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MHD wave characteristics inferred from correlations between X-rays, VLF, and ULFs at Syowa Station, Antarctica and Tjörnes, Iceland ($L \sim 6$)

Yo Hirasima[1], Hisashi Shimobayashi[1], Hisao Yamagishi[2], Hiromu Suzuki[1], Hiroyuki Murakami[1], Akihiro Yamada[1],
Takamasa Yamagami[3], Michiyoshi Namiki[3], and Masahiro Kodama[4]

[1] *Department of Physics, Rikkyo University, Nishi-Ikebukuro, Toshima-ku, Tokyo 171-0021, Japan*
[2] *National Institute of Polar Research, Kaga, Itabasi-ku, Tokyo 173-0003, Japan*
[3] *The Institute of Space and Astronautical Science, Yoshinodai, Sagamihara, Kanagawa 229-0022, Japan*
[4] *The Institute of Physical and Chemical Research, Wako, Saitama 351-0106, Japan*

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The Polar Patrol Balloon No. 6 (PPB#6) observed quasi-periodic pulsations of bremsstrahlung X-rays ($E = 30 \sim 120$ keV) in the daytime of 0855 UT (0914 MLT) $\sim$ 1630 UT (1614 MLT) on January 5, 1993, near Syowa Station, Antarctica ($L \sim 6$). The X-ray pulsations near the noon (1208:00 UT (1216 MLT) $\sim$ 1225:04 UT (1232 MLT)) include a period of about 260 sec, which corresponds to Pc 5 magnetic pulsations. It was found that at Syowa Station and Tjörnes, Iceland, which are both pair locations of the geomagnetic conjugacy, the X-ray pulsations are in correlation with the ULF-D pulsations. Also the Tjörnes VLF (2 kHz) pulsations correlated well with the X-ray pulsations of the period corresponding to Pc 5. It is probable that the VLF- and ULF-associated X-rays or precipitating energetic electrons in the vicinity of the $L \sim 6$ shell are in synchronization with the electron-cyclotron resonance. Lastly, the so-called ballooning-mirror instability (the BMI) is a candidate to explain the compressional MHD waves that occur during the short time interval (1216 MLT $\sim$ 1232 MLT) in which the experimental results were interpreted.

1. Introduction

An important mechanism of the energetic electron precipitation into the ionosphere during a substorm, is the electron-cyclotron resonance between VLF waves and trapped electrons in the magnetosphere (Kennel and Petschek, 1966; Park *et al.*, 1981; Kennel and Ashour-Abdalla, 1982; Lazutin, 1986; Kremser *et al.*, 1986; Yamagishi, 1989). From the morning side to the noon side magnetosphere, VLF emissions such as chorus and ELF hiss are often observed after a major substorm activity. These whistler mode type waves have an important role in the loss mechanism of the trapped energetic electrons which are injected from the magnetotail near midnight and drifted eastward to the dayside magnetosphere. General association with VLF emissions and CNA observed on the ground supports this idea of pitch angle scattering of electrons with the whistler mode waves being the main cause of the electron precipitation (e.g., Lazutin, 1986).

It was initially revealed by Barcus *et al.* (1966), Parks (1967), Parks *et al.* (1968), and McPherron *et al.* (1968) that depending on the magnetic local time, bremsstrahlung X-rays, due to the precipitating energetic electrons, exhibit frequently, fast pulsating features. The typical pulsation period is from less than 1 sec to about 10 sec in the magnetic local time sector of midnight to dawn. These fast pulsations are closely associated with VLF pulsations (e.g., Rosenberg *et al.*, 1981). Moreover, X-ray pulsations with longer periods (>10 sec) have also been observed. Many kinds of X-ray pulsations were described by Lazutin (1986) and Yamagishi *et al.* (1985). The association of the pulsating nature in magnetic fields, VLF emissions, and energetic particle precipitation has been an interesting subject from the view points of magnetic pulsation study, as well as studies in the wave-particle interaction in the magnetosphere. With respect to the comparatively fast pulsations, there have been many balloon experiments conducted to study this subject. There have also been studies which show a good correlation between particle precipitation, whistler mode waves, and magnetic pulsations. In particular, Yamagishi *et al.* (1985) have presented pulsation features of three different phenomena with a long period ($20 \sim 30$ sec). Briefly, after analyzing X-rays, VLF emissions, and Pc 3 magnetic pulsations, they have found a clear correlation among them. However, for long-period pulsations like Pc 5, there have been no successful works which show a relationship between energetic electron precipitation, whistler mode waves and magnetic pulsations.

With respect to the magnetic pulsations of Pc 3–4, Sato (1980), Yamagishi *et al.* (1985), and Fukunishi (1987) pointed out that MHD waves of the compressional mode penetrate into the magnetosphere and propagate toward the earth. It is noticeable that the compressional MHD waves are excited when conditions are satisfied.

In this paper, we analyze the bremsstrahlung X-rays observed by the Polar Patrol Balloon No. 6 (hereafter referred to as PPB#6) launched from Syowa Station, Antarctica. The balloon and the ground-based stations, the geomagnetically conjugate pair of Syowa Station and Tjörnes, Iceland ($L \sim$

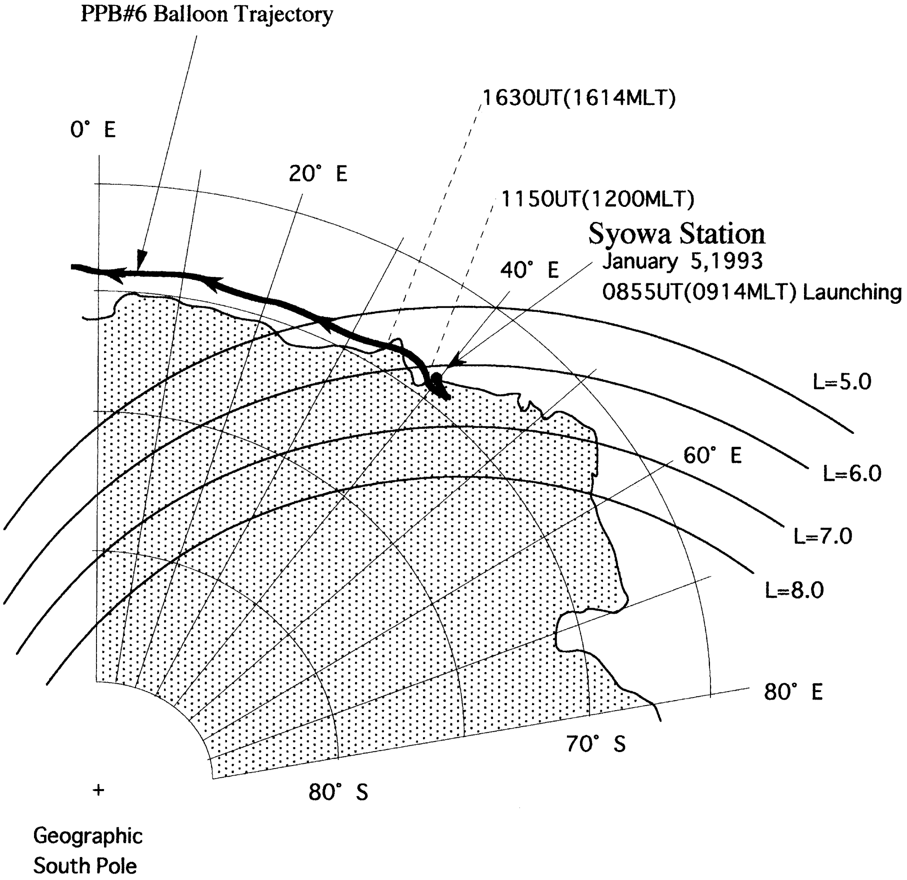

Fig. 1. The initial portion of the trajectory of the PPB#6 balloon launched from Syowa Station ($L = 6.1$) is illustrated by a thick line with arrows on the geographic coordinates. UTs and MLTs at the real time observation are indicated in the figure.

6), observed a good correlation between X-rays, VLF emissions and magnetic pulsations in the Pc 5 frequency range. These are especially notable in the results of Fig. 5 which follows.

Numerous works with respect to long-period ULF pulsations and/or energetic particle flux oscillations in the equatorial plane have been presented (e.g., Kokubun *et al.*, 1977; Kremser *et al.*, 1981; Kokubun, 1985; Higuchi *et al.*, 1986; Takahashi *et al.*, 1990a,b). Also, MHD wave characteristics have been discussed on the basis of ELF and/or ULF wave observations made from geomagnetically conjugate pair stations (e.g., Sato and Kokubun, 1980; Tonegawa and Fukunishi, 1984).

However, since bremsstrahlung X-ray enhancements are strongly related to energetic electron precipitation, bremsstrahlung X-ray observation with stratospheric balloons in the auroral zone is another powerful method to research the correlation between long-period ULF pulsations and energetic electron precipitation. Then a research in the wave-particle interactions in the magnetosphere is able to be advanced.

2. Balloon Flight and Instrumentation of X-Rays, VLF, and ULFs

PPB#6 was launched from Syowa Station on January 5, 1993 and accomplished one and a half circumpolar flight over Antarctica within 27 days (Yamagami *et al.*, 1994). Regular data acquisition of the PPB#6 was made by the ARGOS beacon onboard the balloon with a sampling interval of 30 s. The sampled data were collected by the ARGOS system onboard NOAA satellites when the satellite came over the balloon. Global characteristics of the auroral X-rays were already derived using a bulk of 30-sec data after the whole flight of 27 days had been performed (Kodama *et al.*, 1995; Suzuki, 1996). Besides this basic data acquisition, real-time telemetry of 1-sec was obtained. This was possible when the balloon was within the telemetry range from Syowa Station. These 1-sec data covered the dayside period from 0855 UT (0914 MLT) to 1630 UT (1614 MLT) on January 5, 1993. In this paper, we analyze the bremsstrahlung X-ray data obtained during this real-time telemetry. Figure 1 shows the initial part of the PPB#6 trajectory. Real-time telemeter data were available at 1630 UT, about 8 hours after the launch, when the balloon was located within ~300 km from Syowa Station. The balloon traversed an L-value range of 5.5~6.5 during the real-time telemetry period when the 1-sec data were obtained. UT and MLT values of three selected locations on the trajectory were also marked. These three locations denote the start and end sites of real time observation, and the MLT noon site. Time differences between UT and MLT during the period from 0855 UT to 1630 UT were as small as 6~38 min.

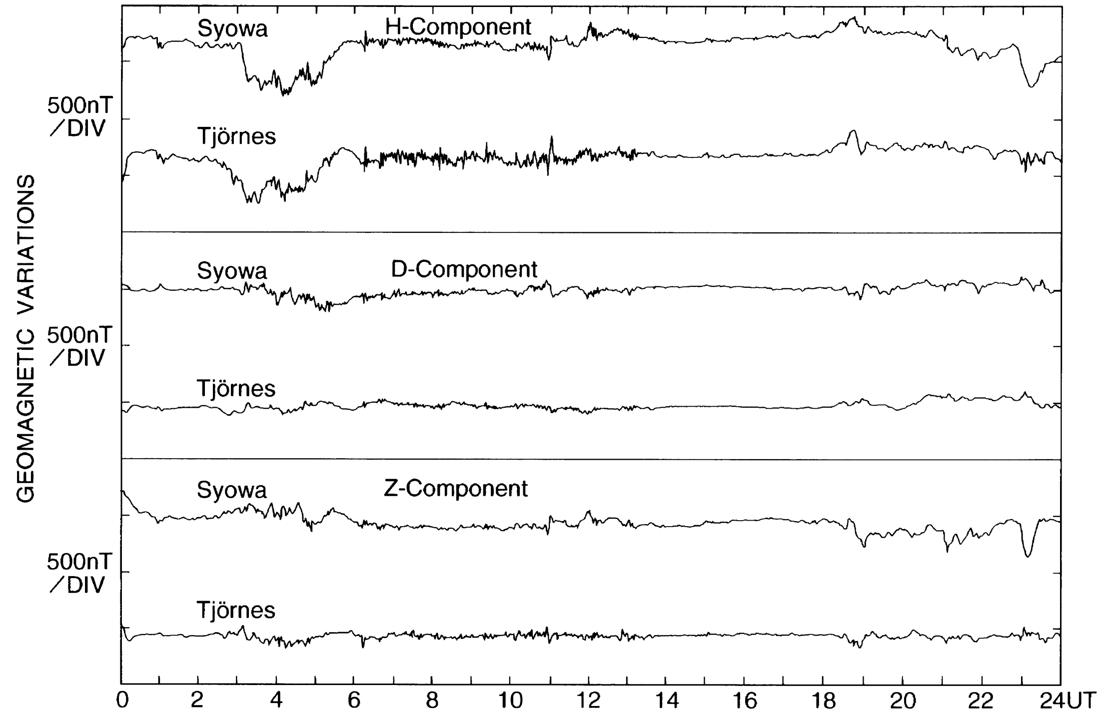

Fig. 2. The H-, D-, and Z-components of magnetograms at Syowa Station and Tjörnes are traced. The analyzed events occurred near the noon. Geomagnetic variations persisted until about 1330 UT. Geomagnetisms at the two stations were comparatively calm after around 1330 UT.

The X-ray instrument onboard PPB#6 was equipped with the omnidirectional X-ray detector, consisting of the NaI(Tl) scintillator with a diameter of 2 inches and a thickness of 5 mm. The opening angle of the instrument is 165° with a geometrical factor of 52.7 cm^2 str. The energy range of the detector was 30~120 keV. The representative 2 kHz VLF emission data measured by the triangle-shaped, three-turn loop antenna (10 m in height, 20 m in bottom length) were used in comparing with the other data. The search coil sensors (permalloy cores with 4000 turns of 0.4 mm diameter copper wires) were operated to measure ULF pulsation components in the frequency range of 0.001~3 Hz.

3. Experimental Results and Analysis

Figure 2 shows 3-component magnetograms of Syowa Station and its geomagnetically conjugate point, Tjörnes in Iceland on January 5, 1993. A geomagnetic disturbance of considerable magnitude (-500 nT in the H-component) occurred at 03 UT at both the stations. This was followed by geomagnetic pulsations which continued until about 13 UT. Another moderate disturbance was found at 1055~1240 UT.

Figure 3 shows a time profile of X-ray counting rates in the time interval of the balloon ascent to the telemetry fade-out (panel (a)), together with the ground-based observation of VLF emission intensity at 2 kHz observed at Tjörnes (panel (b)) and time derivatives of the magnetic D-components (ULF-Ds) observed at Tjörnes (panel (c)) and Syowa Station (panel (d)). The X-ray counting rates before 11 UT were small because the balloon did not reach the ceiling altitude and so, the thick atmosphere absorbed the X-rays. The X-ray counting rates from 11 UT to 13 UT show burst pulsations. The counting rates greatly increase after 13 UT and show large amplitude with slow variation. The burst pulsations still remain after 13 UT, but the superposed fluctuating amplitude becomes smaller as time progresses.

The most significant pulsative events of X-ray counting rates in panel (a) of Fig. 3 were observed in the period of 1208 UT (1216 MLT)~1233 UT (1239 MLT) ($L \sim 6$), as marked by the double arrows in panel (a) of Fig. 3.

It must be noted that in panels (c) and (d) of Fig. 3, the strong magnetic pulsation persists until 1310 UT, and it becomes calm afterward. A similar feature is found in the temporal variation of VLF intensity in panel (b) of Fig. 3. Strong pulsation activity before 13 UT is common with X-rays, VLF and ULF-Ds. This suggests that these three phenomena, i.e., energetic precipitating electrons, whistler mode VLF emissions, and geomagnetic pulsations, are interrelated. To make this point clear, these time profiles are displayed in the extended time scale as shown in Fig. 4. In panel (a), the X-ray counting rates show pulsations with a period of about 5 minutes. It must be noted that the pulsations form a group of pulse train, consisting of 5 pulses. They are found within 1208~1233 UT as marked by the arrows. Each pulse is numbered from 1 to 5. A similar pulsation period and pulse train structure are found in the VLF intensity panel (d). Panel (b) shows the H-components of the fluxgate magnetometers at Syowa Station (thick line) and Tjörnes (thin line). Presented in panel (c) are the D-components observed at Syowa Station and Tjörnes. (Pulsations of the D-components were complicated as described later.) We used this display in order to show the phase relation of the geomagnetic pulsations at the conjugate points. A pulsation period of about 5 minutes,

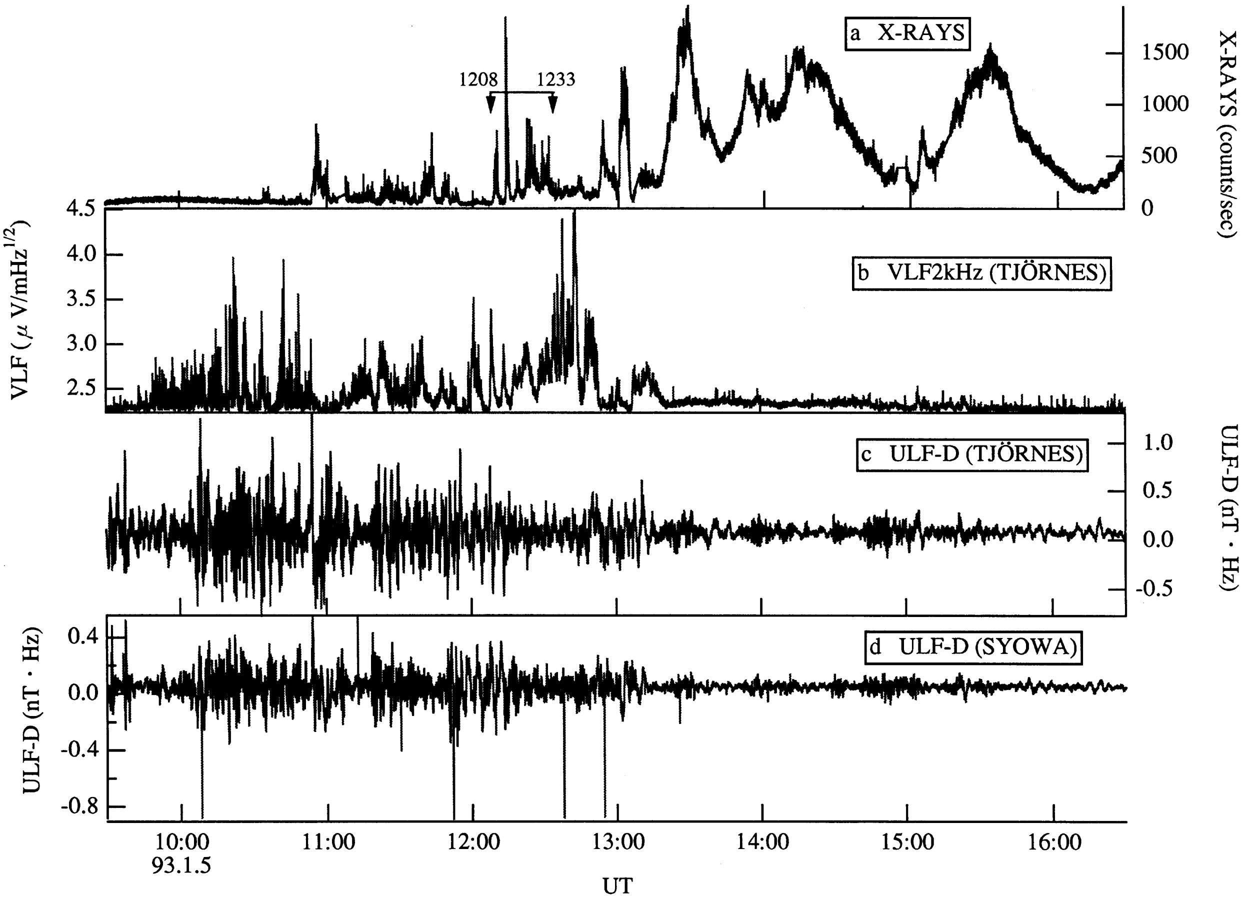

Fig. 3. Time profiles of (a) bremsstrahlung X-ray counting rates observed with the balloon near Syowa Station (the balloon reached a ceiling altitude at about 1030 UT), (b) representative 2 kHz VLF emissions at Tjörnes, Iceland, (c) 0.001~3 Hz ULF-D pulsations at Tjörnes, and (d) 0.001~3 Hz ULF-D pulsations at Syowa Station during 0930~1630 UT on January 5, 1993. The time interval in which typical quasi-periodic pulsations were analyzed is indicated by the double arrows in the top panel.

common to X-ray and VLF pulsation, can be found in both the H- and D-components. The field line resonance theory (Sugiura and Wilson, 1964; Chen and Hasegawa, 1974) tells that the phase relation of the fundamental mode (odd mode) is in phase in the H-component and out of phase in the D-component as observed at the conjugate points. Our observations show that both the H-components at the conjugate pair sites are in phase. But the D-components are not as simple. They are in phase at the beginning of the pulse train, but become out of phase near the end of the train.

Next, the power spectral analysis of the bremsstrahlung X-rays and ULF-D pulsations at Syowa Station and Tjörnes was performed for the selected time interval of 1208:00~1225:04 UT (2^{10} sec) (1216~1232 MLT). The planetary 3-hourly index K_p was 3+ in 1200~1500 UT. Figure 5 shows the power spectra by the FFT (fast Fourier transformation) method of X-rays and both ULF-D pulsations at Syowa Station and Tjörnes. The power densities are represented as functions of frequencies. Apparent peaks at a frequency of 3.9 mHz (the 260 sec period corresponding to Pc 5) were found in the three measurements; X-rays, Syowa and Tjörnes ULF-Ds. The power spectrum of VLF waves at Tjörnes is also shown in Fig. 5, indicating a peak at a frequency of 3.9 mHz. It is of interest that the peaks in the X-ray power spectrum are synchronous with those of the ULF-D pulsations and the VLF emissions in the Pc 5 period. This is the first important experimental evidence that the four power spectra of X-rays, ULF-D pulsations, and VLF emissions are well synchronized in Pc 5 with each other in covering two geomagnetically conjugate locations of the northern and southern hemispheres.

4. Discussion

4.1 Interpretation of the geomagnetic pulsation phase analysis

Let us take notice of a series of X-ray pulsations in the interval of 1208~1233 UT. The field of view of the X-ray instrument shows that the energetic electron precipitation took place within about 60 km from the balloon position, which was in turn located at about 50 km west of Syowa Station. Therefore, both the balloon and Syowa Station were inside this pulsative precipitation region, and the ionosphere in this precipitation region experienced periodic enhancement of ionization.

Being synchronized by these X-ray pulsations, the H- and D-components of the fluxgate magnetometer at Syowa Station and Tjörnes showed pulsations. It must be noted that the H-components at Tjörnes and Syowa Station were in phase all through this time interval. On the other hand, the D-

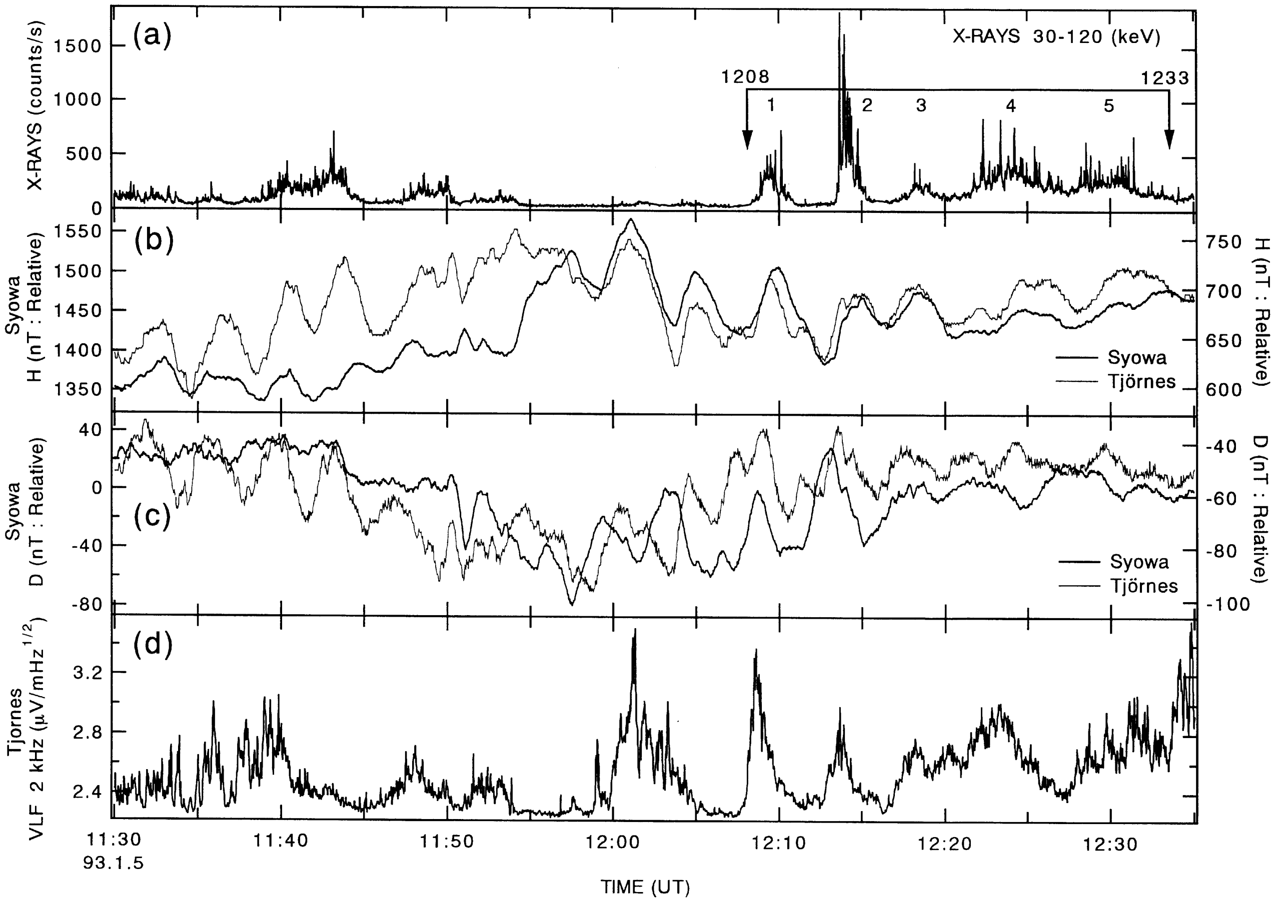

Fig. 4. Extended time profiles of X-rays measured with the balloon very close to Syowa Station, the H- and D-components at Syowa Station and Tjörnes, and Tjörnes VLF emissions. Bremsstrahlung X-ray counting rates are shown in panel (a) in Fig. 4 (referred hereinafter as Fig. 4(a)). Five peaks numbering as 1~5 in Fig. 4(a) were observed in the time interval of 1208 UT~1233 UT. The H-components at both conjugate locations, Syowa Station and Tjörnes, are shown in panel (b). In panel (c), the D-components are presented. The phases at the conjugate sites were complicated. See text as for a detailed description. Panel (d) indicates 2 kHz VLF waves at Tjörnes.

component at Syowa Station was almost in phase in the first half, but became almost completely out of phase in the latter half of the time interval. In general, the phase relationship of the field line resonance for the fundamental mode (odd mode) as observed at the conjugate point is in phase in the H-component but out of phase in the D-component. The observed phase relationship in the H- and D-components at the conjugate points suggests that the observed magnetic pulsation was not caused by the field line resonance, but by the inductive effect of the ionospheric current increased periodically by the enhanced conductivity due to the periodic particle precipitation. If we consider along this conductivity enhancement, the coincidence of having an X-ray enhancement and an H-component increment at both Tjörnes and Syowa Station suggests that both sites were in the afternoon cell of the polar ionospheric convection, i.e., in the regions of eastward currents at the geomagnetic latitude of 66° (corresponding to $L = 6$). In fact, Hall and Pedersen conductivities of the ionosphere increase when an X-ray enhancement occurs (Oguti and Hayashi, 1984; Ebihara *et al.*, 1996). Moreover, in the first half of the analyzed term, the H- and D-components at Syowa Station (thick lines in panels (b) and (c) of Fig. 4) are almost out of phase. This means that the magnetic pulsation was linearly polarized. One criterion to distinguish the induction field of the ionospheric current from the field due to the MHD waves propagated from the magnetosphere is that the former is linearly polarized, while the latter is elliptically polarized except near the resonance field line. The linearly polarized feature of the magnetic pulsations observed at Syowa Station is consistent with inductive effect of the ionospheric current caused by the electron precipitation. So, it is probable that the long-period electron precipitation pulsation is origin of the long-period magnetic pulsation.

The global circumpolar ionospheric convection current in the southern hemisphere flows almost eastward at the noon in the afternoon current convection cell. Just after the MLT noon, absolute values of the H-component are greater than those of the D-component as shown in panels (b) and (c) of Fig. 4. This is reasonable, considering the usually acceptable global circumpolar plasma convection vortexes (e.g., Nagata and Kokubun, 1962; Heppner and Maynard, 1987). At the geomagnetic latitude of 66° in both polar hemispheres, the plasma flow and the electric current do not display so much change, as it is below moderate activity.

In addition, it is noticeable that the magnetic phase rela-

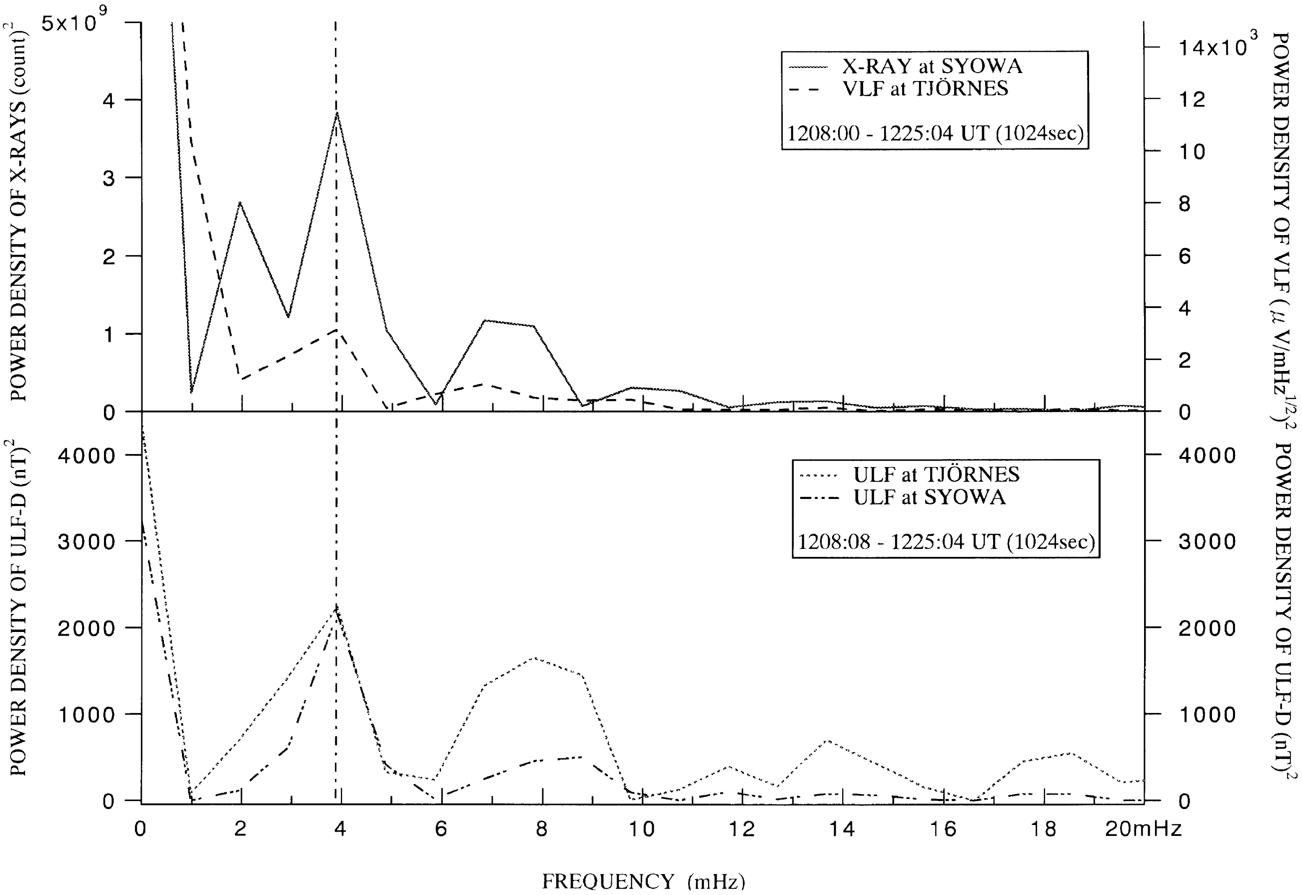

Fig. 5. Power spectra of X-rays, Syowa ULF-D pulsations, Tjörnes ULF-D pulsations, and Tjörnes VLF emissions. The time interval analyzed is 1208:00~1225:04 UT. At the conjugate locations of the southern and northern polar regions, the peak of the X-ray power spectrum at 3.9 mHz (260 sec period corresponding to the Pc 5) is synchronous with the peaks in the power spectra of ULF-D pulsations, and also in the VLF emissions.

tions of the H- and D-components at the two geomagnetically conjugate pair sites were not stable, but these changed in the time interval of 1208~1233 UT.

4.2 The power spectra and Pc 5 synchronization

As seen in Fig. 5, each of the power spectra of X-rays, VLF emissions, and ULF-D pulsations, has its respective peak at the frequency of 3.9 mHz (corresponding to Pc 5). Sato (1980) analyzed ELF-VLF waves and ULF waves at the geomagnetic conjugate pair stations at high latitudes, and then proposed the model of quasi-periodic VLF emissions modulated by compressional mode Pc 3–4 magnetic pulsations. Furthermore, Yamagishi *et al.* (1985) presented correlations between VLF emission pulsations, ULF pulsations, and X-ray pulsations by ground and balloon observations at conjugate locations. The period of their pulsations was concerned with Pc 3. They suggested the electron-cyclotron resonance between VLF emissions and trapped energetic electrons. Moreover, they revealed compressional mode Pc 3 waves. However, it should be noted that our new correlation analysis especially containing pulsative X-rays is related with the longer period corresponding to Pc 5.

4.3 The ballooning-mirror instability as a possible candidate for interpretation

There was almost one to one correspondence between pulsative X-ray enhancements and the intensifications of the VLF emissions at the 2 kHz band. This coincidence suggests a pitch angle scattering of the energetic electrons by the whistler mode waves in the magnetic equatorial plane. When the magnetic field intensity in the magnetic equatorial plane varies periodically for some reason, the growth rate of the whistler mode waves is modified and their intensity also changes periodically. This in turn modifies the pitch angle scattering rate, and the precipitating electron flux varies periodically. This process is shown in the block diagram of Fig. 6, where δB is the pulsative component of the magnetic field intensity in the magnetic equatorial plane, and $\delta W_\perp$ is the pulsative component of perpendicular electron energy $W_\perp$ ($W_\perp = p_\perp^2/2m_e$, where m_e is the electron mass, and $p_\perp$ is the electron momentum component perpendicular to the magnetic field). A magnetic moment $W_\perp/B$ of gyration electrons, the first adiabatic invariant, is constant. The whistler mode wave growth due to the electron-cyclotron resonance in the equatorial region gives a decrease in $W_\perp$, i.e., $\delta W_\perp$ is converted to the whistler mode waves. A trapped gyration electron with $W_\perp - \delta W_\perp$ enters into the loss cone, and then generates bremsstrahlung X-rays in the upper atmosphere. In other words, the electron-cyclotron resonance is related to a compressional ($|\delta B| > 0$) MHD wave.

Then, what causes the periodic variation in the magnetic field intensity in the magnetic equatorial plane? Field line

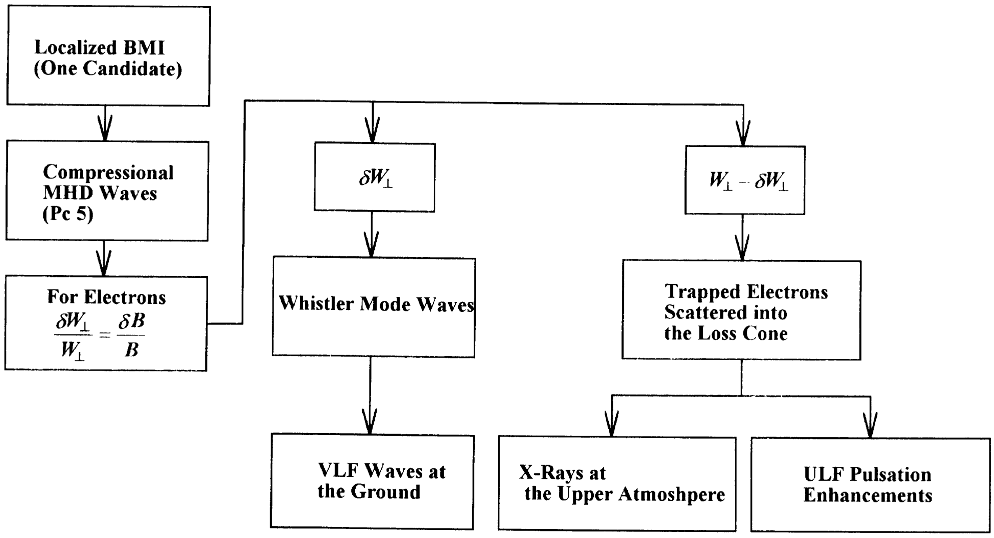

Fig. 6. Block diagram description of geophysical processes which explain the analyzed event in the present work. B is a geomagnetic field strength, and $W_\perp$ is an energy determined from an electron momentum component perpendicular to the geomagnetic field. δB and $\delta W_\perp$ are increments of these quantities.

resonance of shear Alfvén waves is ruled out because shear Alfvén waves do not change the magnetic field intensities. One candidate is the compressional Alfvén mode, often observed in the afternoon magnetosphere and called "stormtime Pc 5". This mode can be excited by the ballooning-mirror instability (hereafter, referred to as the BMI) (e.g., Hasegawa, 1969; Higuchi *et al.*, 1986; Miura *et al.*, 1989; Takahashi *et al.*, 1990a; Cheng *et al.*, 1994). The BMI model is discussed as one possible candidate in the present work. The X-ray enhancements at Syowa Station and the VLF waves at geomagnetically conjugate Tjörnes suggest the electron-cyclotron resonance at the equatorial region. Because X-rays, VLF waves, and ULF-D pulsations were synchronized in the period corresponding to Pc 5 in the present experiment, and the D-component phases at Syowa Station and Tjörnes were disturbed as shown in panel (c) of Fig. 4, it seemed that an instability occurred at a localized equatorial region of $L \sim 6$ for about a quarter of an hour. Possibly the MHD waves accompanied with the BMI were a compressional mode. Theoretical works on MHD waves with respect to the BMI in the magnetosphere have recently been developed by numerous researchers (e.g., Miura *et al.*, 1989; Ohtani *et al.*, 1989; Chen and Hasegawa, 1991; Cheng and Qian, 1994; Cheng *et al.*, 1994; Hurricane, 1997; Sundaram and Fairfield, 1997; Treumann and Baumjohann, 1997).

It was experimentally suggested by Ullaland *et al.* (1993) that the BMI occurs on the nightside substorm onset at 6.6 R_E of the geomagnetic equatorial plane and triggers the loading phase of the substorm. However, Cheng *et al.* (1994) discussed and suggested the BMI for the dipole model which is symmetric with respect to the nightside and the dayside. Therefore, it seems that the BMI is able to occur in the global region, regardless of the nightside or the dayside. The noon side is especially remarkable as the geomagnetic reconnection process occurs frequently in active time like in the midnight side. Furthermore, the particles are accelerated in both reconnection regions (e.g., Terasawa and Nishida, 1976; Nishida, 1978; Saunders, 1991; Hughes, 1995). Lin *et al.* (1988) observed geomagnetic pulsations and fluxes of energetic electrons and protons in the equatorial zone, and discussed propagation of the compressional Pc 5 waves. They did not deny the possibility of the BMI, but urged that it should be a problem to be researched continuously.

As for the correlations between PPB#6 X-rays, VLF emissions, and ULF-D pulsations in the present work, we note that the pulsative events of interest occurred near 1200 MLT of the dayside. Takahashi *et al.* (1990b) found that a proton (68~100 keV) flux oscillation was measured in 6.5~6.9 R_E, at about 1300 MLT, near the noon, and that this flux oscillation was associated with the Pc 5 magnetic pulsation acceptable to the BMI model in the equatorial zone. In plasmas, a proton flux oscillation is accompanied by an electron flux oscillation. Moreover, energetic electrons with small pitch angles in the equatorial region are easy to precipitate into the upper atmosphere by pitch angle scattering into the loss cones. Kokubun *et al.* (1977) indicated that an energetic electron flux variation is associated with Pc 5 MHD waves in the region $L = 6 \sim 11$. They pointed out that the energetic electron flux oscillations were in phase with the compressional Pc 5 waves. Syowa Station and Tjörnes are close to both foot points of the geomagnetic field line through about 6 R_E of geomagnetic equatorial plane. The L value in our case is close to the L value in which the above-mentioned particle flux oscillation occurred.

Thus, generation of the compressional Pc 5 MHD waves in the equatorial region is possible. The electron-cyclotron resonance then occurs. Trapped energetic electrons are scattered into the loss cone when the pulsative component of perpendicular electron energy, $\delta W_\perp$, finally converts to the whistler mode VLF waves as a result of the electron-cyclotron resonance. In particular, as seen in Fig. 6, the following matter must be notable; the compressional MHD waves with the

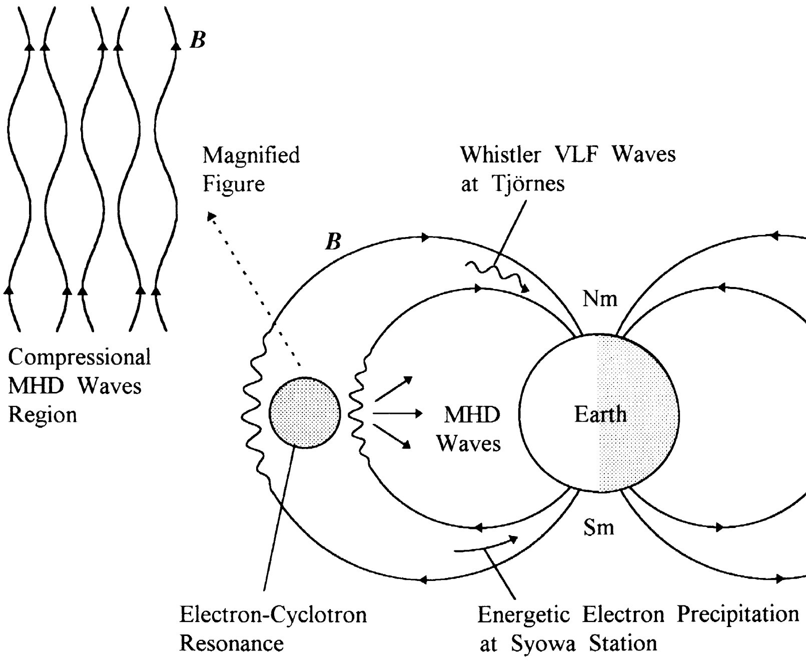

Fig. 7. Schematic diagram illustrating the compressional MHD waves and the electron-cyclotron resonance between the trapped energetic electrons and the whistler mode VLF waves. Compressional MHD waves in the localized equatorial region are magnified.

Pc 5 period consistent with the BMI are the origin of the pitch angle scattering of the trapped energetic electrons in the equatorial zone which are concerned with the electron-cyclotron resonance. Then, the bremsstrahlung X-ray pulsations in the Pc 5 period are observed in the upper atmosphere. Also Cheng *et al.* (1994) who have suggested the BMI have indicated many events of the compressional mode of MHD waves. Therefore, it is possible that the BMI is a candidate for the MHD wave model, in which the pulsative X-rays, ULF pulsations, and VLF emissions at the conjugate pair sites of the $L \sim 6$ were synchronized at the Pc 5 period for about a quarter of an hour.

5. Summary

With respect to correlations between X-rays, VLF emissions, and ULF pulsations, the important experimental results have been indicated. The geophysical processes inferred from the present experimental analysis have then been described, consulting many other theoretical and experimental researches in the discussion process.

Peaks of power densities of the bremsstrahlung X-rays and VLF waves at the geomagnetically conjugate sites were observed with a period of Pc 5. Also ULF-D pulsations at both conjugate stations were synchronized with the X-rays and the VLF waves for about a quarter of an hour at the MLT noon.

A schematic picture describing the geometrical configuration of the processes is illustrated in Fig. 7, which should be considered together with Fig. 6. In the present work, the compressional mode of the MHD waves were generated in the localized equatorial region of $L \sim 6$, where the electron-cyclotron resonance between trapped energetic electrons and whistler mode VLF emissions occurred. The energetic electrons precipitated to the upper atmospheres in both polar hemispheres, and emitted bremsstrahlung X-rays, while the whistler mode VLF emissions propagated to both polar hemispheres. As it seemed that the electron precipitations occurred at both geomagnetically conjugate sites, ULF pulsations enhancements which were modulated with the Pc 5 period, occurred in both conjugate sites.

Compressional MHD waves propagated to both conjugate sites. The pulsative X-rays, VLF, and ULF-Ds happened with the period corresponding to Pc 5. The BMI is one possible candidate which can explain the results of the X-rays, VLF emissions, and ULF pulsations analyzed in the present work.

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Y. Hirasima (e-mail: hirasima@pc.highway.ne.jp), H. Shimobayashi, H. Yamagishi, H. Suzuki, H. Murakami, A. Yamada, T. Yamagami, M. Namiki, and M. Kodama