Studies on Plasma and Plasma Waves in the Plasmasphere and Auroral Particle Acceleration Region, by PWS on board the EXOS-D (Akebono) Satellite

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Plasma wave and sounder experiments (PWS) on board the EXOS-D (Akebono) satellite are continuously providing the wide variety of data which contribute to the studies on plasma wave phenomena associated with the wave particle interactions in the regions of the cusp, auroral particle acceleration, and magnetic equator. Observation results of the auroral kilometric radiation (AKR) with Poynting vector, polarization as well as the dynamic spectra, have indicated that the generation mechanism of AKR is not necessarily due to the cyclotron maser mechanism but majority parts of AKR's are caused by the conversion of upper hybrid waves through the Doppler conversion processes and also through irregularities of the plasma in the auroral particle acceleration regions. Propagating electromagnetic wave phenomena in the plasmasphere are 1) banded rising and falling LF waves (BRIFLE), 2) discrete HF emissions, and 3) terrestrial hectometric radiations. There are localized modes of the plasma waves such as 4) upper hybrid mode waves, 5) Z-mode waves and 6) quasi-electrostatic whistler mode waves. Reflecting the evidence of the strong wave particle interactions, in the region of the cusp and auroral particle precipitation region, 7) broad band electrostatic noises are frequently observed and these become good indicator of the particle precipitation when the low energetic particle detector makes a pause of their operation in the low latitude range. Storm time effects of the plasma waves show also unique and important features; plasmaspheric odd harmonic, $(n+1/2)f_c$ emissions which have never detected in the plasmasphere inside of the plasmopause in the regular condition of the magnetic field activities take place even in the plasmasphere inside of the plasmopause in the times of large magnetic storm.

The plasma density profiles obtained from the observed upper hybrid waves provide wide variety of variation of the plasmasphere and plasmopause structure with informations of the plasma instabilities there. A review has been made for the instabilities identified in the magnetic equator whose occurrence region is circulating at the magnetic equator covering the altitude from 1,000 km to 10,000 km. In the storm time, the plasmopause has apparently been disrupted with depressed density and loosing sharp edge of the density variation. In the recovery phase of the large magnetic storm, the plasma density distribution shows large disturbances where the amplitudes of the irregular variation of the plasma density become 5 to 6 times or sometimes an order of magnitude of the background density itself. Also during recovery phase of the storm, a large scale cavity of the plasma is formed centered at the magnetic equator coinciding with the position of expected ring current. All of these results show that the PWS on board the EXOS-D satellite are making effective contribution to study on the energy transfer through the plasmasphere providing data of the electron density, temperature anisotropy and informations on existing free energy of the plasma and the energetic particles.

1. Introduction

After successful launching of the Akebono (EXOS-D) satellite, on Feb. 22, 1989, the turns on of the science instrument have effectively been made for the on board eight science instruments:

- 1) Magnetic Field Detector (MGF)
- 2) Electric Field Detector (EFD)
- 3) Plasma Wave and Sounder Experiments (PWS)
- 4) Very Low Frequency Plasma Wave Detector (VLF)
- 5) Low Energetic Particle Detector (VLF)
- 6) Suprathermal Mass Spectrometer (SMS)
- 7) Temperature and Energy Detector for Electron (TED) and
- 8) Auroral Television Camera (ATV).

Turn on of the waves and field experiments has been made early March 1989, and the turn on of the instruments using high voltage power sources has been made early April 1989.

In addition to main 8 science experiments, an instrument for radiation belt monitor in an energy range from 0.5 MeV to 3 MeV has also been installed. The details of the instrumentations have already been published with initial results (Special issue of JGG, No. 4, 1990 and GRL, Vol. 18, No. 2, 1990).

Though the initially designed life time of Akebono satellite is 1 year from the engineering analyses stand point, the satellite is expected to continue the observations during 5 year. The operation of the satellite will therefore contribute to the early parts of STEP projects, the world most extensively organized program of SCOSTEP for the solar terrestrial physics in 1990's.

In these widely integrated observations, the present paper concentrates on the observation results of PWS (Plasma Wave and Sounder Experiments); from a variety of the results, we will select here subjects directly related to the plasma wave phenomena in high frequency range (higher than 20 kHz) and also phenomena related to the plasma dynamics based on the plasma density deduced from the observed upper hybrid wave emission frequency. The region of the present studies are then divided into

- 1) Plasma wave phenomena relating to the wave-particle interactions,
- 2) Polar regions,
- 3) Equatorial region plasmasphere, and
- 4) Plasmasphere structure.

During early phase of the EXOS-D (Akebono) satellite, three major magnetic storms had taken place; i.e., in March 13 to 14th, Oct. 20 and 21st and Nov. 17 and 18th, in 1989. These data of large magnetic storms have been associated with evidences that have never been disclosed by the previous observation, in polar region, plasmasphere, and equatorial plasmasphere. Observations of these evidences become important keys to solve the hidden question of dynamics and energy transfer through the plasmasphere and polar region plasmas. The contents of the present paper, then, consist of reports on the newly discovered evidences including the review of the already reported new finding from PWS on board the EXOS-D satellite.

2. Plasma Waves Observed by the EXOS-D Satellite

Plasma wave phenomena observed by the EXOS-D satellite have been summarized by adding already found phenomena (OYA *et al.*, 1990), as

- I) Propagating electromagnetic waves;
 - 1) Solar type III radio bursts,
 - 2) Auroral kilometric radiations (AKR),
 - 3) Banded rising and falling LF waves (BRIFLE),
 - 4) Discrete HF emission,
 - 5) Terrestrial hectometric radiation (THR).
- II) Quasi-propagating mode waves;
 - 1) Upper hybrid mode waves,
 - 2) Z-Mode waves,
 - 3) Quasi electrostatic whistler mode waves.
- III) Insitu electrostatic plasma waves;
 - 1) Plasmaspheric odd harmonic emissions $(n+1/2)f_{ce}$,
 - 2) Broad band electrostatic noises.

In the above items, auroral kilometric radiations (AKR) belong to the subject which is considered with special interest in the field of the studies on the auroral processes and substorms activities, also in the field of the origin of the auroral particle acceleration. AKR will, then, be described separately in the next section.

The observations of the type III radiation using the satellite have been made the start with the ATS-II satellite for the frequency range of 3.0 MHz to 450 kHz (ALEXANDER *et al.*, 1969), then observation study of long wave type III radio burst has been expanded by using OGO-III (GRAEDEL, 1970), and by Radio Astronomy Explorer (RAE-1) satellite (MOHR *et al.*, 1969; EVANS *et al.*, 1971), OGO-5 and IMP-6 (FRANK and GURNETT, 1972; EVANS *et al.*, 1973; ALVAREZ *et al.*, 1972 and 1975; KAISER, 1975). Discussions have been raised for the generation mechanism of type III radio bursts; whether the source is fundamental frequency of the Langmuir waves or the second harmonics of the generated waves, which are formed as the results of the nonlinear coupling processes. To clarify these points many observation studies have also been continued. One of these efforts is to identify the source position of the type III radio bursts by multi satellite observations (WEBER *et al.*, 1977; GURNETT *et al.*, 1978). ISEE-3 (LIN *et al.*, 1981) and also Voyager (SAWYER and WARWICK, 1987) have made contribution to study the energetic particle effects through the interplanetary space generating the kilometric range type III radio bursts. To studies the generation mechanism and also interaction processes of the energetic electron through the interplanetary media, EXOS-B (Jikiken) data have also made contribution (MIYAKE and OYA, 1989). By the EXOS-D satellite large volume of data of the solar type III radio bursts, in the frequency range from 5 MHz down to 20 kHz are obtained; especially in the time of active solar surface conditions very frequent occurrence with rate of every 30 sec (in the case of maximum) has been identified. These data of type III radio bursts will contribute to future studies on the origin of the type III bursts in the interplanetary space.

2.1 Banded rising and falling LF waves (BRIFLE)

The special dynamic spectrum feature of radiation in the frequency range of LF (20 kHz–1 MHz) has first been identified by the PWS on board the EXOS-D satellite (OYA *et al.*, 1991; KIKUCHI *et al.*, 1991). The banded spectra of these newly identified emissions show the

rising and falling variation with the maximum frequency range at the magnetic equator, and named the waves BRIFLE (Banded Rising and Falling LF Emission).

An example of BRIFLE is given in Fig. 1. The minimum frequency of BRIFLE is always identified in a range of $L = 1.2$ – 1.6 ; and the theoretical studies (KIKUCHI *et al.*, 1991) show that the BRIFLE's are the phenomena of the propagating whistler mode waves, in the LF frequency range, which are generated at $L = 1.2$, to 1.6 regions in the relatively higher altitude about 1000 km. Detail description will be given in another paper (OYA *et al.*, 1991; KIKUCHI *et al.*, 1991).

2.2 Discrete HF emissions

In the frequency range above 100 kHz, emissions with discrete flat nature has been observed. An example related to the discovery of these phenomena is reproduced in Fig. 2 (OYA *et al.*, 1990). The phenomena apparently show that the origin of the HF emissions is associated with the large density irregularities; and the origin of this discrete emissions is in the conversion processes of the plasma waves into electromagnetic waves. (OYA, 1971a, 1974; JONES, 1976; OKUDA *et al.*, 1982).

2.3 Terrestrial hectometric radiations (THR)

THR has been discovered by PWS on board the EXOS-C (OYA *et al.*, 1985); and has also been observed by the EXOS-D satellite (OYA *et al.*, 1990). The PWS on board the EXOS-D will make important contributions for studies on the generations of THR for its mechanism and relation to the auroral activities and even for the similarity of the generation with Jovian decametric wave radiations.

2.4 Upper hybrid mode waves

In early part of the studies on the upper hybrid mode waves, WALSH *et al.* (1964); HUGUENIN *et al.* (1964); HARVEY (1965); and BAUER and STONE (1968) have made important contribution. BAUER and STONE (1968) had provided more complete report of the upper hybrid emissions based on the ATS II satellite observations in the altitude range about 1,000 km to 10,000 km. In parallel to these reports, there are also several important reports for existence of the upper hybrid mode waves (HARVEY, 1968; GREGORY, 1969; MOISIER *et al.*, 1973). For the generation mechanism, Cerenkov radiation in the form of electromagnetic waves in cold plasma had been proposed (WALSH *et al.*, 1964; BAUER and STONE, 1968; GREGORY, 1969; MULDREW, 1970; LAASPERE *et al.*, 1971). Importance of the upper hybrid mode waves as the channel which connect between the electrostatic plasma waves and the Z-mode electromagnetic waves, had first been pointed out by OYA (1971a) based on the full wave treatment of the dispersion relation; and also it is pointed out that the upper hybrid mode waves have possibility to be generated making resonance with beam of very wide range of the energy. Studies on the upper hybrid mode waves have also been continued (LIM and LAASPERE, 1972; MOISIER *et al.*, 1973; TAYLOR and SHAWHAN, 1974; MAGGS, 1978; KURTH *et al.*, 1979 and 1981).

Detail points of the new observation results of upper hybrid mode waves obtained by the EXOS-D satellite have already been published (OYA *et al.*, 1990, 1991); we will not then repeat here for this subject. Generation processes of the upper hybrid waves are related to two complementary features of free energy; i.e., one is the case of the plasma velocity

distributions enhanced in the perpendicular direction with respect to the magnetic field, and the another is the case of the plasma with electron or ion beams.

Because PWS on board the EXOS-D satellite has the capability to detect even very weak upper hybrid mode waves (the threshold is $0.1 \mu\text{V/m}$) we can always detect the waves and can

use the detected UHR frequency $f_{\text{UHR}} = \sqrt{f_p^2 + f_c^2}$, where f_p and f_c are, respectively, plasma frequency and the electron cyclotron frequency, to deduce the precise plasma density distributions.

2.5 Z-mode waves

After pointing out of the existence of the naturally generated Z-mode waves in space (OYA and MORIOKA, 1983) evidences and theories for Z-mode waves are reported (JONES, 1984; OMIDI *et al.*, 1984; DUSENBERY and LYONS, 1985; OMIDI and WU, 1985; MENIETTI, 1985; BAHNSEN *et al.*, 1987; HASHIMOTO *et al.*, 1987; HORNE, 1988; MORIOKA *et al.*, 1988; HORNE, 1989; HASHIMOTO and CALVERT, 1990). As has been given in the example given in Fig. 3a very remarkable existence of the Z-mode waves are frequently identified by the

Fig. 1. Example of BRIFLE, in the dynamic spectrum of the PWS on board the EXOS-D satellite. The ordinate of the diagram shows the frequency from 20 kHz to 5 MHz with abscissa which indicates the observation time in UT., and Satellite position in MLT (magnetic local time), ILAT (invariant latitude), FLAT (Foot latitude of dipole magnetic field), and ALT (altitude) in km at corresponding observation time. The intensity is indicated by color code for relative level from 0 to 255. The faint emission below local electron cyclotron frequency f_c , which show the banded spectra whose center frequency makes continuous variation with maximum at the magnetic equator is BRIFLE.

EXOS-D, PWS data. It is also clarified that even no separate signature has been recognized in the dynamic spectra of PWS (see Fig. 3b), Z-mode waves are always associated with the existing upper hybrid mode waves, as we can see in Fig. 3c, where the Z-cutoff frequency is identified very close to the upper hybrid frequency because of the condition $f_p \gg f_c$.

2.6 Quasi electrostatic whistler mode waves

It is well known that the whistler mode waves are naturally connected to the electrostatic plasma wave modes when the wavelength makes change while the waves propagate through inhomogeneous media. Between the electrostatic plasma waves and electromagnetic Z-mode waves there is a regime of the quasi-electrostatic whistler mode waves. The frequency range of this quasi electrostatic plasma waves is almost identical with the resonance; i.e.,

$$2(1-X) - Y^2 \sin^2 \theta - \sqrt{Y^4 \sin^4 \theta + 4Y^2(1-X)^2 \cos^2 \theta} = 0, \quad (1)$$

$$X = \frac{f_p^2}{f^2}, \quad Y = \frac{f_c}{f},$$

Fig. 2. Example of the discrete HF emissions observed on March 24, 1989. The dynamic spectrum is indicated with the same format as Fig. 1; straight line shape (except for a disturbance at 500 kHz) of the emission which merges at the local upper hybrid waves at 06:33 UT and 07:03 UT are the discrete HF emissions that are understood as the manifestation of the conversion of the upper hybrid waves into electromagnetic waves (After OYA *et al.*, 1990).

Fig. 3(a). Example record of the Z-mode wave given in the dynamic spectra in the same format with Fig. 1. The emissions that are filling the frequency range from the local Z-cut off frequency f_z and the upper hybrid frequency f_{UHR} are the propagating Z-mode waves.

in the frequency range $f < \text{Min}(f_p, f_c)$ where $\text{Min}(f_p, f_c)$ shows lower frequency between f_p and f_c . Therefore, many of the propagating mode waves are identified as the regular whistler mode waves but when the satellite is passing through the region of the particle precipitations, the mode is taken to be electrostatic or quasi electrostatic plasma wave mode. One typical example of these phenomena is identified in the time of the large magnetic storm

Fig. 3(b). Example of the dynamic spectrum observed on August 29, 1990 in same format with Fig. 1.

Fig. 3(c). The spectrum of Z-mode wave which is located very close to the spectrum of the upper hybrid mode waves because f_{UHR} is very close to f_z for the condition of $f_p \gg f_c$.

as given in Fig. 4 where intense quasi static plasma waves can be identified below the local plasma frequency f_p because $f_p < f_c$.

2.7 Plasmaspheric odd harmonic $(n+1/2)f_c$ emissions

The first report of the odd harmonic emission had been made by KENNEL *et al.* (1970) based on the observations of the OGO-5 satellite in the magnetospheric plasma sheet region. Almost in parallel, the diffuse resonance f_{Dn} has been identified being based on the Alouette II data; the resonance is tightly connected to the $(n+1/2)f_c$ emissions though the phenomena also involve the nonlinear plasma wave effects (OYA, 1970, 1971b). After these report there were many research works for this $(n+1/2)f_c$ emissions.

The present result belongs, however, to new subject because the plasmaspheric odd harmonics $(n+1/2)f_c$ waves have first identified within the plasmasphere by the EXOS-D satellite observation. An example record is given in Fig. 5 where the $(n+1/2)f_c$ emissions are indicated through whole the range of the satellite path in the plasmasphere inside of the plasmopause in the time of the large magnetic storm which started from 01:30 UT, on March 13, 1989. It has well been established that the $(n+1/2)f_c$ emissions are caused by the free energy state where the velocity distribution of particles is enhanced in the direction perpendicular to the magnetic field (FREDERICS, 1971; OYA, 1971b; KARPMAN *et al.*, 1973; YOUNG *et al.*, 1973). The existence of $(n+1/2)f_c$ emissions in the plasmasphere, therefore,

Fig. 4. PWS data observed on Oct. 20, 1989 in the main phase of the large magnetic storm. The format of the diagram is same with Fig. 1. Below the upper hybrid frequency there are widely distributed broad band emission that show vertically structured emission spectra. Below the electron cyclotron frequency there is a fairly wide band trend of the emissions which are identified as the quasi electrostatic whistler mode waves.

Fig. 5. (a) The plasmaspheric odd harmonic, $(n+1/2)f_c$ emissions observed on March 13, 1989 in the main phase of the large magnetic storm. The observed dynamic spectrum is indicated in the same format with Fig. 1. (b) The same case with (a) is expressed with scaling by the electron cyclotron frequency f_c .

Fig. 6. Typical example of the broad band electrostatic noise observed in the cusp region on March 28, 1990. The dynamic spectrum is given in the same frame with Fig. 1, but the intensity is indicated by gray code.

Fig. 7. Example of the discrete AKR which shows the harmonic relation. The dynamic spectra are displayed for the two polarizations, wave modes are identified to be R-X (top) and L-O (bottom) when the waves come from the source in the anti-sun ward direction. Format for each panel is same with Fig. 1. The data show that the relative intensities of the left hand to the right hand polarized components for the case of the 2nd harmonics $2f_{emi}$ are completely opposite to the case of the fundamental f_{emi} where f_{emi} indicate the emission frequency (after OYA, 1990).

indicates the evidence of the large free energy injection in the plasmasphere in the time of the large magnetic storms.

2.8 Broad band electrostatic noise (BEN)

The phenomena of BEN have first been reported by GURNETT *et al.* (1976). In the region of the auroral particle precipitation, the electrostatic broad band noises have been identified using the DE-1 satellite data (LIN *et al.*, 1989) and the BEN phenomena have also been identified in the region of the cusp in the height close to the ionosphere by using Viking data (POTTELETTE *et al.*, 1990). The phenomena are very sensitive indicator of the existence of the beam injected through the plasma. As given in Fig. 6, we can see that the broad band emissions are closely associated with the cusp region particle precipitation where large flux of soft electrons are injected.

One of the important new evidences of the observation of the broad band emission which is not necessarily related to the cusp particle precipitation is the case of low latitude precipitation in the time of the large magnetic storms. As has been given also in Fig. 4, there are widely distributed area of BEN in lower latitude than usual cusp and also the auroral particle precipitation regions; the region of the occurrence of BEN is expanded even close to the equatorial region. There are largely enhanced region of broad band emissions in low latitude range suggesting the existence of large flux precipitation of the soft energetic electron even in middle and low latitude regions, in the time of the large magnetic storms.

Fig. 8. An example of EPWAT phenomenon observed on Sept. 14, 1989 in the period of 05:10 to 06:20 UT; the format of the diagram is the same with Fig. 1. In the trend of the upper hybrid mode waves, there is a very intensified portion when the satellite passed through the magnetic equator.

3. Auroral Kilometric Radiations to Detect the Acceleration Region of Auroral Particles

For the studies on the auroral particle acceleration and polar region phenomena, observations of AKR phenomena by PWS on board the EXOS-D satellite are making one of the most remarkable contribution.

After suggestions of the noises from the polar region (BENEDIKTOV *et al.*, 1965; DUNKEL *et al.*, 1970; STONE, 1973), GURNETT (1974) has made first identification of the terrestrial kilometric radiation which is generated in connection with the auroral phenomena. The observational evidences (KAISER and STONE, 1975; KURTH *et al.*, 1975; GREEN *et al.*, 1977; VROOTS *et al.*, 1977; GALLAGHER and GURNETT, 1979; MORIOKA *et al.*, 1981) give a clear feature of AKR as the electromagnetic wave emission generated in the region of the auroral particle accelerations which are formed in the range from 3000 km (BENSON and CALVERT, 1979) to $2 R_E$ (GURNETT, 1974) where R_E is the earth's radius.

Because the generation of AKR is directly related to the acceleration of the particles, the detailed investigation of AKR provides important informations for the environment to generate AKR associated with the magnetospheric sub-storm activities. To understand the back ground condition of AKR generation, however, precise emission mechanism should be clarified for the origin of AKR. The presently well known theory is the cyclotron maser mechanism, original back ground of this theory has been proposed by WU and LEE (1979). In their theory, the most important and unique point is in the resonance condition where they proposed the relativistic situation as

$$\omega - k_{\parallel} V_{\parallel} - \Omega \sqrt{1 - \beta^2} = 0 \quad (2)$$

where $k_{\parallel}$, $V_{\parallel}$, β and Ω are the wave number in parallel to the magnetic field, the particle velocity in parallel to the magnetic field, and the V/c value for the total velocity of the particle V , and angular electron cyclotron frequency, respectively. Along this line of the resonance condition, the studies have further developed by OMIDI and GURNETT (1982, 1984) to cover the case of the real velocity distribution where the trapped particles makes resonance. CALVERT (1982) has proposed laser mechanism where the standing waves of AKR trapped in the cavity region of the plasma, in the acceleration of the auroral particles, make coherent tuning with incoming beam of the auroral particle.

Contrary to this relativistic cyclotron mechanism, there was the proposal of the conversion theory (BENSON, 1975) based on the theory of the generation of the Jovian decametric radiation in terms of the conversion of the electrostatic plasma waves into electromagnetic waves (OYA, 1974); afterwards, Benson has changed his stand point, to support the maser mechanism (BENSON *et al.*, 1980). Based on the studies of the EXOS-D observations of AKR, the conversion theory has been newly proposed by OYA (1990). In the case of the EXOS-D, new results have been obtained in addition to the regular spectra observations. That is, the observations of the polarization and the Poynting vector (MORIOKA *et al.*, 1990) provide important information for the mode of AKR at the source. The studies on the source plasma condition of AKR by using observed upper hybrid mode wave frequency and also the radio wave sounder (OYA *et al.*, 1990) provide important key to check the theory.

The result shows that the AKR source condition has not necessarily fits with plasma conditions required by the cyclotron maser mechanism which has originally been proposed by WU and LEE (1979). The results show that the source conditions are favorable to the

processes of conversion of electrostatic plasma waves into electromagnetic waves (OYA, 1990). That is, in the conversion studies there are three important points:

1) Observed plasma conditions in the source region of AKR in terms of the f_p/f_c value is not necessarily less than 0.1 but very frequently over 0.3; i.e. the result indicates that AKR's are observed clearly even the plasma conditions for the cyclotron maser mechanism is not satisfied.

2) The polarization of AKR is thought simply to be intense R-X mode with weak L-O mode waves in the cyclotron maser mechanism. The studies based on the EXOS-D observation (MORIOKA *et al.*, 1990) however reveal that the waves show L-O mode for the case of weak auroral activities and the mode is changed to the intense R-X mode with weaker L-O mode in the case of the intense auroral activities.

3) Evidence of discrete AKR with the second harmonics has been discovered. This is very new subject whose example is reproduced in Fig. 7 where 2nd harmonics $2f_{\text{emi}}$ of the burst are identified with AKR emissions at the fundamental frequency f_{emi} . The results suggest that the source waves are generated in the form of the local upper hybrid mode waves; and these source mode of plasma waves are converted to electromagnetic waves. The fundamental waves of upper hybrid mode waves in the source region are converted through the linear conversion processes while the 2nd harmonics are possibly converted through the nonlinear coupling processes including three wave interaction of the plasma waves at the upper hybrid mode wave frequency branch (OYA, 1990).

The evidence of polarization of AKR given in the item 2) is consistent with the Doppler conversion processes in the auroral particle precipitation regions (OYA, 1990; OYA and IIZIMA, 1991).

4. Equatorial Region Effects—Enhancements of the Upper Hybrid Mode Waves

One of the most remarkable new finding of the PWS experiments on board the (EXOS-D) satellite is the equatorial enhancements of the upper hybrid mode waves (OYA *et al.*, 1990), which is called EPWAT (Equatorial plasma wave turbulence). An example of EPWAT is given in Fig. 8. The regions of enhancements of the upper hybrid waves are localized in a belt circulating at the magnetic equator forming the disc region like the Saturnian ring (see Fig. 9). The EPWAT phenomena are always observable even in the time of the quiet magnetic conditions; in the intensity of EPWAT, there is however, component which is strictly related to the ΣKp index.

In the period of extremely enhanced magnetic storms, the EPWAT phenomena are also enhanced in its intensity with expansion of region of the occurrence of EPWAT. The EPWAT phenomena are understood as the results of an inherent mechanism to generate free energy of the plasma in the magnetic equator region inside the plasmapause. One of the possible mechanism is inferred to be the plasma drifting across the magnetic field in the direction perpendicular to the magnetic field being caused by the electric field. The transport of the dawn to dusk electric field crossing the plasmapause is plausible mechanism; the drift effects may be raised most effectively at the magnetic equator in the downward direction. Considering the distribution of the EPWAT phenomena, however, it is very likely that there may be the electric field component in radial direction towards or from the earth generating the circular drift motion in the equatorial disc. The drifting plasma across the magnetic field can easily generate the instabilities being coupled with the plasma in the plasmasphere. Precise studies are deferred for future to solve the problems relating to the mechanism of the

Fig. 9. The region of the occurrence of the EPWAT encircling the magnetic equator covering the altitude from 1000 km to 10,000 km (after OYA *et al.*, 1991).

EPWAT, especially relating to the possible existence of the electric fields in the plasmasphere in the magnetic equator.

5. Plasmasphere Structure

After the discovery of the plasmopause by CARPENTER (1963, 1966), the concept of the plasmasphere has been established and plasmopause has been understood as the boundary region which is formed between the co-rotation plasma region and the magnetospheric convection region where plasma escapes by the magnetospheric convection (NISHIDA, 1966; BRICE, 1967).

The plasma distribution in the lower regions of the plasmasphere has been initially studied by ANGERAMI and THOMAS (1964) and by EVIATOR *et al.* (1964) and ANGERAMI (1966) also studied for the trough region. The model has been applied with a modification (AIKYO and ONDOH, 1971) to fit with the plasmopause formation. Observation results of the EXOS-D satellite have indicated that the feature of the wide variety of the plasma distributions which are not able to be simply understood in the frame of the previously established theories and concepts of the plasmopause.

5.1 Disruption of the plasmopause

Along the path of the (EXOS-D) satellite, sometimes, the feature of the plasma distribution shows clear existence of the plasmopause. In Fig. 10, a typical example of the plasmopause when the satellite traverses crossing the relatively lower altitude range has been shown. Though the satellite is in the altitude of 6000 km, we can expand the observed data of plasmopause structure at the level corresponding to the magnetic equator. Very surprising changes take place in the time of the magnetic storms. To see this storm time variation we have selected here the storm period from Oct. 20 to Oct. 23, in 1989, where the largest Dst value of about 300 nT had taken place at 16:00 UT Oct. 21, 1989. As has been given in Fig. 11, there are no remarkable structure of plasmopause in the time of the main phase of the magnetic storm. It was believed from the traditional convection theory that the plasmopause is formed as the result of the plasma convection that makes differential flow between the corotating plasma in the plasmasphere. The theory requires, consequently that the plasmopause can be formed inner side with sharper edge of the density variation with

Fig. 10. Typical example of the plasmopause crossing observed on Oct. 19, 1989 when the Dst value is -28 to -32. The plasma density is obtained from the upper hybrid mode wave frequency.

Fig. 11. The plasma density profile in the case of the main phase of the large magnetic storm on Oct. 20, 1989. No remarkable plasmopause structure can be recognized in the data from 22:35 UT to 24:00 UT though the satellite passed through the region of the plasmopause before the magnetic storm. Two arrows indicate the corresponding positions of the plasmopause before the destruction due to the start of the magnetic storm.

increasing convection velocity associated with the enhancement of the magnetic storms. Contrary to this prediction, the plasmopause observed by PWS on board the EXOS-D satellite shows complete disruption of the plasmopause.

The features of the disruption of the plasmopause have also been confirmed in global range of the plasmasphere of the large magnetic storms. In Fig. 12, where the plasma distribution calculated from the modified diffusive equilibrium theory (OYA and IZIMA, 1991) has been given for the case of Oct. 19 and 20, in 1989 magnetic storm.

Fig. 12. Distribution of the plasma in the plasmasphere calculated by the modified diffusive equilibrium theory starting with the data observed at the EXOS-D satellite position. The number density values are shown with iso-density contours for a) pre-storm time, b) mainphase.

5.2 Ring current effects

In recovery phase of the magnetic storm, there are peculiar variation of the density distribution of the plasmasphere as has been given in Fig. 13a. This plasmaspheric plasma distribution is characterized by the existence of the two enhanced plasma density maxima located in the middle latitude with density depression in the low latitude region centered around the magnetic equator. Looking the shape of the plasma density distribution we call here the feature donkey ears. When this density variation is traced time by time through the main phase of the magnetic storm, the density depression regions are currently in the equatorial region where the upper hybrid mode wave frequency shows rather constant value

Fig. 13(a). The plasma density distribution along the satellite path in the recovery phase of the large magnetic storm which started 18 UT Nov. 27, 1989. Observation has been made from 19:53:30 UT to around 21:00:00 UT, Nov. 30, 1989.

Fig. 13(b). Dynamic spectra of PWS in the same format with Fig. 7. Observation had been made from 02:26 UT to 03:26 UT, on Oct. 23, 1989. Between two maxima at 20:04:30 UT and at 21:33:30 UT, there is a region of the depressed plasma density with relatively constant and steady plasma distribution centered around the magnetic equator where the existence of the ring current was inferred from the magnetic field intensity that largely exceeds the IGRF model.

though the satellite changes the position (see Fig. 13b). Considering the variation of the magnetic field intensity deduced from observed electron cyclotron frequency around this equatorial region, we can conclude that the observations were made inside of the current sheet where the magnetic field intensity increases from the value given by IGRF in the large magnetic storms. In the recovery phase of the magnetic storm, therefore, the plasma possibly starts to fill the region of the ring current where the plasma is confined by the diamagnetic balance conditions and making compression due to the retraction action of the expanded magnetic field towards the dipole type field. When the satellite makes crossing of the enhanced plasma regions as has been indicated in Fig. 14, we can see the two density enhanced regions making the two maxima of the plasma density distribution.

5.3 Large turbulence in the plasmasphere

In the last period of the recovery phase of the magnetic storms, the plasma density distribution inside the plasmopause shows the large turbulent feature as given in Fig. 15, where the density distribution is characterized by large oscillations. Interesting point is that the large oscillations of the plasma density appear in the region where the ring current regions are removed.

The complete theory to understand whole procedure of the storm time plasmasphere is not yet been presented. The EXOS-D results may provide important data for this direction of the studies to establish the real theory of the dynamics that is controlling the plasmopause and plasmasphere structures.

Fig. 14. A model to make interpretation of the compression processes of the plasmasphere in the recovery phase where the region of the strong ring current is removed. i) The magnetic field is largely expanded due to the distortion caused by intense ring current. ii) During recovery phase, the largely expanded magnetic field starts to move to return to the dipole magnetic field by decreasing ring current. The plasma in the flux tube is largely compressed due to retro-action of the magnetic field to return to the dipole magnetic field.

Fig. 15. Large turbulence of the plasmasphere indicated by large oscillation of the upper hybrid wave frequency. The dynamic spectrum is shown with same format with Fig. 7, for the observation of the EXOS-D satellite made from 23:07 UT to 24:07 UT on Oct. 23, 1989.

6. Conclusion

After the successful launching of the EXOS-D (Akebono) satellite, on Feb. 22, 1989, Plasma Wave and Sounder Experiments (PWS) has been providing data with high frequency resolution (1 kHz) for the wave spectra from 20 kHz to 5MHz, time resolution of 2 sec and with threshold of 0.1 μ Volt/m. The results are not only restricted to the wave phenomena but the contribution is widely expanded to the related effects such as the particle precipitation and the free energy input which is generating the upper hybrid mode waves, $(n+1/2)f_c$ emissions and also broad band noises. The plasma density distribution profiles deduced from the upper hybrid mode waves are also providing the data of the plasmasphere indicating the largely disturbed features of the plasmaspheric plasma density which has never been identified in the previous observations.

Wave phenomena in wide variety of the modes are observed:

- 1) Solar type III radio burst,
- 2) Auroral kilometric radiation (AKR),
- 3) Banded Rising and Falling LF waves (BRIFLE),

- 4) Discrete HF emissions,
- 5) Terrestrial Hectometric Radiation (THR),
- 6) Upper hybrid mode waves,
- 7) Z-mode waves,
- 8) Quasi electrostatic whistler mode waves,
- 9) Plasmaspheric odd harmonic $(n+1/2)f_c$ emissions, and
- 10) Broad band electrostatic noises.

AKR is important indicator of the acceleration regions providing the position, motion and range of the distributed acceleration regions. For the detail of the generation mechanism of AKR, the theory has not yet been settled whether cyclotron maser mechanism is operating or the Doppler conversion of the Z-mode waves which are converted from the upper hybrid mode waves is major processes. The PWS data are providing important keys with plasma parameters of AKR sources, such as the plasma density profiles, polarization, and Poynting flux data together with these source conditions. The results show that there are many cases indicating plasma conditions which are consistent with the conversion of Z-mode waves generated by the conversion of the upper hybrid mode waves. Among the plasma waves observed by the EXOS-D satellite, BRIFLE, discrete HF emissions, and plasmaspheric odd harmonic, $(n+1/2)f_c$ emissions are new findings achieved by the PWS observations of EXOS-D. Even for the previously identified subjects there are plenty of newly identified evidences based on the EXOS-D PWS data, for all of the other mode of above listed plasma waves; especially, it is important that the Z-mode waves are always existing associated with the upper hybrid mode waves which also exist in whole range of the plasmasphere in the altitude range higher than 1000 km.

The upper hybrid mode waves show remarkable enhancements at the magnetic equator. A review has been made for this equatorial enhancements of the upper hybrid mode waves (OYA *et al.*, 1990). The enhancements take place at the magnetic equator circulating around the entire plasmasphere ranging from the altitude of 1000 km to 10,000 km (upper limit of the orbit); the enhancements of the turbulent state of plasma circulating entire plasmasphere show the existence of the free energy input in the corresponding regions. The most possible cause of the origin of this free energy input is related to the radial electric field in the equatorial plane which generates the drift motion of the plasma at the magnetic equator. A candidate of this radial electric field is the potential difference between the earth and the magnetosphere.

From the upper hybrid mode waves, the accurate electron density profiles of the plasmasphere are deduced. The density profiles have revealed that the plasmopause is completely disrupted in the time of the large magnetic storms with decreasing electron density and the smoothed gradient of density distribution instead of the sharp edge of the density profile which is usually thought as the typical plasmopause structure. In the main phase of the large magnetic storm, the plasmaspheric odd harmonic, $(n+1/2)f_c$ emissions are observed; the phenomena are not observed in the regular state of the magnetic conditions even the ΣKp value is fairly large. The plasmaspheric odd harmonic phenomena suggest that plasma velocity distributions are largely distorted from the Maxwellian distribution, especially the energy of the plasma is enhanced in the direction perpendicular to the magnetic field. The phenomena also suggest that the large energy is injected from the magnetosphere into the plasmasphere.

In the recovery phase of large magnetic storms, wide variety of the plasma turbulences revealed in the plasmasphere. While the large sharp depression of the plasma density durates

close to the position of the ring currents, there take place the local increments of the plasma density in the higher latitude ranges showing very unusual concave type plasma density distribution. That is, two maxima appear in north and south hemisphere of the plasmasphere, and we call the feature of the plasma density distribution donkey ears type distribution, here. In the phase of progress of the recovery of the magnetic storm, the plasmasphere starts to make retract from expanded feature to the dipole magnetic field controlled feature. During this phase of the contraction, the plasmasphere shows extremely large compression corresponding to the ring current position flux; and in further progress stage the plasma density distribution shows highly irregular feature. The density variation shows the change of 2–5 times increments in terms of the ratio of the maximum value to the minimum value.

The PWS data are thus providing important results not only for the studies on pure wave particle interaction processes but also for the studies on the dynamics of the plasmasphere. The present EXOS-D satellite observation will contribute to understand the whole feature of the energy input and corresponding dynamics of plasmasphere related to the case of extremely large irregularities of the plasma distribution.

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