Plasma Wave Observation and Sounder Experiments (PWS) Using the Akebono (EXOS-D) Satellite—Instrumentation and Initial Results Including Discovery of the High Altitude Equatorial Plasma Turbulence

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(Received August 5, 1989; Revised December 1, 1989)

Plasma waves and sounder experiments (PWS) onboard the Akebono (EXOS-D) satellite have been successfully made after deployment of antenna and turn-on of the instruments on March 4, 1989. In natural plasma wave observations, the dynamic spectra of the plasma waves in the whole range of the orbits are observed in the PWS frequency range from 20 kHz to 5 MHz. The results are summarized as follows.

i) The upper hybrid emissions that cover a frequency range from the electron cyclotron frequency f_C to the upper hybrid frequency f_{UHR} for the case where f_C is higher than the local plasma frequency f_P , or cover from f_P to f_{UHR} for the case of $f_P > f_C$, are always observed in the altitude range from 1000 km to apogee of the orbit of the satellite. From the global distribution of the upper hybrid frequency emissions, the structures of the plasmasphere are clarified.

ii) Auroral kilometric radiations are observed in the region associated with the auroral particle acceleration regions. Polarization and Poynting vectors of AKR are also precisely measured. The data show the possibility of studies on the structure of the acceleration regions in addition to the generation mechanism of AKR. The AKR data that have been obtained in the acceleration region of the auroral particles are especially important, suggesting the possible co-existence of the electrostatic plasma waves with the Z-mode waves.

iii) In the equatorial region of the plasmasphere the enhancement of the upper hybrid mode waves is discovered; the enhancement shows two possible plasma turbulences, the first is the enhancement of the microscopic instabilities that are identified only as the enhancements of the intensity of the upper hybrid emissions and called “equatorial enhancement of the wave turbulence (EPWAT)”; and the second is the enhancement of the irregular change of the upper hybrid frequency suggesting the turbulent variation of the plasma density that is called “equatorial enhancement of the density turbulence (EPDET)”. EPWAT’s encircle the magnetic equator forming a disc within the altitude range of 1000 km to 9000 km, while EPDET’s encircle the geographic equator within the altitude range of 1000 km to 9000 km, forming another disc.

iv) Sounder experiments of the PWS have also been carried out; the results show the principal resonances such as plasma resonances at f_P , upper hybrid resonances at f_{UHR} , and harmonics of the electron cyclotron frequency at nf_C ($n=1, 2, 3, \dots$). The sequence of diffuse plasma resonances f_{Dn} with the static plasma wave resonance f_{Qn} are also detected even in a high altitude range higher than 3000 km. Very long ducted echoes of sounder

transmitting pulses have also been detected even at the altitude of 6000 km. All these results of the experiments reveal that the PWS/EXOS-D data provide a very promising key for studies of the plasma and plasma waves throughout the entire global ionosphere and plasmasphere, including the regions of auroral particles acceleration.

1. Introduction

There is a long history of plasma wave experiments in space, in both the observation of natural plasma waves and the observations of artificially stimulated plasma waves relating to radio wave sounder experiments of ionospheric plasma. In the study of high frequency plasma wave observations in space plasma, the contributions of the research based on IMP, GEOS, Hawkeye, ISIS-1, EXOS-B and DE satellites have provided very prominent results, including new evidence of auroral kilometric radiations (GURNETT, 1974; KURTH *et al.*, 1975; KAISER and STONE, 1975; BENSON, 1975, 1982; ALEXANDER and KAISER, 1977; KAISER *et al.*, 1978; BENSON and CALVERT, 1979; BENSON *et al.*, 1980; JAMES, 1980; CALVERT, 1981; OYA *et al.*, 1981; MORIOKA *et al.*, 1981; OYA and MORIOKA, 1981, 1983; GURNETT *et al.*, 1983). In parallel to the studies on these passive observations of plasma waves, there is another long history of active experiments on the plasma waves, starting from experiments by sounders on board rockets, Alouette 1, 2 and ISIS-1 satellites (KNECHT *et al.*, 1961; LOCKWOOD and NELMS, 1964; NELMS and LOCKWOOD, 1967; JACKSON and WARREN, 1969; FRANKLIN and MACLEAN, 1969; HAGG *et al.*, 1969).

A series of satellite observations by Jikiken (EXOS-B) (OYA *et al.*, 1981; OYA and MORIOKA, 1983) and Ohzora (EXOS-C) (OYA *et al.*, 1985; MORIOKA and OYA, 1985) have also made current contributions to studies of the plasma waves in the polar region ionosphere and magnetosphere; these results are characterized by the combination of natural plasma wave observations with active experiments using the RF sounder. Following this current, more extensively organized experiments on high frequency plasma waves (above 20 kHz to 11 MHz) have been carried out by the PWS system installed on the Akebono (EXOS-D) satellite.

Akebono (EXOS-D) was launched on February 22, 1989 from Kagoshima Space Center, ISAS, into orbit with initial apogee, perigee and inclination, respectively, of 10,500 km, 275 km and 75°; i.e. the satellite has been put into an orbit that can pass through the acceleration region of the auroral energetic particles. From the standpoint of studies of plasma waves and the structure of plasma distribution, then, we can confirm the developing mechanism for the acceleration of the auroral particles; to clarify the real mechanism of the generation of auroral kilometric radiation with relation to the particle accelerations is also a very important purpose of the EXOS-D observations.

In addition to the studies on the polar regions, the PWS experiments onboard Akebono (EXOS-D) are designed to clarify the global feature of the plasma distribution including the equatorial region, for studies on the generation mechanism of the electromagnetic waves and electrostatic plasma waves in the plasmasphere, as well. The present experiments are also intended to observe the feature of the conversion processes of the electrostatic plasma waves into electromagnetic waves in a wide variety of global plasma distribution features, such as the equatorial turbulent regions, the region of the auroral particle acceleration, and cusp region plasma.

The first step of the present paper is to report the PWS experiments with

information of the detailed instrumentation and initial results of observations. Very successful observation results have been obtained with a wide range of new findings. The present paper is, therefore, intended to provide up-to-date results for these discoveries and to be source information on the PWS experiments and a basic introduction to the typical data for future use of the world STP community. More extensive and detailed analyses are expected in future studies.

2. Instrumentation

2.1 System

In the PWS experiments, both natural and stimulated plasma waves are observed with a largely integrated PWS system that is able to provide and handle a wide variety of data on both observations of natural plasma waves and active sounder experiments to observe the responses of artificially transmitted plasma waves. The artificial excitation of the waves is also intended to make radio wave sounding of the plasma structure in the topside ionosphere as well as in the region of auroral particle accelerations. The PWS system, therefore, consists of i) a sub-system for natural plasma wave observation (NPW), ii) a sub-system for stimulated plasma wave experiments (SPW) and iii) the instrumentation for measurement of the number density of electrons (NEI) (see Table 1).

Table 1. System, subsystems and operation modes.

System	Subsystems	Operation Modes	Frequency	Time Resolution
PWS	NPW	Spectra	Sweep --- 20 kHz-5 MHz-----	1 sec
			Fix ----- 8 points -----	0.25 sec
		Polarizations	Sweep --- 20 kHz-5 MHz-----	1 sec
			Fix ----- 8 points -----	0.25 sec
		Poynting Fluxes	Fix ----- 8 points-----	0.25 sec
	SPW	Sweep	Normal	H-band --- 0.3-11 MHz ----- 32 sec
			L-band --- 20-900 kHz -----	16 sec
		Ne-Track	F_{UHR} --- $F_0 + 60$ kHz -----	1 sec
			F_p --- 20-170 kHz -----	1 sec
		Fix -----	8 points -----	62.5 msec
	NEI	Sweep -----	20kHz-5MHz -----	1 sec
		Fix -----	8 points -----	0.25 sec

The sub-system for the observation of natural plasma waves (NPW) consists of three components: a) dynamic spectra observation, b) polarization observation and c) Poynting vector observation. Five modes of operation can be carried out in the sub-system for the artificially stimulated plasma wave experiments (SPW). The measurement of the plasma density (NEI) is made by a swept frequency impedance probe. For accurate measurements of the electric field component, a fixed frequency impedance measurement is also possible.

The PWS system is devoted to the phenomena in the frequency range from 20 kHz to 5.12 MHz in the NPW sub-system and from 20 kHz to 11.4 MHz in the SPW sub-system by considering the plasma condition of the media surrounding the spacecraft. A block diagram of the whole PWS system is given in Fig. 1.

Fig. 1. Block diagram of PWS system. The signals of space plasma waves are picked up by two dipole antennas *X* and *Y* and three loop antennas *X*, *Y* and *Z* and are fed to the data handling unit (DHU) after being analyzed through the system.

2.2 NPW sub-system

2.2.1. Main facility

As the main sensors of the SPW system, two sets of 60 m tip-to-tip dipole antennas consisting of 0.381 mm wire elements and a three axial loop antenna are used (see Fig. 2). The wire and loop antennas were successfully deployed on March 4, 1989 and March 6, 1989, respectively. The loop antenna has dimensions of 600 mm×600 mm square for each

Fig. 2. Two dipole antennas A1–A3 and A2–A4 and loop antennas. The dipole antenna A1–A3 is rotated by 45° from the X axis of the satellite towards the Y direction and the dipole antenna A2–A4 is also rotated by 45° from the Y axis towards the $-X$ direction. Axes of the three loop antennas H_ξ , H_η and H_ζ coincide with the satellite x , y and z coordinates; there is a fixed relation between the X, Y and Z system and the ξ , η and ζ system.

component with a loop winding of 10 turns; the effective height is estimated as 0.4 m at 300 kHz (OKADA *et al.*, 1987).

2.2.2. *Dynamic spectra observations—DS mode spectra analyzer*

Received signals from the dipoles and the loop antennas are fed to the preamplifier that covers the frequency range from 20 kHz to 5.12 MHz for amplification of the signal by 20 dB for the loop antenna system; the preamplifier works only for impedance matching to achieve high impedance for the wire antennas with attenuation of 8.0 dB. The spectrum analyzer consists of a two-stage super heterodyne receiver; the frequency range from 20 kHz to 5 MHz is converted to the signal with center frequency at 25 MHz at the first stage with a band width of 10 kHz, and is converted to a second IF signal centered at 455 kHz where the bandwidth gives the restriction to the final frequency resolution. The frequency resolution of 1 kHz is, therefore, given at this stage for the NPW operation. The threshold level for the signal detection is then $0.08 \mu\text{V/m}$ for high gain operation and $10 \mu\text{V/m}$ for low gain operation.

The local frequencies of the heterodyne receiving operations are generated by frequency synthesizers which consist of phase locked loops (PLL's). Since the PLL circuits are a complex electronic system, the set-up was originally very large and heavy in the early stage of the study; however, the PLL system was made very compact in the final set-up for the flight module by achieving hybrid-IC assembly.

A detailed block diagram of the dynamic spectra analyzer system is given in Fig. 3. By applying programmed control to the PLL synthesizers, then, the frequency range of the observation is controlled to sweep from 20 kHz to 5.12 MHz with a speed of 1 sec for the high speed mode and a sweep rate of 16 sec for low bit rate operations.

The output level of the dynamic spectra data of the natural plasma wave is integrated with the characteristic time of 100 Hz for each frequency step with a 1 kHz bandwidth; and the integrated output levels are transmitted with 8 bits PCM data through quasi-logarithmic compression circuits with a sample rate of 1024 data points per second for the high bit rate and 64 data points per second for low bit rate operation.

2.2.3. *Polarization*

Using crossed dipoles, polarization of the naturally radiated waves are measured in the frequency range that completely coincides with the frequency range of the dynamic spectra observations. For this purpose, the antenna system is also arranged as given in Fig. 2. The separation of the polarized signals between the left-hand and right-hand helicities to -28 dB is achieved through a signal separation system (see Fig. 4). The separated signals are amplified through analyzer channels which are exactly the same those for the dynamic spectra (DS-mode) observations.

The observations of the polarization are also possible at the fixed 8 frequencies to coincide with the Poynting vector observations. The fixed frequencies are selected in a frequency range from 50 kHz to 1.5 MHz as given in Table 2.

2.2.4. *Poynting vector observations*

Observations of Poynting vector of the naturally radiated electromagnetic waves are made at 8 fixed frequencies from FIX 1 to FIX 8 (see Table 2). Considering the geometric relation of the dipole antennas and loop antennas with respect to the satellite from X , Y and Z (see Fig. 2), electric fields components E_x and E_y and magnetic fields components H_x , H_y and H_z can be decided. Using these field values, the Poynting vector $\mathbf{P}$ (P_x , P_y , P_z) is obtained by applying the method of multiplication for the coherent components of the electromagnetic fields as

Fig. 3. Block diagram of the receiving systems. Two stage super-heterodyne receivers are employed for five channels which are used for seven purposes; i.e., 2 components of the RF electric fields for NPW and 3 components of the RF magnetic fields for SPW, the x component of RF electric fields for SPW mode, and an impedance probe. For the Poynting measurement, the signals from the second IF stages are converted to a 1 kHz signal mixed with the third local frequency; i.e. from PYEx, PYEy, PYBx, PYBy and PYBz, the Poynting vector is calculated. DS1 and DS2 indicate the output of the dynamic spectra for the E_x and E_y components, respectively. After detection of the signal, the data integrated with the characteristic time of 0.01 sec are sampled and held for telemetry (S/H).

Fig. 4. Block diagram of the sub-system for separation of the helicity between the left-hand and right-hand polarizations.

Table 2. Fixed frequencies.

Code	Frequency
Fix 1	59.3 kHz
Fix 2	81.5 kHz
Fix 3	137.1 kHz
Fix 4	181.5 kHz
Fix 5	259.4 kHz
Fix 6	371.3 kHz
Fix 7	593.7 kHz
Fix 8	1358.1 kHz

$$P_X = E_Y H_Z - E_Z H_Y,$$

$$P_Y = E_Z H_X - E_X H_Z,$$

$$P_Z = E_X H_Y - E_Y H_X,$$

for the electric fields E_X and E_Y and the magnetic field components H_X , H_Y and H_Z . Though the E_Z component is not directly measured, we can decide from the measured values in principle.

From the feature of the spectra we may decide whether the mode is the electrostatic or the electromagnetic; for the electromagnetic mode, it follows that

$$E_Z = - \frac{E_X H_X + E_Y H_Y}{H_Z},$$

while E_z is expressed by

$$E_z = (\cot\theta_s \cdot \sec\phi) E_y$$

or

$$E_z = (\cot\theta_s \cdot \operatorname{cosec}\phi) E_x$$

for the electrostatic mode waves, where θ_s and ϕ are angles between the satellite spin axis and azimuthal direction from the sun, respectively. By applying computer solving techniques, therefore, we can obtain E_z .

To obtain the component of the Poynting vector in the coordinate system (x, y, z) for the inertial frame with its z -axis in the direction of the magnetic field and with x and y axes chosen to make a right-hand Cartesian coordinate system with respect to the z -axis, we have to find the transformation of the co-ordinates between the (x, y, z) frame to the (X, Y, Z) frame; i.e.

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = (A) \begin{pmatrix} X \\ Y \\ Z \end{pmatrix},$$

where

$$(A) = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix}$$

is the transformation matrix with the elements of a_{ij} ($i=1, 2, 3; j=1, 2, 3$). To pursue this calculation the measured wave data are converted down to a 1 kHz signal; the sampled signals with a 5 kHz rate from this 1 kHz signal are transmitted down to the computer system on the ground through PCM telemetry channels.

2.3 System of stimulated plasma wave experiments

The sub-system of stimulated plasma wave experiments (SPW) is basically operated by utilizing common PWS facilities effectively by adding a high power transmitter to the NPW sub-system (see Fig. 1). The high level radio frequency electric field (from 100 V up to 1000 V) from the high-power transmitter is fed to a set of dipole antennas and the response of stimulated plasma waves in the surrounding plasma and the radio wave echoes from the ionosphere are detected by another set of dipole antennas.

2.3.1. Power amplifier

The basic design of the power amplifier is the same as those in the EXOS-B and EXOS-C satellites (OYA *et al.*, 1981, 1985). The signal from the PLL generator is fed to the pre-stage amplifier and the amplified signal is finally powered up to the maximum

level of 600 W at the power amplifier stage. The newly developed point of the present EXOS-D system added to the previous EXOS-B and EXOS-C systems is in the 600 W transmission level (100 W for EXOS-B and 300 W maximum for EXOS-C). For this purpose, the voltage for the power transistors is stepped up to 40 V from the regular 20 V of the satellite source power bus-supply.

2.3.2. *Operation modes*

Stimulated plasma wave experiments are made in several different modes, as given in Table I. We can select operations with either high power of 600 W (maximum) or low power (-20 dB from the maximum level) modes; in each power level five modes of operation are possible.

i) *Normal sweep mode in high frequency range*

In this normal high frequency operation mode, a stimulated plasma wave experiment is designed using the RF pulse transmitted with a swept frequency ranging from 300 kHz to 11.4 MHz within 32 sec.

ii) *Normal sweep in low frequency range*

In this mode of operation, the transmission of the RF pulse is made with a frequency swept from 20 to 890 kHz within 16 sec. This operation is basically used for observations in the high altitude acceleration region of auroral particles.

iii) *F_{UHR} mode*

To transmit the RF pulse near the upper hybrid frequency, for the case $F_p < F_c$, the RF frequency is swept in the 60 kHz range starting from the measured F_c value. To set the F_c value, the measured magnetic field intensity value provided from MGF is used. The frequency sweeping is made by 16 steps with frequency step of 3.78 kHz.

iv) *F_p measurement mode*

To track the F_p resonance in each swept interval for measurements of the fine structure of the cavity region of the auroral particle acceleration, the RF frequency is swept from 20 kHz to 170 kHz within 1 sec. This F_p measurement mode can therefore be effectively utilized to find the fine structure of the plasma density distribution in the cavity region where the plasma number density is expected to be in a range from 5 to 350/cc.

v) *Fix-cyclic mode*

Eight fixed frequencies are selected where the pulse is transmitted every 62.5 msec. By this operation, we can trace high spatial variation of the plasma distribution in detail.

2.4 *Impedance probe*

This impedance probe is achieved along the same current of the studies using a balanced type gyroplasma probe (OYA and OBAYASHI, 1967). The gyroplasma probe has a long history. After its application to ionospheric sounding rockets (OYA and OBAYASHI, 1967), gyroplasma probes have been used in the Taiyo satellite (OYA and MORIOKA, 1975; OYA *et al.*, 1982), the Hinotori satellite (OYA *et al.*, 1985; WATANABE and OYA, 1985) and the Ohzora satellite (TAKAHASHI *et al.*, 1985). In addition to the normal mode of the swept frequency impedance probe, fixed frequency (from FIX-1 to FIX-8) impedance probe measurement is also possible in this PWS system.

3. Observation Results in the Initial Phase of Operation

3.1 Overview

After deployment of the 2 dipole antennas on March 4, 1989 and expansion of the loop antenna on March 6, 1989, the natural plasma wave observations were successfully started. Since turning on the power amplifier on March 29, stimulated plasma wave experiments have also been successfully conducted and continuous observations are being made.

By the natural plasma wave observation mode (NPW), we have detected i) continuous coverage of the upper hybrid frequency emissions, ii) solar type III radio bursts, iii) inverse Landau type instabilities relating to electrostatic whistler mode waves, iv) auroral kilometric radiations, v) VLF hiss emissions, vi) very intense LHR emissions and vii) terrestrial hectometric radiations. In addition to the local plasma wave generation the conversion processes of electrostatic plasma waves into electromagnetic waves are also clearly identified.

Stimulated plasma wave experiments have also indicated clear results of i) electron cyclotron resonance and its harmonics, ii) upper hybrid resonances, iii) plasma resonances and iv) the sequence of diffuse resonances. Even at close to 6000 km, the ducted echoes of the transmitted pulses have been detected. The previous maximum record of the EXOS-B satellite was 5000 km.

3.2 Upper hybrid emission

As indicated in the typical NPW observation results given in Fig. 5, very clear upper hybrid emissions are observed with the intensity of 1.5×10^{-7} V/m to the saturation level

Fig. 5. Dynamic spectrum of the sweep mode NPW observation made on May 1, 1989 from 03:57 UT to 04:52 UT, when the satellite moved from the altitude of 9090 km to 2100 km. A clear continuous curve in the middle portion of the diagram indicates the upper hybrid emission. The spectrum is indicated in the format of the frequency axis ranging from 20 kHz to 5.125 MHz versus the observation time UT. In the abscissa, the satellite position corresponding to each observation time is indicated in terms of MLT (magnetic local time), ILAT (magnetic invariant latitude), FLAT (foot latitude of the magnetic field lines) and ALT (altitude). The spectrum intensity is indicated by a color code where the thresholds are given as blue: 3.0×10^{-17} ($\text{V}^2/\text{m}^2\text{Hz}$), green: 9.7×10^{-16} , yellow: 3.1×10^{-14} and red: 1.0×10^{-12} .

Fig. 6. (a) Example of the gradual type (G-type) of the plasmopause indicated by the variation of the upper hybrid emissions. The dynamic spectrum is indicated with the same format as Fig. 5 for the observation on March 16, 1989 from 08:17 UT to 09:17 UT. (b) Example of sharp type (S-type) plasmopause with the same format as Fig. 5 for the observation data obtained on April 6, 1989 from 07:01 UT to 08:01 UT. (c) Example of irregular type (I-type) plasmopause indicated in the dynamic spectrum given with the same format as Fig. 5 for the observation data obtained on April 29, 1989 from 06:23 UT to 07:13 UT.

Fig. 7. Example of the electron density profile (bottom panel) deduced from the observed frequency of the upper hybrid emission (top panel). The format of the dynamic spectra is same as in Fig. 5 but the intensity of the plasma wave emissions is indicated by the gray color corresponding, black and white, respectively, to red and blue in Fig. 5. The thin smooth curve below the upper hybrid emission frequency is the local electron cyclotron frequency f_c indicated as a reference.

of the NPW receiver. The upper hybrid emissions are stably and continuously detected in the altitude range above 1000 km so that we can deduce the plasma density surrounding the earth along the satellite paths around the globe from the observation of emission frequencies. In Fig. 7 an example of an electron density profile is given. The emission covers the range starting from a lower frequency between the plasma frequency f_p and the electron cyclotron frequency f_c and ending at the upper hybrid frequency f_{UHR} .

3.2.1. Plasmapause structure

From the observed upper-hybrid emission data we can obtain profiles of the plasmapause from 3000 km to 10,000 km altitude. The observed structures of the plasmapause can be divided into three types:

- i) Gradual type (G-type),
 - ii) Sharp type (S-type),
- and
- iii) Irregular type (I-type).

Typical examples for these types of plasmopause are indicated from Figs. 6(a) to 6(c). Irregular types of plasmopause (I-type) are also divided into three cases; these are

- i) Detached plasma type (I_D -type),
 - ii) Large oscillatory type (I_O -type),
- and
- iii) Multi-shock type (I_S -type).

The typical examples for these three types are indicated in Fig. 8 from panels (a) to (c).

The detached type irregularity is usually associated with sharp changes of the plasma density, where a large block of the plasma is removed from the main portion of the plasmasphere. The large oscillatory type indicates large turbulences at the plasmopause; the oscillations can be understood as a type of sharp density change. Detailed studies on the plasmopause dynamics based on this upper hybrid emission observation data are deferred for future studies.

3.2.2. *Equatorial enhancement of the turbulences*

In the data of the NPW dynamic spectra, remarkable enhancements of the upper hybrid emissions have been discovered. The enhancements of the equatorial plasma turbulence show two remarkably different types. As shown in the example given in Figs. 9(a) and 9(b), the frequency of the upper hybrid emission changes remarkably; sometimes this change shows systematic oscillations and sometimes sudden dips, step-like changes or very irregular oscillations. A variation of the frequency of the upper hybrid emissions indicates a corresponding variation of the plasma density. Therefore, this type of turbulence enhancement can be understood as an equatorial enhancement of the plasma density turbulence. The other enhancement is an intensification of the upper hybrid emission without any remarkable variation in the frequency. Typical examples are given in Figs. 10(a) and 10(b). This type of emission suggests injections of the free energy of energetic particles such as the plasma drift in the perpendicular direction to the magnetic field or the enhancement of the temperature anisotropy for the bi-Maxwellian plasma velocity distribution. To distinguish the two types of the turbulence, we here call the first type “the equatorial plasma density turbulence (EPDET)” and the second type “the equatorial enhancement of the plasma wave turbulence (EPWAT)”. The data for the 4 month period after the start of the PWS observations are analyzed for statistics of the occurrence of EPDET and EPWAT; a summary of the events is given for the occurrence region and the relation of the condition of the geomagnetic disturbance to the intensity of the upper hybrid emissions.

i) *Occurrence region*

Results of analyses of the occurrence region of the equatorial turbulences EPDET and EPWAT events are given in Figs. 11(a), 11(b), 12(a) and 12(b). Though the analyses are limited to data obtained in the period from early March to the end of June, occurrences of equatorial plasma turbulences completely cover the entire observation longitude, local time and the entire observation altitude ranges within 1000 km to 9000

Fig. 8. (a) Same as Fig. 7 for the detached plasma type (I_D -type) plasmopause. The observation was made on May 2, 1989, from 04:30 UT to 05:27 UT at altitudes from 9800 to 7000 km. (b) Same as Fig. 7 for the large oscillatory type (I_o -type) plasmopause. The observation was made on March 7, 1989 from 13:28 UT to 14:13 UT. Largely oscillating feature of the plasma density is indicated around the region of plasmopause detected from 13:54 UT to 14:02 UT corresponding to the altitude of 8830 km to 8060 km. (c) Same as Fig. 7 for the multi-shock type plasmopause. The observation was made on April 1, 1989, from 07:41 UT to 08:40 UT. Very sharp changes of the electron density distribution are observed at around 07:47 and 07:52 UT, suggesting shock-like features.

Fig. 9. Examples of the equatorial plasma density turbulence indicated with the variation of the frequency of the upper hybrid emissions in the format of the dynamic spectrum of DS mode of the PWS/EXOS-D, given in the same format as Fig. 5. (a) Example of small regular oscillations of the equatorial plasma density turbulence (EPDET) observed on March 11, 1989, from 09:14 UT to 09:59 UT. There is a periodic oscillation of the upper hybrid frequency in the observation data from 09:21 UT to 09:28 UT corresponding to a position very close to the geographic equator. (b) Very large EPDET irregularity. The observation was made on March 25, 1989 from 07:07 UT to 07:39 UT. Remarkably large amplitude irregular oscillation in the upper hybrid frequency is indicated from 07:15 UT to 07:32 UT, again corresponding to the point across the geographical equator.

km, centered around the geomagnetic equator for EPWAT and centered around the geographic equator for EPDET. That is, we can state, within the limitations of the observation coverage, that the earth is surrounded by a disc of plasma wave turbulence circulating in the region of the geographical equator belt for EPDET and in the region of the geomagnetic equator for EPWAT. The results of analyses of the EPDET occurrence localized near the geographic equator show that the turbulent regions are related to the kinematic dynamics; i.e., the plasma density turbulence is controlled by gravity and centrifugal force, while the plasma wave turbulence, EPWAT, is apparently controlled by an electromagnetic cause.

ii) *Relation to the geomagnetic activity*

Fig. 10. Example of the equatorial enhancement of the plasma wave turbulence (EPWAT) indicated as a local enhancement in the intensity of the upper hybrid emission. The data are indicated in the same format as the dynamic spectrum in Fig. 5. (a) Observation data detected on April 15, 1989 from 09:25 UT to 09:59 UT. A very remarkable intensification of the upper hybrid emission can be seen in the region very close to the magnetic equator. When the satellite passes through the magnetic equator, the FLAT value changes its sign from minus to plus or vice versa. (b) Very intense EPWAT observed on March 11, 1989, from 12:55 UT to 13:25 UT. Very remarkable enhancements are observed from 13:00 UT to 13:10 UT, again in the region covering the magnetic equator.

The statistics from 50 EPWAT events have been used to investigate the relation of the EPWAT intensity with the geomagnetic indices ΣK_p . As given in the results in Fig. 13, the EPWAT intensity shows a correlation with the geomagnetic indices, suggesting that the enhancement of EPWAT is intimately related to the energy input from the magnetosphere where the solar wind energy input plays an essential role. There is, however, a component independent of the geomagnetic activities, suggesting that the generation of EPWAT is not only controlled by the field and particles resulting from the solar wind interaction with the magnetosphere, but is also related to the earth's own electromagnetic condition at the magnetic equator.

Fig. 11. Statistics for the occurrence regions of EPDET. (a) The occurrence regions are plotted with thick lines in the Altitude-Geographic latitude diagram, for all possible orbits until July 1, after turn-on of the instrument. The results show that EPDET's cover the entire altitude range from 2000 km to 9000 km in the region centered around the geographic equator. (b) The occurrence regions of EPDET plotted in a Magnetic local time-Geographic latitude diagram. The results show that EPDET's take place distributed widely in local time across the geographic equator.

Fig. 12. The statistics for the occurrence regions of EPWAT. (a) The occurrence regions are plotted with thick lines in an Altitude-Geomagnetic latitude diagram for all possible orbits across the geomagnetic equator in the period until July 1, after turn-on of the instrument on March 6, 1989. The results show that EPWAT's take place in the entire altitude range above 2000 km to 8500 km in the region centered around the geomagnetic equator. (b) The same type of plotting is made for EPWAT in the Magnetic local time and Geomagnetic latitude diagram. The result indicates that EPWAT's take place over the entire possible local time in the region centered around the magnetic equator though the observation possibility is limited from 10:30 to 21:00 for the present.

Fig. 13. Occurrence number of events of the EPWAT (equatorial plasma wave turbulence) in the ΣK_p versus Intensity of EPWAT diagram that is indicated with 5 ranks. The tendency that the high intensity (high rank) of EPWAT phenomenon occurs in the case of high ΣK_p is apparent.

3.3 AKR

Auroral kilometric radiation has been frequently observed in the region outside of the plasmasphere along the magnetic field lines in the region of the auroral oval. Depending on the relative position of the satellite with respect to the AKR sources, a variety of AKR features have been revealed in the AKR dynamic spectra. The most important cases are the observations made when the satellite moved into the AKR source regions. Considering that the emission energy of the AKR is directly proportional to the concentrated electron beam density, we can conclude that the intense portion of AKR emissions is generated in connection with the acceleration region of auroral particles as the origin of the electron beam. From the observed pattern of dynamic spectra of AKR, therefore, we can identify the spatial distribution of the auroral particle acceleration regions assuming that the emission frequency is near the local electron cyclotron frequency. Starting from the weakest AKR observation extending to the maximum AKR intensity, we have identified five degrees of AKR phenomena in terms of intensity and duration as given from Figs. 14(a) to 14(e). The weakest radiation (see Fig. 14(a)) is found in faint AKR spectra that cover from the local upper hybrid emission frequency near 80 kHz to 780 kHz, corresponding to the level from the satellite height at about 9000 km to below 2000 km. When the AKR emissions become slightly intense emissions (see Fig. 14(b)), forming time-series with the characteristic time of about 5 minutes, they indicate a dynamic spectra whose intensity maxima form three separate groups in frequency ranges

corresponding to the acceleration regions in three different levels. The first source is near the satellite level around 10,000 km that can be concluded from the coincidence to the local upper hybrid frequency. The second region is identified in the range from 6000 to 3000 km corresponding to 220 kHz to 540 kHz. The third source is identified around 800 to 1500 km, corresponding to the emission frequency ranging from 700 to 1100 kHz. The tendency of the source regions to separate into these three groups can be seen more clearly in the case of the higher intensity than the case given in Fig. 14(b); i.e. in the AKR observations given in Figs. 14(c) and 14(d). Further enhancements are indicated in Fig. 14(e), in the maximum intensity of the emission. When the AKR emissions become intense, we can see the fine structure of the emissions where each maxima of the multi peaks of the spectra show that acceleration regions are commonly produced with spatial gaps of 50–200 km. Sometimes these fine structure have very fast time variations; detailed analyses of the dynamical feature of the acceleration regions are also deferred for future studies.

3.4 Whistler mode radiation

Whistler mode radiations are frequently observed relating to the precipitation of energetic particles in the auroral region as well as in the cusp region. One of the remarkable results relating to this whistler mode wave radiation is that there are apparently two types of emissions; in the first the whistler mode waves shows regular electromagnetic wave nature and in the second the whistler mode waves clearly show the nature of electrostatic waves. As given in Fig. 15(a), the results of the B_x component detected by the loop antenna are also displayed with the same format as Fig. 5. It is apparent that even though the two emissions show the same intensity levels for the electric field component, there is a portion of no response to the magnetic field in the whistler mode wave emissions observed from 08:29 UT to 08:34 UT. The latter case shows that the whistler mode waves are generated as the result of an inverse Landau interaction, rather than cyclotron interaction. In Fig. 15(b), another example of whistler mode emissions is indicated; the broad band emissions are well correlated with the magnetic field variation (FUKUNISHI *et al.*, 1990) suggesting an intimate correlation with the auroral particle precipitation.

4. Conversion Processes

After studies on the connection of electrostatic waves to electromagnetic waves through the upper hybrid mode wave channel (OYA, 1971a), the conversion processes of electrostatic plasma waves into electromagnetic waves have been proposed as one of the most important process for the generation of electromagnetic radiation in the space plasma (OYA, 1974). The observed evidence of the continuum radiation (GURNETT, 1975; KURTH *et al.*, 1979) from the plasmopause was interpreted based on this conversion concept by JONES (1976), and more extensively by OKUDA *et al.* (1982).

Direct evidence of the conversion processes in the region of the plasmaspheric boundary, plasmopause regions, turbulent distribution of the plasma and from the topside ionosphere in polar regions are disclosed by these PWS/EXOS-D observations.

4.1 Direct observation of the conversion process

From the highly irregular distribution of the plasmasphere electromagnetic radi-

Fig. 14. Examples of AKR observed near the source regions of auroral particle acceleration. All data from (a) to (c) are given in the same format given in Fig. 5. Polarization data are displayed in panels (d) and (e) both for left-hand (top) and right-hand (bottom) polarizations in each panel; each format of polarization data is exactly the same as the format of Fig. 5. (a) Example of a faintest AKR emission. (b) Weak AKR case. Above the local upper hybrid emission weak AKR emission and medium intensity emissions are indicated. Further above 300 kHz, there are also groups of faint emissions around 500 kHz. (c) Example where AKR emissions are intensified. Fine structure can be identified in the main portion of the AKR emissions that

are clearly cut at the local plasma frequency, suggesting that AKR are generated in the form of the L-O mode in this case. (d) Very intense AKR emissions that cover the entire frequency range from 120 kHz to 700 kHz being separated again into three frequency groups as given in Fig. 14(b), associated with very fine structures in the emissions. The level of the emission diminished at the local upper hybrid frequency as the result of the impedance effect of the receiving antenna. (e) Example of extremely intense AKR displayed for both polarizations with the same format as Fig. 14(d). All tendencies of the data are similar to Fig. 14(d) but the entire AKR emissions are more intense, in this case, indicating very wide frequency coverage.

Fig. 15. (a) Examples of whistler mode radiations observed in the north polar ionosphere crossing on March 13, 1989 from 08:09 UT to 09:09 UT when the satellite moved from the altitude of 498 km to 7565 km. Correlating with auroral particle precipitation in the auroral regions, the emissions in the upper hybrid branch and the quasi-electrostatic wave branch are enhanced remarkably. Above the upper hybrid emissions there are series of type III solar radio bursts whose spectra are cut at the ionospheric plasma frequency. (b) Dynamic spectra obtained during the recovery phase of the large storm that started on March 13, 1989. The format is the same as the top panel of Fig. 5. A very clear group of broad band emissions can be identified in the frequency range of the whistler mode waves starting from 09:25 UT and ending at 09:40 UT on March 14, 1989. The occurrence of broad band whistler mode waves coincide with the large excursion of the magnetic field value from the average, suggesting the correlation of the particle precipitations as causes of the local field aligned currents in the auroral regions.

Fig. 16. Results of PWS observations made on March 24, 1989 from 06:23 UT to 07:23 UT; the data are indicated in the same format as Fig. 5. The straight lines of the spectra which merge with the local upper hybrid emissions associated with the largely irregular plasma state are manifestations of the conversion processes of electrostatic radiation into electromagnetic waves at the turbulent plasma regions.

ations are generated. At the source, intense upper hybrid waves are generated. In Fig. 16, a typical example in which we can trace the conversion processes is given. At 06:24 UT on March 24, 1989, remarkable radiations were detected at around 160 kHz, 260 kHz, 340 kHz and 440 kHz with fairly wide band frequency. The first band at around 160 kHz continued for about 10 minutes and terminated at the moment when the spacecraft crossed the point where the upper hybrid frequency merges into the frequency of the radiated electromagnetic waves. The second band at 260 kHz continued for 30 minutes until the spacecraft entered the turbulent region of the plasmasphere at about 06:55 UT, where the upper hybrid frequency coincides with the radiation frequency at 260 kHz. The third band at 340 kHz merged around 07:00 UT and the fourth band merged at 07:02 UT. From 07:00 UT to 07:23 UT, very large plasma irregularities took place. We can assume an effective conversion process from electrostatic plasma waves into electromagnetic waves around each source region.

4.2 Terrestrial hectometric radiation

Terrestrial hectometric radiations (THR) from the polar region ionosphere have been discovered from the observation data of the EXOS-C satellite (OYA *et al.*, 1985). Since the maximum altitude of the EXOS-C satellite was 870 km, the observations could not provide complete confirmation that the hectometric radiations escape into outer space. Because of the high altitude of the apogee (10,500 km) of the EXOS-D satellite orbit, very clear images of the escape of THR are apparently identified in many orbits of the EXOS-D NPW observations. In Fig. 17, an example of THR emissions is given from 700 kHz to 3.2 MHz; the whole range of the band is occupied by THR emissions. The emission band has been curved out at the limit of the ionospheric plasma frequency at the distant dayside location. We can therefore see a silhouette of the ionosphere in the direction of the sunlit ionosphere. The blank area in the spectra between the edge of the sunlit ionosphere and the local satellite level plasma frequency (the lower edge of the upper hybrid emission) at each moment indicates the shadow of the THR radiation.

Fig. 17. Observation results of the terrestrial hectometric radiations given in the same format as Fig. 5. The continuum radiations, below 2.1 MHz, whose frequency spectra are cut at the dayside ionospheric plasma frequency (higher than the local upper hybrid frequency at the satellite level in the evening) are the terrestrial hectometric radiations radiating from the topside ionosphere of the polar region.

5. Results of the Sounder Experiments

After turning on the high power transmitter on March 29, 1989, sounder experiments have been also successfully initiated. EXOS-D sounder experiments are successfully made even in very high altitudes, up to 10,550 km.

The sounder on board EXOS-B was utilized up to 30,050 km, but its effective power was very low. The EXOS-D sounder experiment is therefore expected to be very successful both for the active plasma wave experiments and for sounding the plasma structure in both the ionosphere and in the plasmasphere.

5.1 Typical ionograms

The sounder experiments carried out in the topside region provide echoes from the ionosphere. Typical results obtained in the topside ionosphere at 1942 km and 5665 km are given in Figs. 18(a) and 18(b) respectively. Though the results are the same as in the Alouette 1 and 2, ISIS 1 and 2 and EXOS-C, the very successful sounder experiments on board EXOS-D are able to provide new findings in the field of the active sounding of the plasma distribution and plasma wave phenomena relating to the acceleration region of the auroral particles.

When there are ducts in the plasmasphere, very long propagations of the pulsed echoes are possible. In Fig. 18(b) we can see a typical example of ducted echoes which have been detected at higher than 5000 km.

5.2 Sequence of diffuse plasma resonances

In high altitude regions very long duration sequences of diffuse plasma resonances are detected. In Figs. 19(a) and 19(b), we can see a typical example of these diffuse plasma resonances originally discovered by OYA (1970, 1971b) from the Alouette 2 and ISIS ionograms. There is an interesting relationship between the electrostatic plasma

Fig. 18. Plasma wave response diagram (Plasmagram) of the stimulated plasma wave experiment. The format is the same as the Alouette, ISIS, Jikiken and EXOS-C ionograms; i.e. the responses of the transmitted pulse are indicated with four intensity ranks for the transmitted RF frequency (abscissa in MHz unit) and the delay-time of the pulse response after the transmission of the pulse (ordinate). The intensities given by blue, green, yellow, pink and red indicate the threshold levels of 1.0×10^{-16} , 3.2×10^{-16} , 3.4×10^{-15} , 3.2×10^{-14} and $1.1 \times 10^{-13} \text{ V}^2/\text{m}^2\text{Hz}$, respectively. The resonances f_c , f_p , f_{UHR} , f_{D1} , f_{Q3} and f_{Q4} (not necessarily appearing together in the same panel) indicate the plasma resonances, i.e. electron cyclotron resonance, the plasma resonance, the upper hybrid resonance, the first sequence of the diffuse resonance, the third sequence of electrostatic resonance and the fourth sequence of the electrostatic resonance, respectively. (a) The result obtained on April 1, 1989 around 08:52:15 UT when the satellite was at the altitude of 1942 km and magnetic latitude of 53.1° . In addition to the principal plasma resonances, very clear echo trains from the topside ionosphere are indicated. (b) The results of sounder experiments with the same format as Fig. 18(a). The observation was made on March 30, 1989, around 07:18:12 UT when the satellite was at the altitude of 5665 km, with a geomagnetic latitude of 9.6° . Very long ducted echoes are indicated in the frequency range from 0.78 MHz to 2.5 MHz.

Fig. 19. (a) Plasmaprogram in the same format as Fig. 18(a) obtained on March 30, 1989 around 07:24:36 UT when the satellite was at the altitude of 4673 km, with magnetic latitude of 19.6°. (b) Plasmaprogram obtained at very high altitude (6130 km) with geomagnetic latitude of -20.7° as the result of the sounder experiment on May 12, 1989, around 03:12:50 UT.

resonances F_{Qn} ; a non-linear interaction of the expected waves was proposed by OYA (1971b) to generate this relationship.

After establishment of the studies on the instability processes for plasma wave excitation by artificially injected processes, instabilities stimulated by the RF pulse were also proposed (OYA and ONO, 1981; ONO and OYA, 1988). The results obtained by EXOS-D experiments will also provide important data in this field of endeavor.

6. Conclusion

Plasma Wave and Sounder Experiments (PWS) on board EXOS-D (Akebono) are successfully observing natural plasma waves after the deployments of two sets of 60 m tip-to-tip wire antennas and three axial loop antennas with 60 cm×60 cm receiving area, on March 4 and 6, 1989. Sounder experiments were also successfully started after turn-on of the high power RF signal on March 29, 1989. The instruments are designed for a wide variety of operations on plasma waves in the frequency range from 20 kHz to 5 MHz and we can extend the operation frequency to 11 MHz for sounder mode operations.

Natural plasma wave observations (NPW) are being made with dynamic spectra, polarization, and Poynting vector observations. The sounder mode experiments can be made with a variety of operation modes; i.e., i) a High frequency mode in the frequency range from 300 kHz to 11 MHz, ii) a Low frequency mode in the frequency range from 20 kHz to 500 kHz, iii) an F_{UHR} mode in tenuous plasma, iv) an F_p mode operation in the dense plasma and v) an Eight fixed frequency mode for high time resolution.

Results of the natural plasma wave observations indicate that hybrid mode waves are always generated surrounding the spacecraft. From the detected upper hybrid emission frequency the plasma density profiles can be obtained. Various features of the plasmopause structures are disclosed from the global distribution features of the upper hybrid emission frequency. These are classified as i) G-type, ii) S-type and iii) I-type plasmopause, which respectively indicate gradual, sharp and irregular changes of the plasmopause density. I-type plasmopause is further classified into a) Detached plasma type (I_D -type), b) Large oscillatory type (I_O -type) and c) Multi shocks type (I_S -type).

The hybrid mode waves are enhanced in the region of i) the auroral particle precipitation, ii) magnetic equator regions and iii) regions of sporadic precipitation of energetic particles. Equatorial enhancements of the turbulences relating to the upper hybrid emissions are a new finding especially made by the present EXOS-D experiments and here called "the equatorial enhancement of the plasma turbulence (EPWAT)". The occurrence of EPWAT is fairly well confined to the region of the magnetic equator covering the altitude range above 2000 km to 9000 km and covering the whole range of local time, though there is a limitation of the orbital coverage of the EXOS-D satellite. The intensity of EPWAT is sharply correlated with ΣK_p .

In addition to EPWAT, there are another category of plasma instabilities that are revealed as variations of the upper hybrid emission frequency which occur in the form of wave-like oscillations, large amplitude irregular variations, sudden dips, or large amplitude irregular oscillations, centered around the geographic equator. This is called equatorial plasma density turbulence (EPDET). The occurrence of EPDET also covers the altitude range from 2000 to 9000 km for all possible cases of observed local times. The difference of the occurrence regions between EPWAT's and EPDET's can be attributed to the underlying mechanisms; i.e., the former is dominated by electromagnetic effects while the latter is dominated by the kinetic effects such as the balance of forces between centrifugal force and gravity.

Auroral kilometric radiations (AKR) are always observed when EXOS-D enters into the region of auroral particle accelerations. The intensities and frequency band widths vary over a wide range depending on the substorm activities and distance of the spacecraft between the AKR sources. The intensities are classified into 5 ranks.

Independent of the rank of the AKR activity there are three groups of sources distributed in different altitude ranges; near the 10,000 km region, in the range from 6000 to 8000 km and in the range 800 to 1500 km. The dynamic spectra of AKR indicate many fine structures. Assuming that each structure corresponds to the emission from each localized source and assuming that the emission frequencies are very close to local cyclotron frequencies at source regions, we can understand that there are multiple structured acceleration regions aligned with gaps of 50 to 200 km and moving with speeds ranging over a few km/sec. NPW observations also include information on the polarization and Poynting vectors of AKR. Some results of these observations will be given in a different paper (MORIOKA *et al.*, 1990) and more extensive analyses are deferred to future studies.

The NPW/EXOS-D spectra show very clear evidence that the electrostatic waves are converted into Z-mode electromagnetic waves, when the hybrid mode emissions are greatly enhanced. Furthermore it is directly indicated that Z-mode waves are converted to L-O mode electromagnetic waves when the plasma distribution made irregularities. Terrestrial hectometric radiation has been frequently observed. The present EXOS-D observations confirm for this terrestrial hectometric radiation that the emissions are generated from the top-side region of the polar ionosphere as the result of the conversion of electrostatic mode waves, associated with auroral particle precipitation, into electromagnetic waves.

Stimulated plasma wave experiments have also provided data indicating the principal resonances such as the harmonics of the electron cyclotron resonances nf_c ($n=1, 2, 3, \dots$), plasma resonance f_p and upper hybrid resonance f_{UHR} . In addition to these principal resonances, there are also sequences of diffuse plasma resonances f_{Dn} as well as the electrostatic plasma resonances f_{Qn} . All these results of SPW/EXOS-D experiments are characterized by evidence that the observations are made in very high altitude regions; i.e. f_{D1} resonances are detected even at the altitudes of 4673 km and 6130 km. These results indicate that we can use sounder experiments to diagnose various parameters of the plasmasphere, such as plasma density, local magnetic field intensity and temperature anisotropy as well as diagnosis of wave particle interaction processes in collisionless plasma in future studies.

We would like to express our sincere thanks to the ISAS M-3S-II-4 launching team and also to all members of the Akebono (EXOS-D) satellite team for very successful achievement of the projects.

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