AURORAL ZONE X-RAY PULSATIONS ASSOCIATED WITH VLF PULSATIONS: B_{15}-3N BALLOON EXPERIMENT

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***Abstract*:** A stratospheric balloon, carrying a NaI (T1) scintillation counter for measuring 20–100 keV bremsstrahlung X-rays was launched from Stamsund (L=5.6) in Norway during the recovery phase of a magnetic substorm. The scintillation counter recorded many examples of X-ray microbursts and pulsations at a ceiling altitude of 7 mb (33 km). The ground-based VLF receiver at Andøya (L=6.1), located at 160 km northeast of Stamsund, and at Syowa Station, Antarctica (L=6.1) observed polar chorus emissions and quasi-periodic (QP) emissions during the balloon flight. In the study of cross correlations between the X-ray and the VLF emissions, it has been found that the X-ray microbursts precede VLF chorus at Andøya by about 1.7 s, while the VLF chorus at Syowa occurred almost simultaneously with the X-ray microbursts. This is qualitatively explained by the nature of counterstreaming type wave-particle interaction and the echoing of whistler mode wave packets in the magnetosphere. X-ray pulsations and rising-tone type QP emissions with periods of 20–30 s showed a good coherency. This similarity suggests that both phenomena are closely related to each other through the cyclotron wave-particle interaction in the magnetosphere.

1. Introduction

Microburst precipitation of energetic electrons is a persistent feature of the dayside precipitation in the auroral zone, which has been observed by bremsstrahlung X-ray detectors on board balloons (ANDERSON and MILTON, 1964; BARCUS *et al.*, 1966; PARKS, 1967), and by energetic particle detectors on board rockets (ANDERSON *et al.*, 1966; LAMPTON, 1967) and polar orbiting satellites (OLIVEN *et al.*, 1968). A close association of electron microbursts and VLF chorus emissions was found by OLIVEN and GURNETT (1968), based on satellite observations. Simultaneous observations of bremsstrahlung X-rays and VLF chorus emissions at the subauroral zone station (Siple, L=4) showed that individual bursts sometimes correspond to chorus

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riser elements with a short time delay (ROSENBERG *et al.*, 1971; FOSTER and ROSENBERG, 1976; ROSENBERG *et al.*, 1981). These facts imply that the cyclotron interaction between energetic electrons and chorus emissions causes a strong pitch angle diffusion of electrons into the loss cone, which is observed as microburst precipitation at the foot of the magnetic line of force.

Precipitation phenomena of energetic electrons in the dayside auroral zone sometimes show fairly regular pulsations with periodicities of several tens of seconds (ULLALAND *et al.*, 1967; PARKS *et al.*, 1968; MCPHERRON *et al.*, 1968). They are called "quasi-sinusoidal pulsation" (MCPHERRON *et al.*, 1968) or "daytime slow pulsation" (BARCUS and ROSENBERG, 1966), distinguished from "fast pulsation" (BARCUS and ROSENBERG, 1966; PARKS, 1967) which is associated with pulsating aurora and appears in the midnight-to-dawn sector. In the daytime, Pc 3 and 4 magnetic pulsations with comparable periods, are often observed on the ground (ULLALAND *et al.*, 1967; BEWERSDORFF *et al.*, 1968; MCPHERRON *et al.*, 1968), and also near the magnetic equatorial plane in the magnetosphere (ARTHUR *et al.*, 1979).

In most cases a general association between magnetic pulsations and precipitation pulsations is recognized, and the frequency analysis shows that coincident spectral peaks appear between them (MCPHERRON *et al.*, 1968). One-to-one correspondence of their wave forms, however, is usually not clear. VLF emissions in the dayside auroral zone are sometimes modulated by magnetic pulsations with periods of several tens of seconds. They are called VLF pulsations or quasi-periodic (QP) emissions (*e.g.* SATO, 1981). These VLF waves can cause a pitch angle scattering of energetic particles in the magnetosphere through the cyclotron wave-particle interaction. Therefore, it is suggested that QP emissions are a possible source for precipitation pulsations. This mechanism was theoretically studied (CORONITI and KENNEL, 1970; CHEN, 1974). Nevertheless, there has been no clear evidence of VLF QP pulsations closely associated with precipitation pulsations until the most recent article by WEST and PARKS (1984).

In this paper we report X-ray microbursts closely associated with polar chorus emissions, and also X-ray pulsations closely associated with rising-tone type QP emissions and Pc 3 magnetic pulsations. The former is the same kind of phenomena as those observed in the subauroral zone (*e.g.* ROSENBERG *et al.*, 1981). However, our observation was carried out in higher latitudes (L=5.0–5.4). The latter is the first clear evidence of the close correlation among X-ray, VLF and magnetic pulsations, which supports the theory by CORONITI and KENNEL (1970).

2. Summary of the Experiment

A balloon B_{15}-3N, whose payload consists of a NaI (Tl) scintillation counter for measuring X-rays of 20–100 keV energy and a 0.2–8.0 kHz VLF receiver, was launched from Stamsund (68°09′N, 13°40′E, L=5.6) in northern Norway at 0632 UT on March 19, 1982 during the recovery phase of an auroral substorm.

Figure 1 shows the flight track of this balloon. The balloon drifted eastward for 4 hours across the Swedish territory, and then the payload was cut down over the middle part of Finland. The balloon reached a ceiling altitude of 32 km at about 0800 UT, henceforth the X-ray observation was available. The ranges of L-value

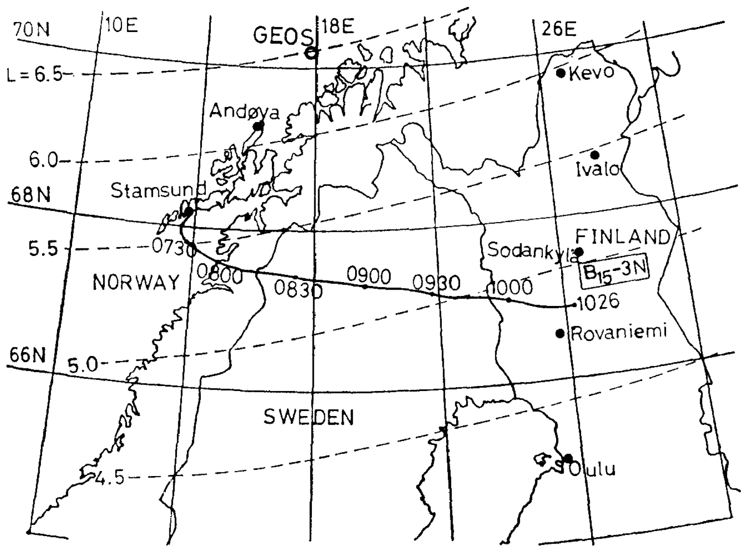

Fig. 1. Flight track of B_{15}-3N balloon, launched from Stamsund at 0632 UT on March 19, 1982. The balloon drifted eastward and the payload was cut down at1 026 UT over the middle part of Finland. The positions of ground-based stations cooperated with this experiment are marked in the figure.

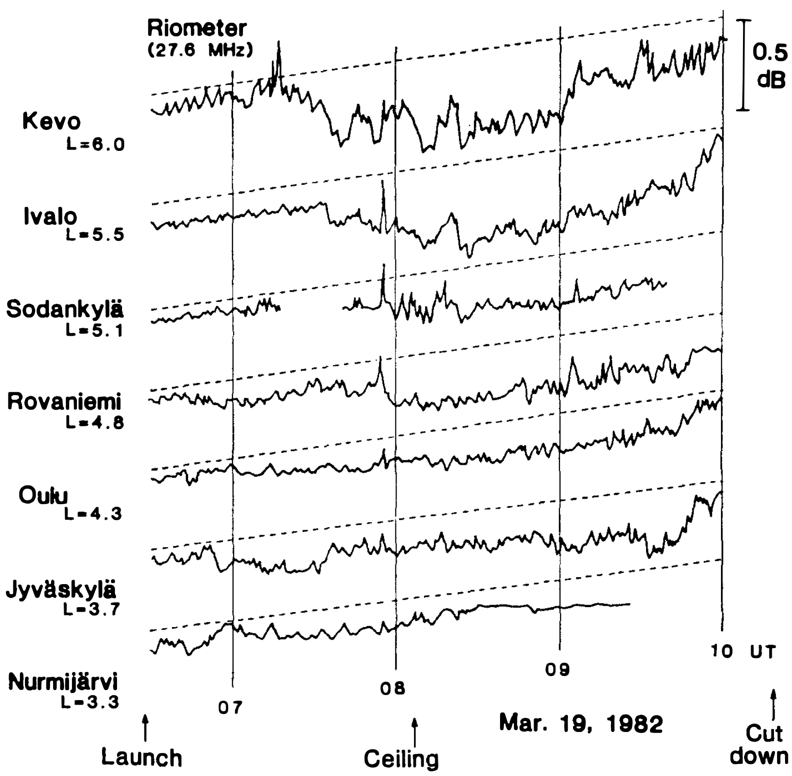

Fig. 2. Cosmic noise absorption (CNA) records of 27.6 MHz from the Finnish riometer network during the balloon flight. The dashed lines indicate the inferred base lines. The times of launching, arrival at the ceiling altitude, and cutting down are marked by arrows. A CNA event at Kevo started at 0730 UT and recovered at 1000 UT. At other lower latitude stations (Ivalo, Sodankylä and Rovaniemi), the CNA event started with a time delay. These data were provided by Dr. H. RANTA, the Geophysical Observatory of Sodankylä, Finland.

and magnetic local time (MLT = UT + 2.0 ~ UT + 2.5 hours) throughout the entire flight are $L = 5.4$ to 4.8, and from 0950 to 1300 MLT, respectively. The signal to noise ratio of the VLF data observed on the balloon was low due to severe telemeter transmitter noise. Therefore, we compared the X-ray data with the VLF data observed on the ground at Andøya (69.2°N, 16.0°E, $L = 6.15$) in Norway. We also used the magnetic pulsation data recorded at Andøya and the riometer data recorded at a chain of stations in Finland. The positions of these stations are marked in Fig. 1.

Figure 2 shows the 27.6 MHz cosmic noise absorption (CNA) recordings from the Finnish riometer network during the flight. The dashed lines indicate the inferred base lines, and the times of launching, arrival at the ceiling altitude, and cutting down are shown by arrows. It is evident in this figure that a CNA event at Kevo started at 0730 UT and recovered at 1000 UT. At other lower latitude stations (Ivalo, Sodankylä and Rovaniemi), the CNA event started with a little time delay. The X-ray detector on board the balloon observed successfully this precipitation event.

In Fig. 3 the time variation of observed X-ray count rate is compared with the CNA recordings at Kevo, Ivalo, Sodankylä, Rovaniemi and Oulu. Enhancements of the X-ray counting rate indicated by dashed lines correspond to increases in cosmic noise absorption, especially at 0810 and 0820 UT when the X-ray showed predominant peaks. The similarity implies that the spatial width of this precipitation event is as

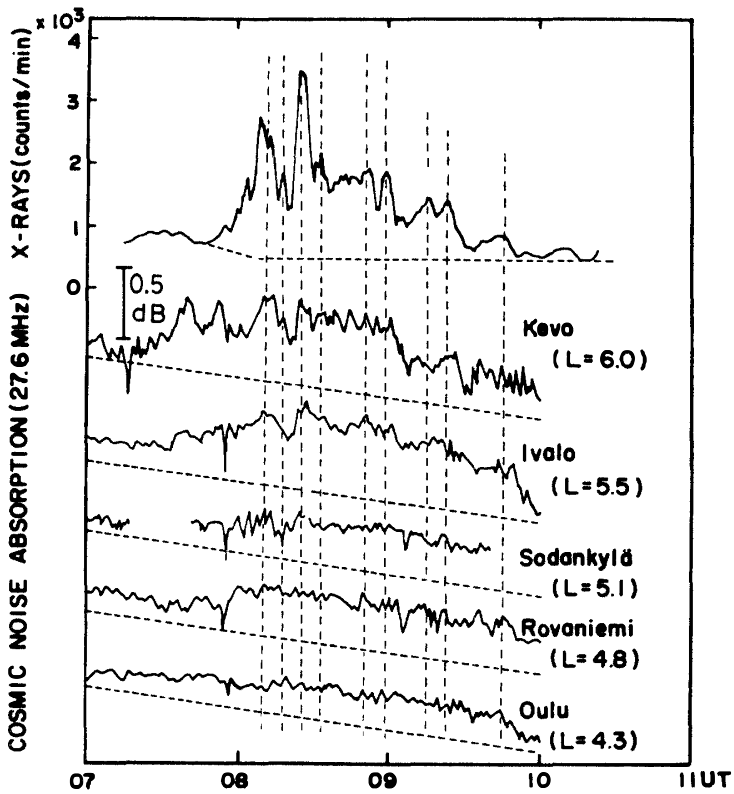

Fig. 3. Comparison of X-ray count rate observed on the balloon with the CNA recordings at Kevo, Ivalo, Sodankylä, Rovaniemi and Oulu. Enhancements of the X-ray counting rate indicated by dashed lines correspond to increases in cosmic noise absorption, especially at 0810 and 0820 UT when the X-ray data showed predominant peaks.

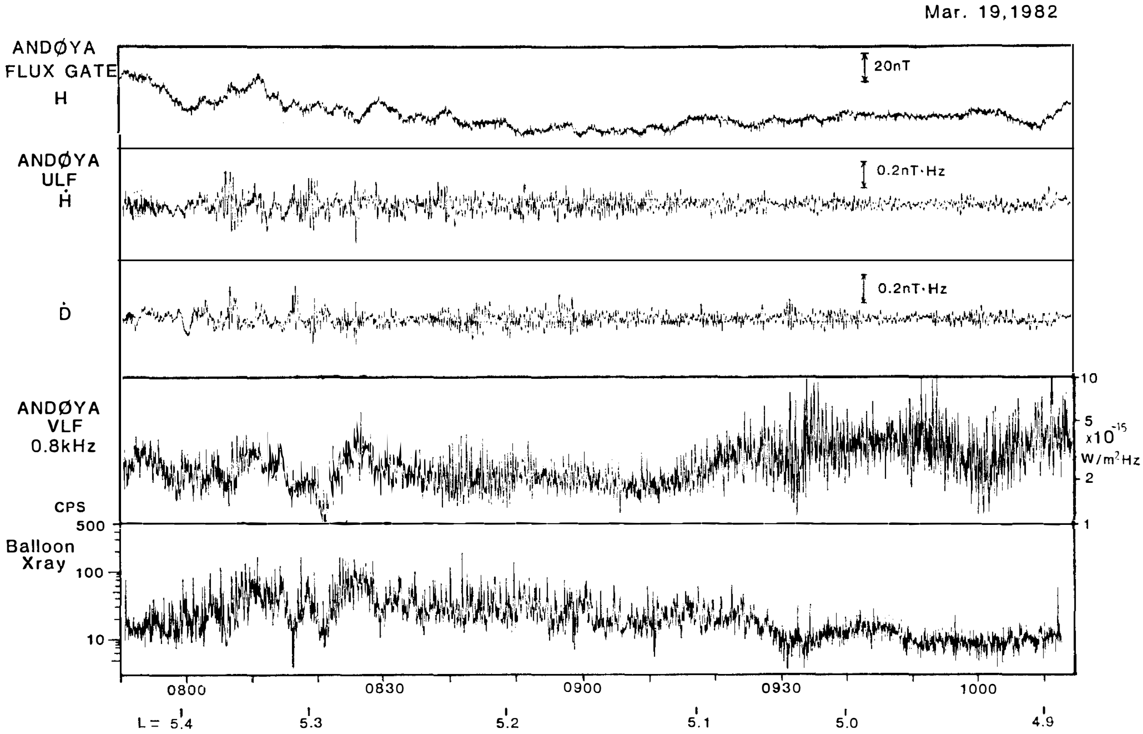

Fig. 4. Data summary of magnetic variation (H-component), ULF magnetic pulsations (H- and D-components) and VLF emission intensity (0.8 kHz) recorded at Andøya, 160 km northeast of the launching place, and count rate (1 s value) of X-ray measured on the balloon. Note that intensity variation of VLF emission is quite similar to that of X-ray.

wide as to cover 15° in longitude and 4.8 to 6.0 in L value (see Fig. 1).

Figure 4 shows the data summary of magnetic variation (H-component), ULF magnetic pulsations (H- and D-components), and 0.8 kHz VLF emission intensity recorded at Andøya, 160 km northeast of the launching place, and count rate (1 s value) of X-ray measured on the balloon. The X-ray count rate is displayed in logarithmic scale. It is evident that the X-ray data show rapid temporal variations. The periods of these variations consist of microbursts of 1 s and pulsations of 20–30 s, though the compressed time scale in Fig. 4 is not enough to find out such periodicities. Note that variations of VLF emission and X-ray are quite similar, suggesting that both phenomena are strongly related through the cyclotron wave-particle interaction in the magnetosphere. Characteristics of these microbursts and pulsation phenomena are studied in the following sections. The magnetic variation record shows occurrences of Pc 5 pulsation with period of $\sim$3 min and slow irregular variations with period of 10 to 20 min. It is found that these variations correspond to the variations in VLF emission intensity and X-ray count rate.

Further information on occurrence of VLF emissions in the magnetosphere is available from the GEOS-2 S-300 experiment on the same day (by courtesies of R. GENDRIN, N. CORNILLEAU-WEHLIN, CRPE and A. BAHNSEN, DSRI). Presented in Fig. 5 is the summary plot of X-ray count rate observed on the balloon, VLF emission records at four frequency bands observed on GEOS-2 and on the ground at Andøya. Slow variations with time scale of 3–10 min are observed synchronously in all of these

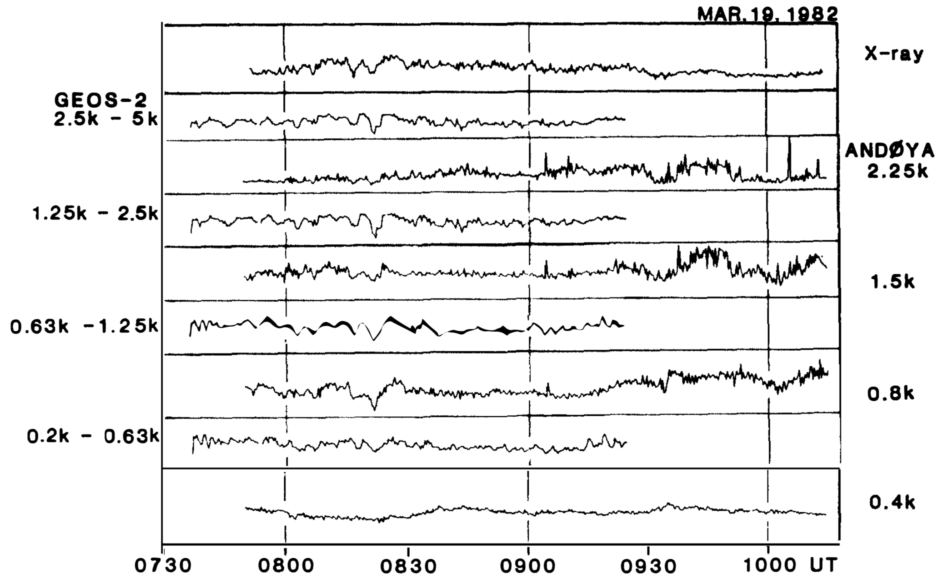

Fig. 5. Summary plot of X-ray count rate observed on the balloon, VLF emission intensity records at four frequency bands observed on GEOS-2 and on the ground at Andφya. At this time GEOS-2 was located at −1.7° in latitude, 33.9° in longitude and 35750 km in altitude. Slow variations with time scale of 3–10 min are observed synchronously in all of these data except the 0.4 and 2.25 kHz band records at Andφya. The GEOS data were provided by N. Cornilleau-Wehlin, CRPE, France and A. Bahnsen, DSRI, Denmark.

data except the records of the 0.4 and 2.25 kHz bands at Andøya. This result suggests that VLF emissions are modulated concurrently in the wide range of L shells from the balloon location at $L=5.0$ to the GEOS-2 locations at $L=6.6$.

3. Microburst Phenomena

During this balloon flight X-ray microbursts with 0.5–2 s spacing were often observed. The VLF receiver at Andøya observed polar chorus bursts. Some of them occurred in association with X-ray microbursts. These two phenomena are compared in Figs. 6 and 7. The upper panel of the figure shows the frequency-time display of polar chorus emission, and the lower panel shows the emission intensity in the 1.5 kHz band and the counting rate of X-ray observed on the balloon in logarithmic scale. The interaction between VLF emissions (whistler mode waves) and energetic electrons in the magnetosphere is of a counterstreaming type, so that the electrons and waves involved in this process go to the opposite hemispheres. Therefore, the VLF emission data observed at the magnetic conjugate point of Scandinavia are very important to understand this process. The VLF data at Syowa Station, Antarctica are available for this event, though Syowa is located 15° in longitude and 1600 km in surface distance westward from the conjugate point of Andøya. In the top panels of Figs. 8, 9 and 10, the time variation of X-ray counting rate is compared with the 1.5 kHz VLF emission intensity records observed at Andøya and Syowa in the time intervals of 0758:40–0759:00, 0803:40–0804:00 and 0840:50–0841:10 UT. In these figures, cross correlation functions between the two of these three data are also

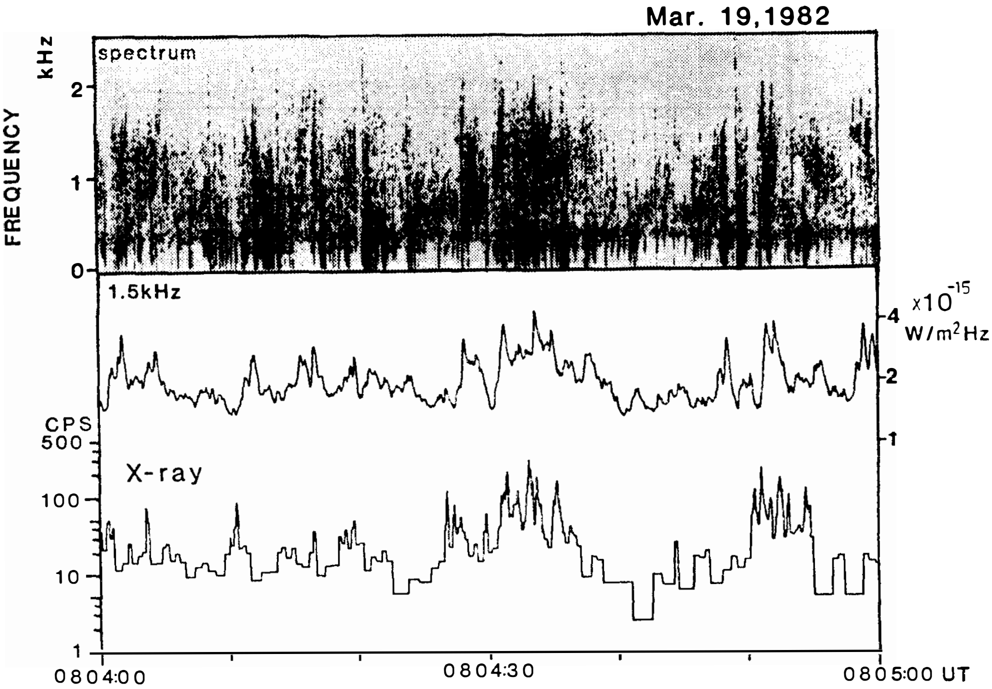

Fig. 6. Comparison of polar chorus emissions and X-ray microbursts in the time interval of 0804–0805 UT. The upper panel shows the frequency-time display of polar chorus emission, and the lower panel shows the emission intensity in 1.5 kHz band and the count rate of X-ray in logarithmic scale. The bursts appear intermittently with a time interval of 20–30 s, resulting in X-ray pulsation and VLF pulsation.

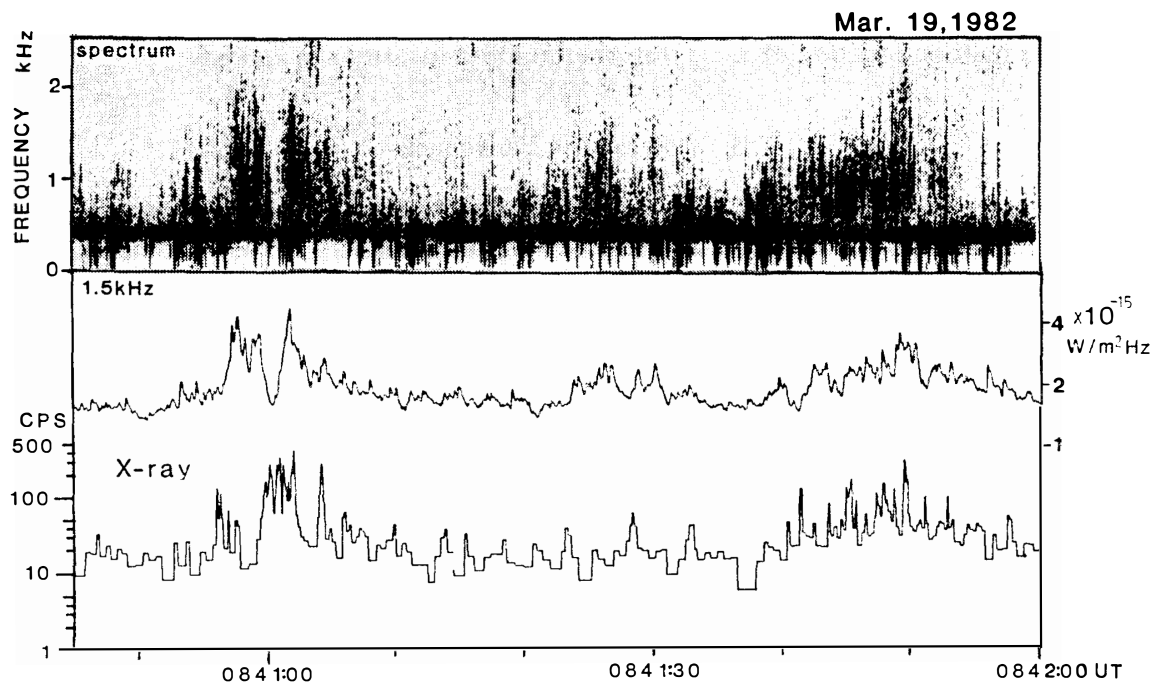

Fig. 7. Same as Fig. 6, except for the time interval of 0840:45–0842:00 UT.

shown. The second panels show the cross correlation functions between VLF emission at Andøya and X-ray, and the third panels show the ones between VLF emission

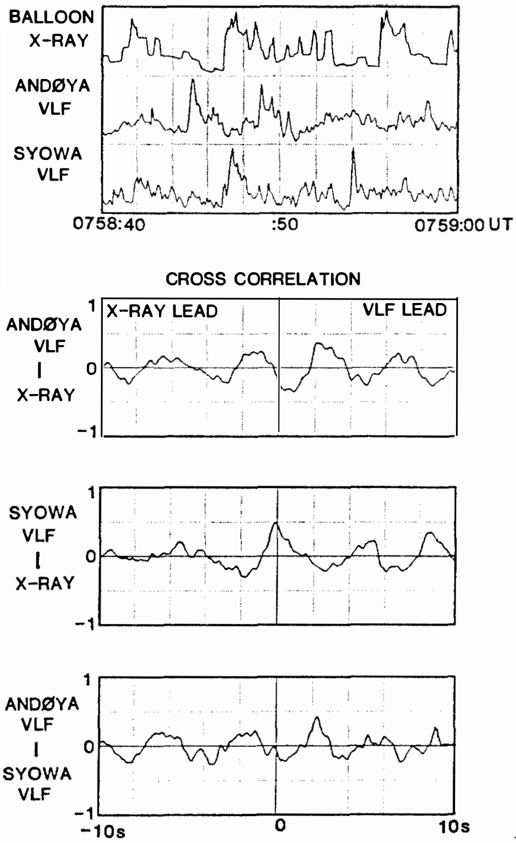

Fig. 8.

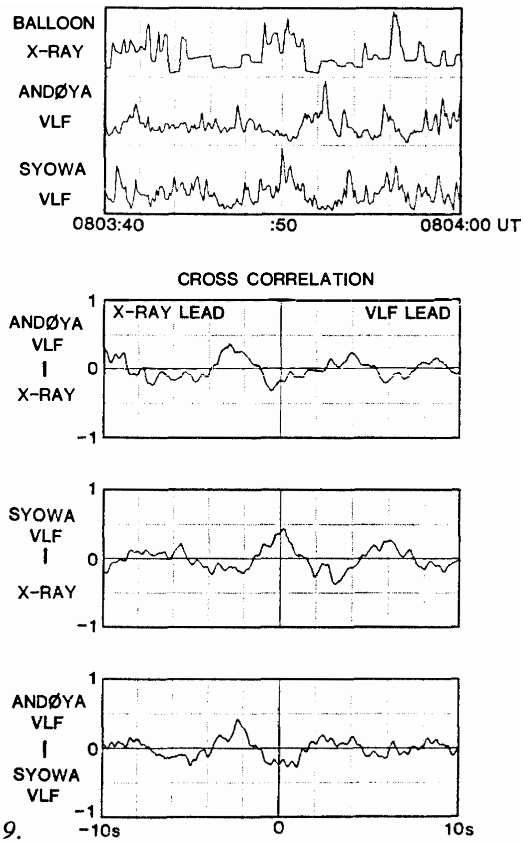

Fig. 9.

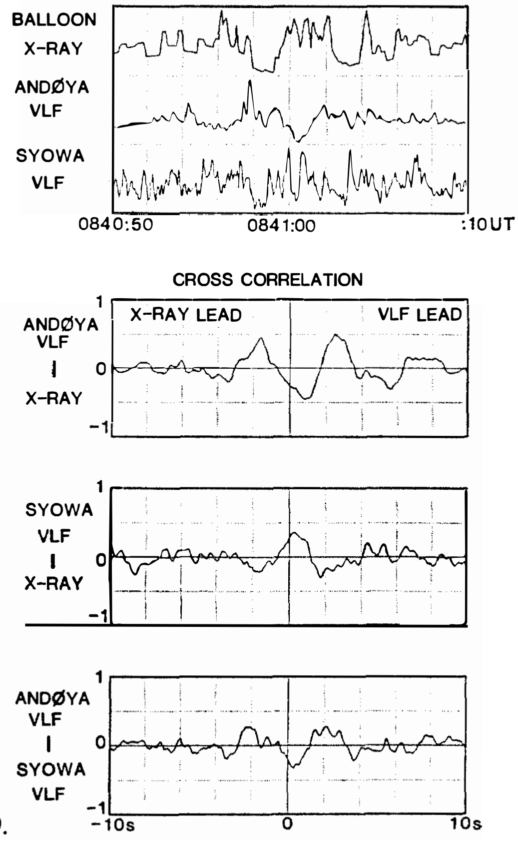

Fig. 10.

Figs. 8–10. Comparison of X-ray counting rate with the VLF emission intensities at 1.5 kHz band observed at Andφya and at Syowa Station, Antarctica in the time interval of 0758:40–0759:00 UT (Fig. 8), 0803:40–0804:00 UT (Fig. 9) and 0840:50–0841:10 UT (Fig. 10). Cross correlation functions between two of these three data are also shown in the lower panels.

at Syowa and X-ray, and the fourth panels show the ones between VLF emissions at Andøya and Syowa, respectively. It is surprising that such a good correlation is attained for these station pairs with a rather poor magnetic conjugacy. This fact implies that VLF emission can spread more that 1600 km on the ground.

It should be noted that X-ray observed in the northern hemisphere shows an almost in-phase relation with the VLF emission observed at Syowa, and the VLF emission observed at Andøya is delayed by 1.5–2.5 s from the one observed at Syowa, and also from the X-ray burst. This is qualitatively explained by the nature of the counterstreaming type wave-particle interaction, that is, waves and electrons involved

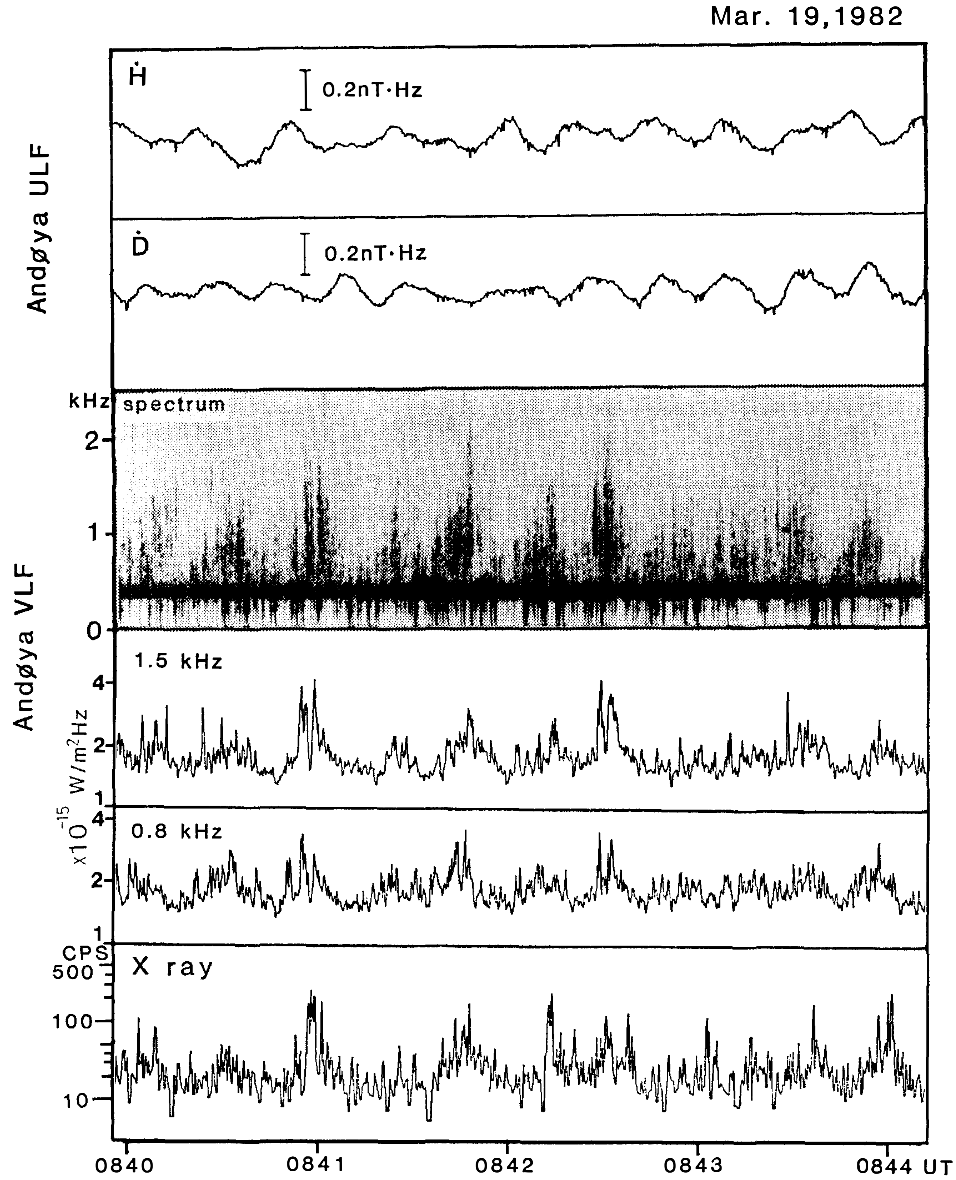

Fig. 11. Relationship among magnetic pulsations, quasi-periodic VLF emissions, and X-ray pulsations in the time interval of 0839:57–0844:15 UT. Here, X-ray count rate is displayed in logarithmic scale. Note that the frequency-time spectra of VLF emission show a rising tone characteristic.

in this process go to opposite direction. The VLF emission observed at Andøya is considered to be an echo of the emission observed at Syowa. In this case, propagation time of VLF waves from Andøya to Syowa is estimated to be 2 s, and their bounce period in the magnetosphere becomes 4 s. On the other hand, energy range of electrons responsible for observed X-ray emission is more than 20 keV, and the bounce period of such energetic electrons is less than 2 s for $L=5.2$ dipole field line. Therefore, a periodicity recognized in these figures is not related to the bounce motion of electrons, but is related to the bouncing of VLF wave packet.

From the above consideration, propagation time of VLF waves and electrons from the magnetic equatorial plane to the observation site is estimated to be 1 s and less than 0.5 s, respectively. If the wave-particle interaction took place in the magnetic equatorial plane, electron precipitation should be observed at least 0.5 s prior

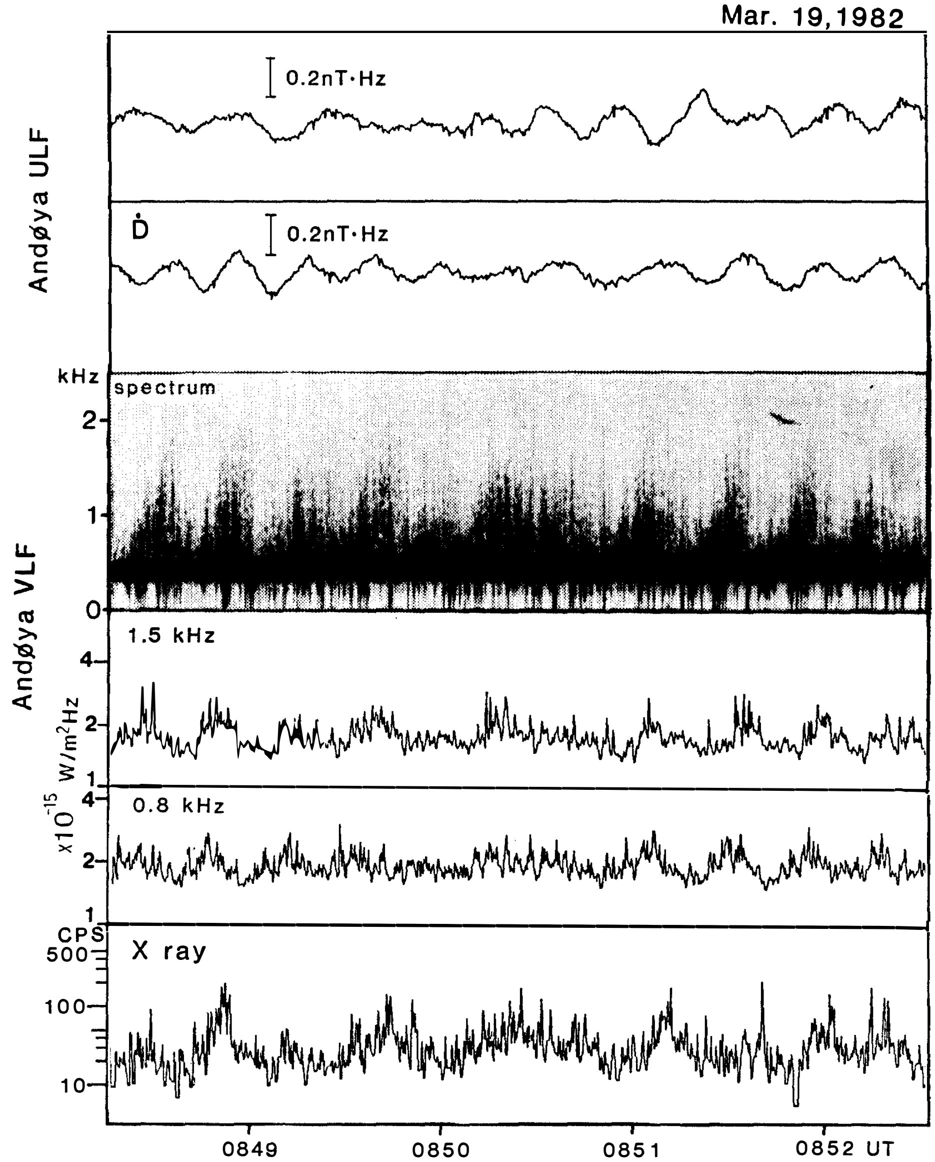

Fig. 12. Same as Fig. 11, except for the time interval of 0848:00–0852:30 UT.

to the VLF emission observed in the opposite hemisphere. However, our data very often show zero time lag between X-ray and VLF emission at Syowa, similar to the results of balloon experiment at Siple-Roverval conjugate pair in the subauroral zone (ROSENBERG *et al.*, 1981). This suggests the possibility that the electron scattering region is not exactly in the magnetic equatorial plane, but shifted to the upstream region of electron flow, as pointed out by ROSENBERG *et al.* (1981).

4. Pulsation Phenomena

As pointed out in Fig. 4, Pc 3 magnetic pulsations with periods of 20–30 s occurred throughout the balloon flight. Pulsations in VLF emission intensity and X-ray count rate were closely associated with magnetic pulsations. A correlation

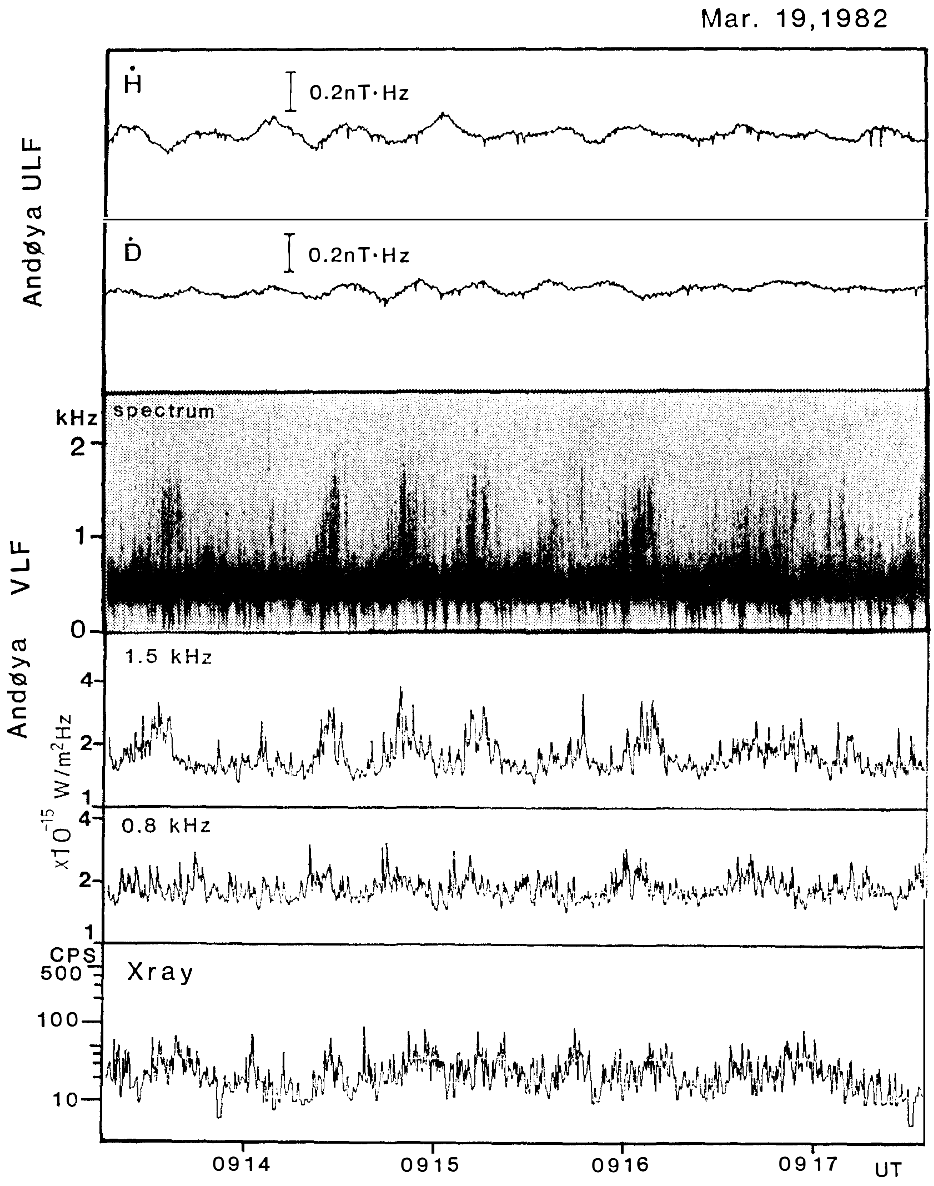

Fig. 13. Same as Fig. 11, except for the time interval of 0913:20–0917:40 UT.

among these three phenomena is clearly seen in the expanded f-t spectra in Figs. 11, 12 and 13. Note that the VLF emissions are classified as quasi-periodic (QP) VLF emissions with a rising tone structure (SATO, 1981).

The *D*-component of magnetic pulsations shows a good correlation to QP emissions and X-ray pulsations, while the correspondence is rather poor for the *H*-component. It is apparent that there is one-to-one correspondence between QP emissions and X-ray pulsations. These relations suggest that Pc 3–4 magnetic pulsations (compressional mode hydromagnetic waves), propagating in radial direction from the magnetopause toward the earth, modulate the growth rate of whistler mode waves to form QP emissions, and that these modulate the pitch angle diffusion rate and precipitation of energetic electrons trapped in the magnetosphere through the cyclotron interaction, as theoretically studied by CORONITI and KENNEL (1970), and CHEN (1974).

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