observed by ISEE 3 have been studied by Hoang et al. [1981]. The frequency of the 2f_p\textsuperscript{-} radio emissions was well correlated with large-scale density changes observed at ISEE 3 about 1 hour earlier in agreement with the solar wind transit time from ISEE 3 to the bow shock. The bandwidth of the 2f_p\textsuperscript{-} emissions varied from about 3 kHz to 20 kHz, and the broadening was attributed to solar wind density variations across the source region. The centroid of the source location was usually found to be within about 30 R_E of the subsolar point.

5. CONCLUSIONS

As this review has shown, much progress has been made in plasma wave research during the IMS, but there are still many unanswered questions, especially concerning the details of the various wave-particle interaction processes. Things that would considerably aid plasma wave research in the future include (1) more and closer theoretical support, (2)
expanded wavelength measurements, (3) higher-time-resolution plasma and particle measurements, (4) more emphasis on wave normal measurements, (5) better methods for data exchange, and (6) increased funding.

Cooperation among the theorists and experimentalists has increased during the IMS and should continue to increase in the future. The theorists' help is needed not only to aid in the interpretation of the data but also to help in the design of new experiments and in the formulation of studies of existing data sets. Improvements in the measurement capabilities of plasma waves, plasma, and particle experiments have been proposed for future spacecraft missions which are waiting to be started and funded. It is possible that the data already exist to answer many of the questions and that the most important problem is getting the right data sets and the right people together. Ideally, all the data resources of the coordinated data analysis workshops should be available for all the magnetospheric problems of interest and at all locations where scientists are working on the problems. Planning for a computer network working toward this goal is under way.

The future of plasma wave research depends critically on funding. As for all of magnetospheric research, money is needed for new instrumentation and new spacecraft if the scientific progress of the last 2 decades is to continue. Money is also needed to continue the data analysis efforts from past and existing missions. A wealth of data from magnetospheric spacecraft exist that have the potential to answer many important questions about wave propagation, wave-particle interactions, plasma characteristics, and magnetospheric dynamics. Continued and expanded data analysis funding for these data sets would be a good investment toward the future of space physics research.

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REFERENCES


Matsumoto, H., et al., Correlation between VLF plasma waves and energetic electrons simultaneously observed by satellite JIKIKEN (EXOS-B), J. Geomagn. Geoelectr., 33, 73, 1981b.


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