MAGNETIC PULSATIONS IN THE PERIOD RANGE FROM 40 TO 170 SECONDS OBSERVED AT SYNCHRONOUS ORBIT: COMPARISON OF SATELLITE AND GROUND DATA

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Abstract: Monochromatic sinusoidal oscillations in the period range from 40 to 170 s were frequently observed by a synchronous satellite, ATS-6, in August of 1975. During the observation period the satellite was located at 35° east longitude and close to the geomagnetic equatorial plane. The present paper concerns with an examination on wave characteristics of these monochromatic sinusoidal oscillations and on an oscillation mechanism by analyzing numerous wave events observed by ATS-6. The results indicate that oscillations show a clear local time variation in the period, shorter in the morning and longer in the evening. With regard to an oscillation mechanism our conclusion strongly supports a hypothesis that the second harmonic resonance oscillation of standing Alfvén wave is most probably an oscillation mode near the synchronous orbit at 6.6 earth radii. Another examination of the satellite and ground correlation of those waves indicates that there is a clear evidence of a rotation of the principal axis of the waves observed by the satellite and on the ground.

1. Introduction

In recent years a study of magnetic pulsations has advanced rapidly based on the both theory (CHEN and HASEGAWA, 1974; SOUTHWOOD, 1974) and observations on the ground and in space (ROSTOKER *et al.*, 1979; CUMMINGS *et al.*, 1969; CUMMINGS *et al.*, 1978; KOKUBUN *et al.*, 1977; HUGHES *et al.*, 1979; SINGER *et al.*, 1979). Nevertheless, the important features regarding generation, amplification and propagation of waves have not been clarified. The coordinated ground-satellite observations should provide us much profitable knowledge on wave properties.

Regarding several important characteristics of the waves, the mode of oscillation and spatial extention of a resonance region should be studied in more detail by using the data obtained both on the ground and in space. As for the waves in the period range from 40 to 150 s, which are registered as Pc4 magnetic pulsations, the mode of oscillations has not yet been examined in detail by using the simultaneous data obtained both on the ground and in space. HUGHES *et al.* (1979) have examined the mode of oscillations of Pc4 by using multiple satellite data and reached the conclusion that the Pc4 oscillates as a second harmonic mode. Such a second harmonic resonant oscillation of Pc4 waves has been suggested by CUMMINGS *et al.* (1969) based on the observational data obtained by ATS-1.

The spatial extention of a resonant region has been examined on the basis of the data obtained both on the ground (ROSTOKER *et al.*, 1979) and by the multiple satellites (HUGHES *et al.*, 1977; HUGHES *et al.*, 1979; SINGER *et al.*, 1979). The results obtained by ROSTOKER *et al.* (1979) indicate that the Pc4 type giant pulsations appear only in a limited region about 1000 km by 1000 km.

In addition, the satellite observations show that the waves have a large azimuthal angular wave number, m, which attains about 100 at the synchronous orbit. The period of the wave dealt with by HUGHES *et al.* (1977, 1979) is assigned to the shorter period Pc4 oscillations of about 55 s. Those waves show a compressional signature occurring during the nighttime, which is different from the waves dealt with in the present study. Highly monochromatic sinusoidal oscillations in the period range from 40 to 170 s were frequently observed by ATS-6 in August 1975. The waves show a transverse character oscillating mainly in the radial component of the magnetic field. During August in 1975 ATS-6 was situated at 35° east longitude, which is close to the equatorial conjugate point of Syowa Station ($\varphi=39.6°$E, $\lambda=69.0°$S).

The purpose of the present paper is to clarify the wave characteristics, such as the mode of oscillations and spatial extention of the resonance region by analyzing the satellite data obtained by ATS-6 and the simultaneous observed data on the ground at higher latitudes. The present paper deals with the ground magnetic field data together with those obtained at the Alberta chain stations in Canada and at Syowa Station in Antarctica.

The wave characteristics of highly monochromatic oscillations will be examined in Section 3 by analyzing the magnetic field data obtained by ATS-6. In Section 4 a theoretical approach to the mode of oscillations in the magnetosphere will be pursued. The satellite and ground correlation studies for clarifying the wave characteristics will be presented in Section 5. A brief discussion and conclusions will be given in the last section.

2. Data Analysis

The satellite data presented in this paper were obtained from the flux-gate magnetometer on board ATS-6, which was located at 35° east in the geographic longitude during August 1975. For detailed description the paper by MCPHERRON (1974) should be referred to. The noise level is sufficiently low, so that it is possible to study ULF waves at the synchronous orbit (MCPHERRON, 1976).

In order to examine the wave characteristics of Pc4 range magnetic pulsations observed on board the satellite we used high resolution data, which were arranged in a common format with a vertical scale of 5 nT per inch and a horizontal scale of 10 min per inch. The Pc4 waves analyzed in this paper are mainly concerned with the data presented by $\boldsymbol{V}$, $\boldsymbol{D}$ and $\boldsymbol{H}$ fluctuations in the dipole coordinate system. The $\boldsymbol{H}$ axis is antiparallel to the dipole axis and positive north, $\boldsymbol{D}$ is in the direction of $\boldsymbol{H} \times \boldsymbol{R}$, where $\boldsymbol{R}$ is the radius vector from the center of the earth to the spacecraft and $\boldsymbol{V}$ is parallel to the magnetic equatorial plane.

In this paper some important aspects of wave characteristics are studied with the usual methods of analysis, *i.e.*, frequency spectrum, polarization in the $\boldsymbol{V}$-$\boldsymbol{D}$ plane perpendicular to the dipole axis and occurrence frequency. The spectrum of waves is obtained by the maximum entropy method. The polarization is studied with the hodograph method, by plotting the data in every 4 seconds. The occurrence frequencies both of the waves depending on the local time and of the mean period during the ten-minutes interval of wave trains are examined.

3. Experimental Results

3.1. Typical examples of highly monochromatic oscillations at synchronous orbit

During a period of magnetically quiet conditions nearly monochromatic sinusoidal oscillations of the magnetic field are frequently observed at the synchronous orbit for a long time up to several hours. These oscillations show a significant wave feature such as almost a transverse oscillation; the largest oscillation in the radial component and nearly monochromatic sinusoidal wave form. Typical examples of these oscillations are given in Figs. 1 and 2, where the magnetic field data are displayed with $\boldsymbol{X}$, $\boldsymbol{Y}$ and $\boldsymbol{Z}$ components in the spacecraft body coordinates, in which $\boldsymbol{X}$, $\boldsymbol{Y}$ and $\boldsymbol{Z}$ correspond roughly to $-\boldsymbol{V}$, $-\boldsymbol{D}$ and $\boldsymbol{H}$ components in the dipole coordinates, respectively. Thus, the event observed on August 11, 1975 shows the dominant oscillations in the radial component compared with the other components of the magnetic field shown in Fig. 1.

The polarization and power spectrum are calculated for the interval of twenty minutes from 1055 to 1115 MLT indicated with two vertical solid lines in the magnetogram and shown in the bottom part of the figure. The wave is characterized with a right-handed polarization and a dominant period of about 57 s. The oscillations given in Fig. 1 are attributed to the shorter period Pc4 oscillations. These shorter period oscillations occur mostly in the early morning. On the other hand, during the late afternoon the oscillations show a longer period of about 160 s, as illustrated in Fig. 2. The wave characteristics are examined in the interval of twenty minutes from 1820 to 1840 MLT. During this interval, the polarization changes from left- to right-hand corresponding to the intervals indicated by A and B in the figure. The spectra of V and D components of the field show a dominant peak of about 160 s.

These monochromatic sinusoidal oscillations are observed in 33 separate cases during a period of magnetically quiet conditions ($Kp<4$) in August 1975. The wave characteristics of these oscillations are summarized in Table 1, in which the duration, the average period and the maximum amplitude of D and V components of all events

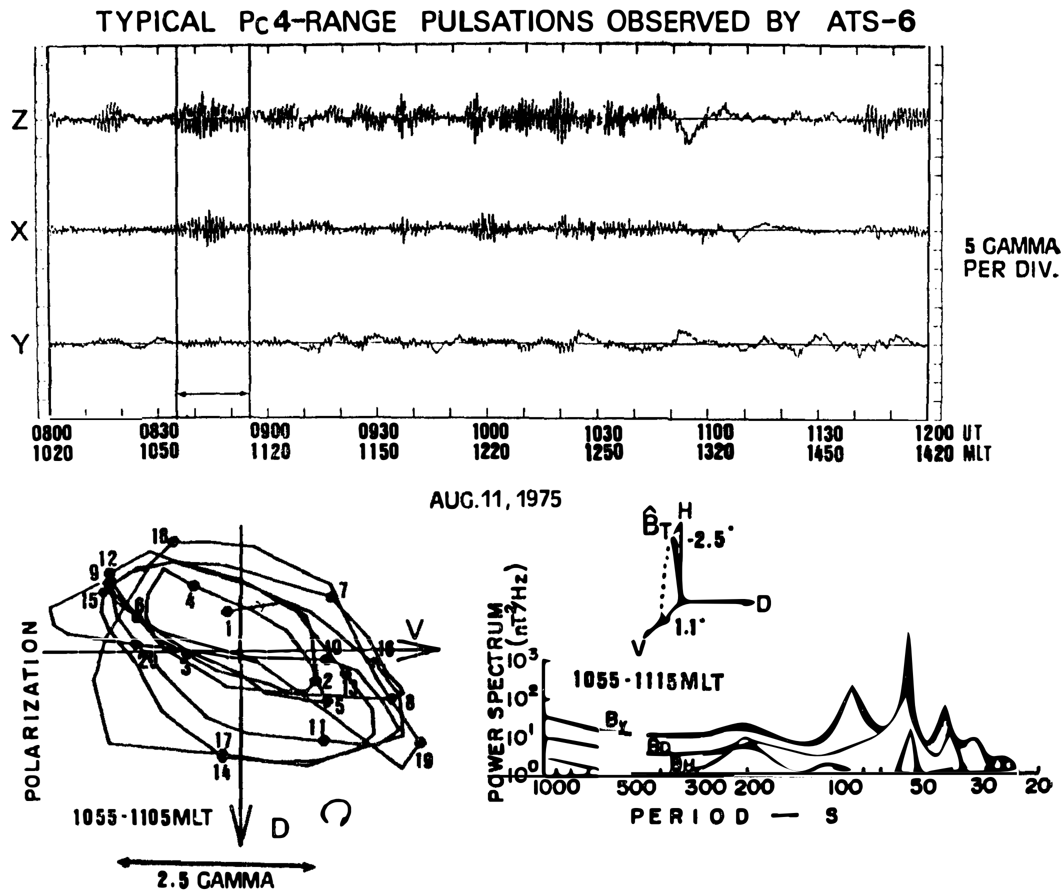

Fig. 1. Highly monochromatic transverse oscillations observed on August 11, 1975 under magnetically quiet conditions. The polarization of the wave during the interval from 1055 to 1155 MLT indicated by two vertical lines shows a right-handed rotational sense in the V-D plane. The average magnetic field during the period directs nearly toward the H-axis in the dipole coordinate. The dominant spectral peak can be seen at 57 s in the three components of the magnetic field.

are tabulated.

3.2. Local time dependence of the period of the waves

Fig. 3 shows the period variations for these observed oscillations as a function of local time with different magnetic activities. One point of the plotted data in the figure shows an average period of the oscillations for an interval of ten minutes. Different marks in the figure represent the events that occurred in the different magnetic activities. The frequency of occurrence in the ten-minutes intervals during each one hour is shown with a histogram at the top of the figure. The histogram shows that the occurrence of these oscillations dominates during daylight mainly from 07 to 21 MLT. On the other hand, the occurrence frequency of the average period of

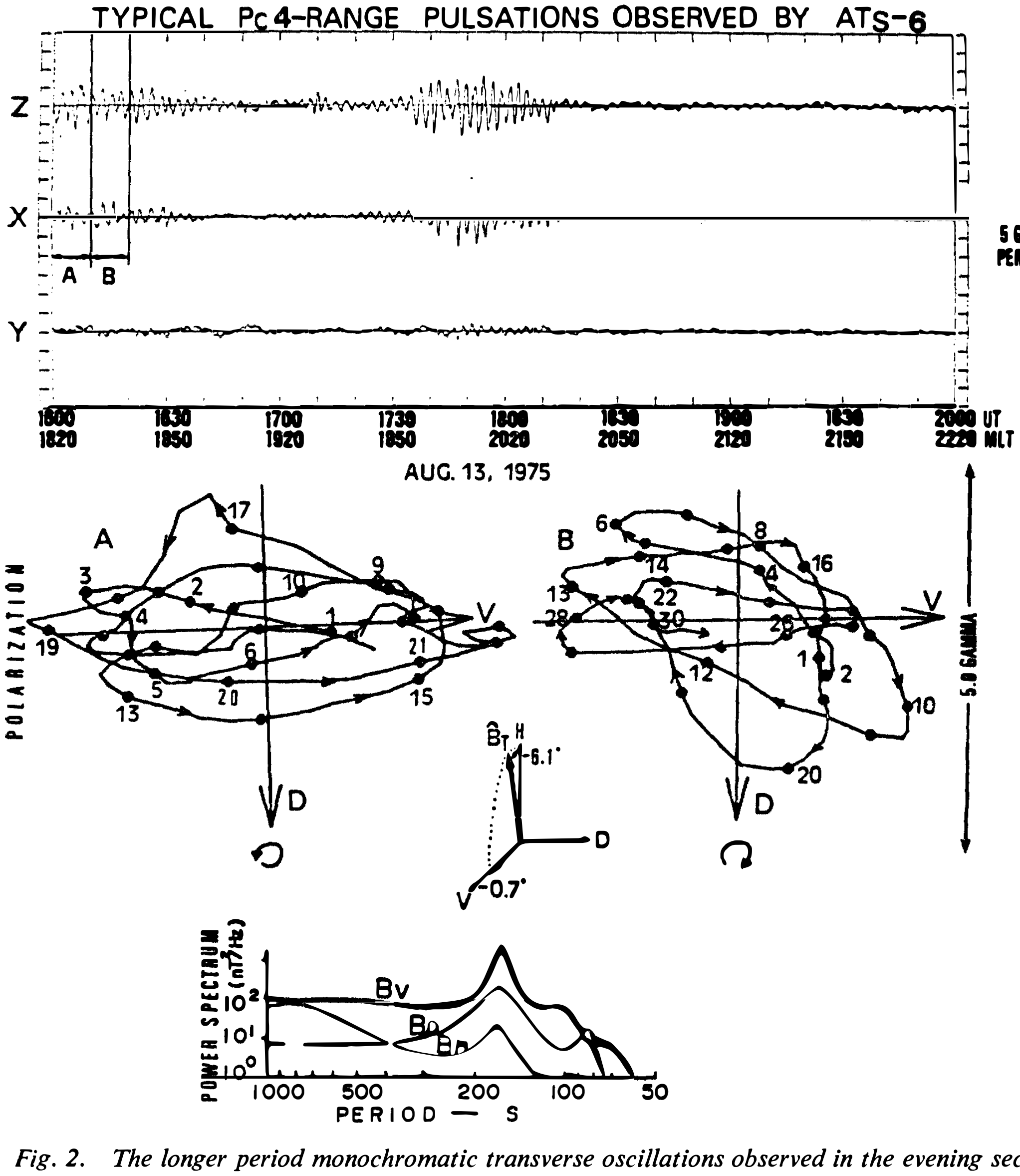

Fig. 2. *The longer period monochromatic transverse oscillations observed in the evening sector on August 13, 1975. The polarization changes from left- to right-handed corresponding to the intervals of A and B. The average magnetic field during the period directs the H-axis in the dipole coordinate. The spectrum shows the dominant peak at 170 s in the bottom panel.*

the oscillations for the interval of ten minutes is given with a histogram on the right-hand side of the figure. The histogram shows that the oscillations concentrate in the period from 50 to 70 s.

In the present analysis using the magnetic data in August 1975, there are 3738 ten-minute intervals for which $Kp<4$ and for which ATS-6 data are available. In 144 cases of these intervals, or 3.9% of the total, there are oscillations with waveforms

Table 1. Monochromatic oscillations observed at ATS-6, August 1975.

Event number	Universal time Beginning d	h	m	Ending d	h	m	Duration (min)	Average period (s)	Maximum peak to peak D, γ	Maximum peak to peak V, γ	Kp
1	1	11	00	1	11	40	40	66	2	3	2
2	1	15	50	1	16	00	10	130	2	2	1
3	1	16	30	1	17	00	30	124	1	4	1
4	2	09	40	2	10	00	20	150	2	6	2−
5	8	12	10	8	17	00	290	109	10	17	1−, 1
6	9	13	05	9	13	35	30	88	2	5	2−
7	9	14	15	9	15	25	70	67	4	7	2−
8	10	12	25	10	13	40	75	92	6	12	2+
9	11	07	15	11	08	00	45	52	2	3	2+
10	11	08	10	11	08	20	10	58	1	4	2+
11	11	08	35	11	11	00	85	58	6	6	2+, 3
12	11	11	40	11	12	00	20	66	2	3	3
13	13	14	25	13	14	45	20	140	4	5	1+
14	13	16	00	13	16	40	40	154	4	7	1+
15	13	17	20	13	18	10	50	144	8	9	1+
16	16	04	40	16	11	30	410	52	4	7	1 , 2
17	16	11	40	16	11	50	10	75	2	2	2
18	17	09	35	16	10	20	45	80	2	4	2
19	17	11	35	17	11	55	20	92	1	3	2
20	18	10	40	18	10	50	10	72	1	2	3−
21	18	11	20	18	11	30	10	87	1	2	3−
22	18	12	10	18	12	25	15	89	2	6	1
23	20	07	40	20	07	55	15	60	1	2	1
24	20	08	15	20	10	35	140	67	3	3	1 , 2
25	21	11	10	21	11	30	20	78	3	3	2−
26	21	11	40	21	12	10	30	71	2	3	2−, 2
27	21	12	40	21	13	50	70	78	3	6	2
28	21	14	10	21	14	20	10	68	1	3	2
29	24	09	00	24	09	55	55	56	2	2	1−
30	24	10	00	24	10	15	15	60	1	2	1−
31	24	12	10	24	12	20	10	58	1	3	3−
32	25	11	15	25	11	30	15	57	2	3	1+
33	31	12	00	31	12	40	40	67	2	3	1

clear enough to permit the use of the procedure for determining the period.

The figure shows the following important characteristics of the oscillations observed by ATS-6.

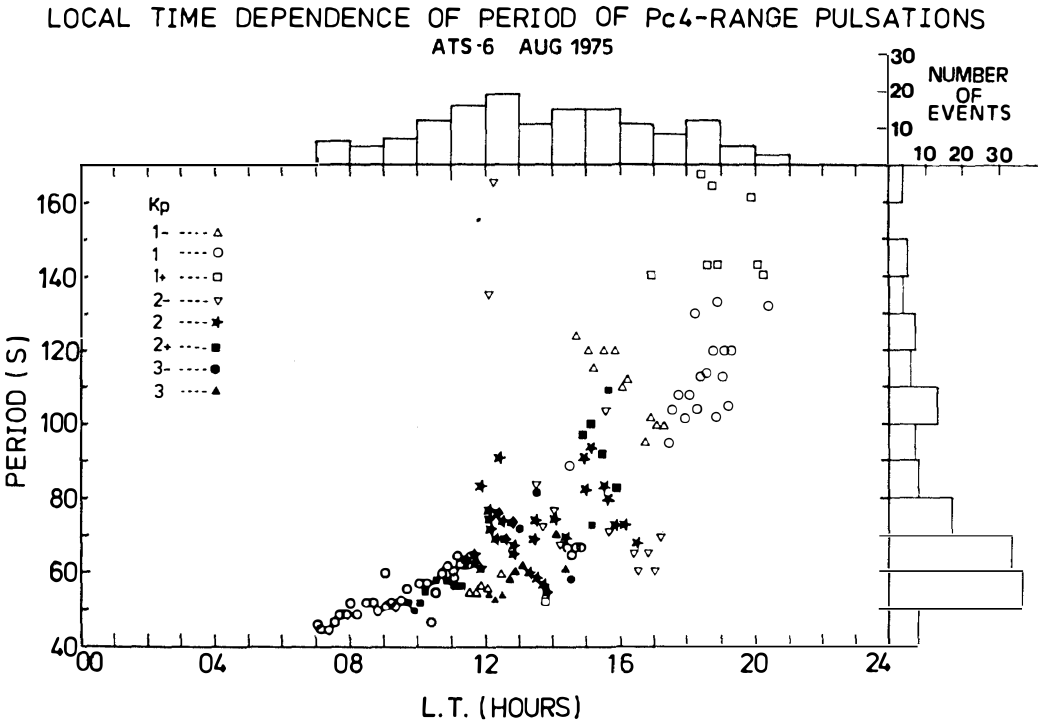

Fig. 3. The local time variation in the period of the monochromatic oscillations observed by ATS-6 in August 1975. The occurrence of the waves in the different magnetic activities is shown by different symbols. A clear tendency in the period variation of the oscillations can be seen; shorter in the morning and longer in the evening. The local time dependence of the occurrence frequency of the monochromatic oscillations is shown in the top histogram and indicates most probable occurrence in the daytime. The period concentrates almost in the shorter period from 50 to 70 s in the morning sector, while in the evening the longer period oscillations dominate.

1) The oscillations indicate clearly a local time dependence on the period variation, *i.e.*, the period of these oscillations changes from about 45 s to 160 s associated with a change of local time from 07 to 21 LT.

2) The oscillations in the local time range from 10 to 16 LT occur in association with moderately disturbed magnetic conditions ($2<Kp<4$) and over the period range less than 100 s.

3) The longer period oscillations than 100 s occur mostly in the late evening sector covering 16 to 21 LT, and in the extremely quiet magnetic conditions ($Kp<1+$).

4. Oscillation Mode of the Wave Observed at Synchronous Orbit

The oscillations of these Pc4-type pulsations appear as highly monochromatic sinusoidal waves, so that they seem to occur with some resonant oscillation mecha-

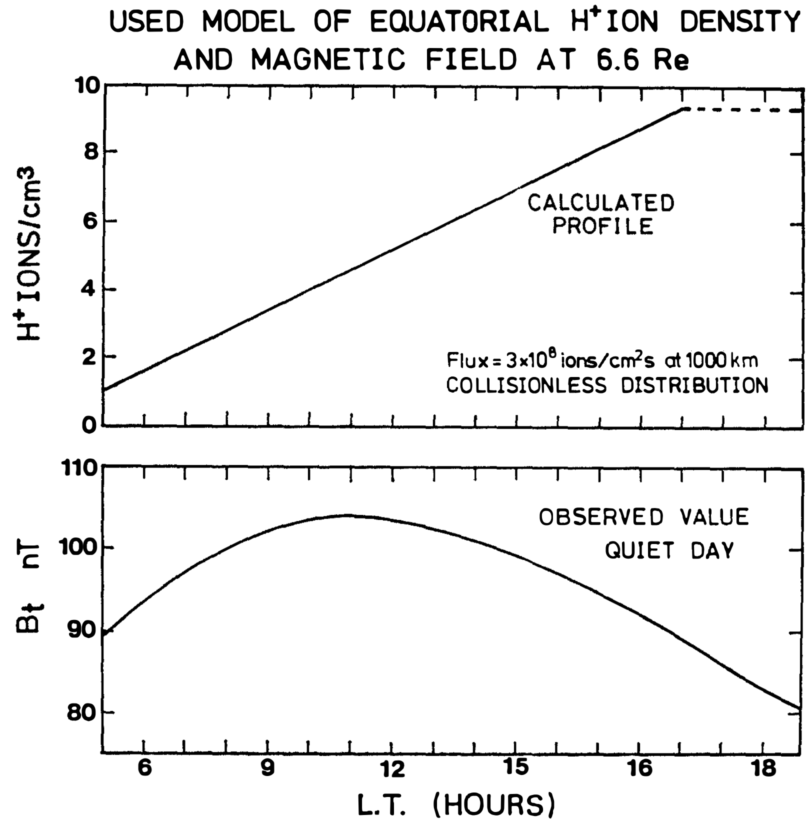

Fig. 4. The local time variation of equatorial H^+ ion density (upper panel) and magnetic field intensity (lower panel) under magnetically quiet conditions.

nism near the synchronous orbit. In order to examine the oscillation mechanism of these waves, we will attempt to calculate a local time variation of eigenperiod by assuming it as a standing Alfvén wave oscillation at the synchronous orbit. The period of a standing Alfvén wave oscillation varies sensitively with the distribution of plasma densities and background magnetic field intensities. The local time variations of the hydrogen ion density and the magnetic field intensity used in the present calculation are shown in Fig. 4. The upper and lower panels show the local time variation of the ion density and the magnetic field intensity under magnetically quiet conditions, respectively. The local time changes of the hydrogen ion density along the magnetic field line are calculated on the basis of the assumption that the hydrogen ion obeys a collisionless model with a constant upward flux of 3×10^8 ions/cm$^2\cdot$s at a 1000 km height and accumulates in the equatorial plane filling the tube of force of the magnetic field line. The distribution model of hydrogen ion density described above is based on the calculation proposed by CHAPPEL *et al.* (1971). The lower panel shows an observed value of total magnetic field intensity under a magnetically quiet condition at the synchronous orbit. These local time distributions of the calculated

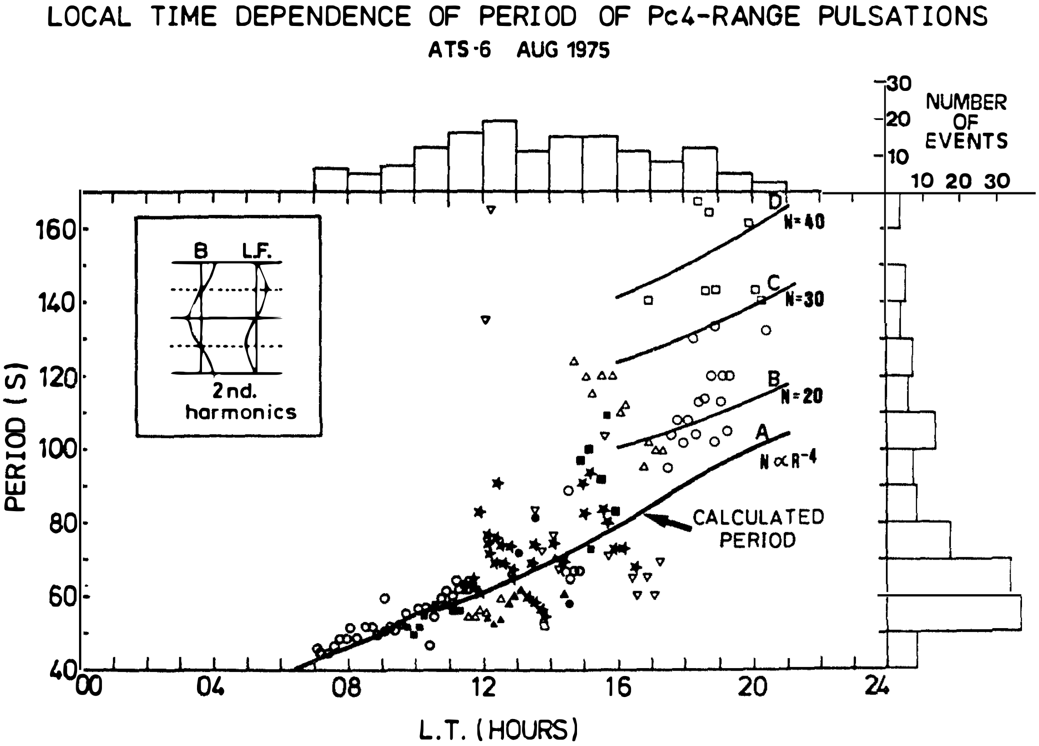

Fig. 5. The local time variation of the period of the oscillations seems to coincide well with a solid curve indicated by A, which is calculated by an assuming it as a second harmonic standing oscillation at the synchronous orbit. The H^+ ion density and magnetic field profiles used in this calculation are shown in Fig. 4. The calculated curve A deviates from the observed data in the evening sector, where three different curves are calculated with three different density values indicated by $N=20$, 30 and 40. These curves seem to be coincident well with the observed period variations during this sector and to reflect the different density conditions in the plasmapause region.

ion density and the observed magnetic field intensity are applied to the calculation of eigenperiod of a standing Alfvén wave oscillation at the synchronous orbit. The eigenperiod of standing wave is calculated by means of the refined process, which was originally developed by CUMMINGS *et al.* (1969).

Based on the calculation of eigenperiods described above, the local time variation of the period of the second harmonic oscillation is illustrated with a solid curve indicated by an arrow in Fig. 5, which is best fit to the observed values of the oscillations. On the other hand, the other three curves in the upper part of the figure during the evening quadrant represent the eigenperiod variations of the second harmonic oscillation corresponding to three different density distributions in the plasma bulge region, where the plasma density distribution along the magnetic filed line is taken as the diffusive equilibrium distribution. The observed period variations in the late evening sector seem to be coincident with the calculated period variations using

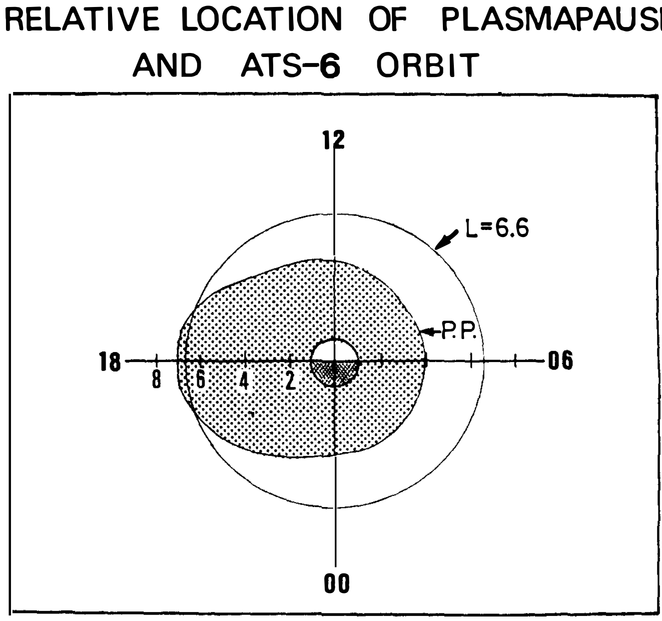

Fig. 6. Relative location of the plasmapause and ATS-6 orbit. It seems probable that under magnetically quiet conditions ATS-6 tends to cross the plasmapause bulge region in the evening sector.

three different density models, $N=20$, $N=30$ and $N=40$. In the magnetically quiet condition, the evening quadrant plasmasphere extends beyond the synchronous orbit shown in Fig. 6. It is reasonable to consider that the satellite passes through such a bulge region under magnetically quiet conditions. The assumed three different density profiles seem to be coincident with those obtained by the satellite observations during a quiet period. Therefore, it is concluded that the second harmonic oscillations of standing Alfvén waves can be one of the candidates for explaining the resonant oscillation mechanism occurring near the synchronous orbit.

5. Satellite and Ground Correlation

In order to clarify propagation characteristics of Pc4 type pulsations, the satellite and ground data comparisons for different two wave events will be examined in this section.

The magnetometer at the Alberta chain stations was operated in September 1974. ROSTOKER *et al.* (1979) reported that giant pulsations in the period range of Pc4 waves were observed on three successive days in September 1974. These Pc4 giant pulsations were registered simultaneously at all the Alberta chain stations covering the latitudes from 64.5° to 67.5° in the corrected geomagnetic coordinate, and appeared first at the lower latitudes and then developed poleward in a half or one hour as

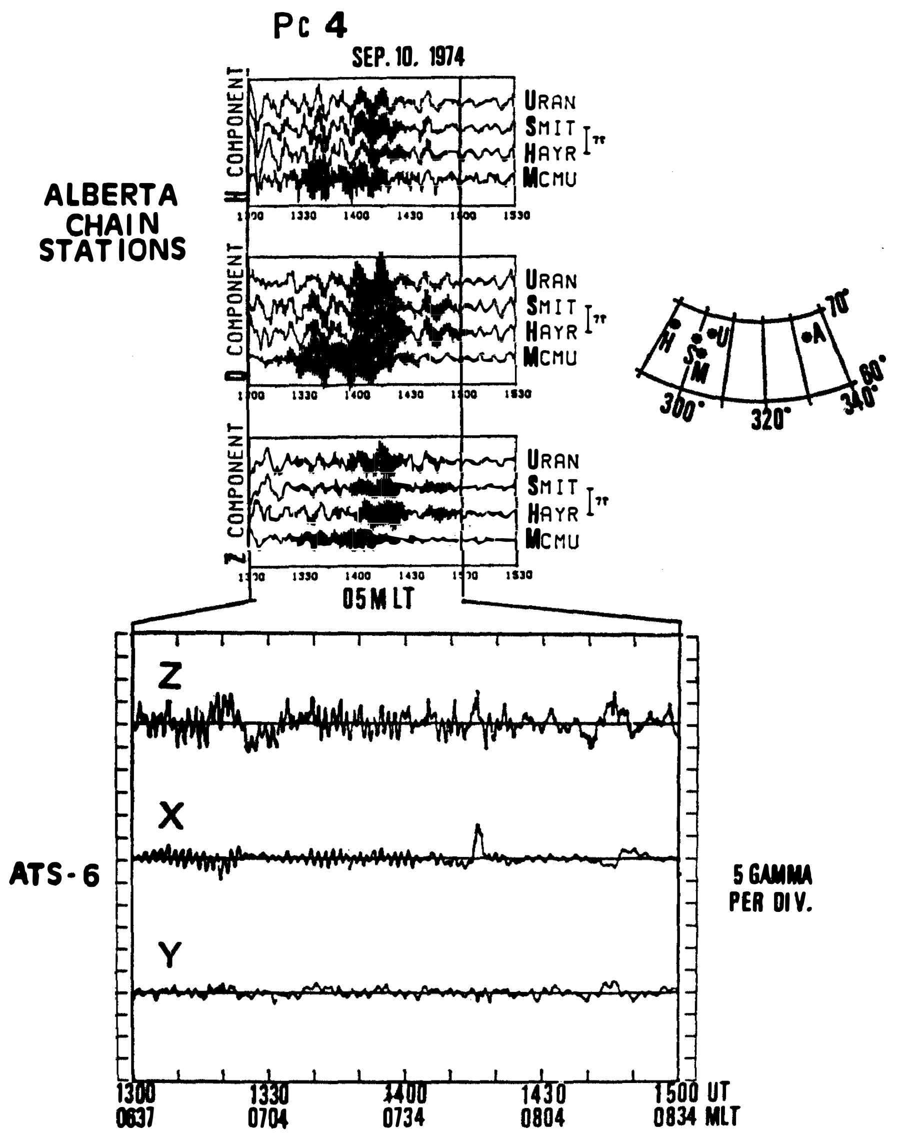

Fig. 7. Simultaneous occurrence of monochromatic, sinusoidal and transverse oscillations in the period of Pc4 observed both on the ground, Alberta chain stations (top panel) and aboard the synchronous orbit satellite, ATS-6 (bottom panel). Note that we can see a clear evidence of a rotation of polarization axis of the waves, which oscillate in the east-west direction on the ground and in the radial at the synchronous orbit.

shown in the top panel of Fig. 7. The figure indicates that the amplitude of those waves is maximized in the D-component of the magnetic field relative to H and Z. Analysis of those waves also show that they appear with a limited spatial extention; the power of those waves has dropped one order of magnitude within 5° in latitude on either side of the peak.

Table 2. Locations of the stations used in the present paper.

Station	Code	Geographic		Corrected dipole		L
		°N	°E	°N	°E	R_e
Uranium City	Uran	59.6	251.5	67.4	304.3	6.8
Fort Smith	Smith	60.0	248.0	67.3	300.0	6.7
Hay River	Hayr	60.8	244.2	67.3	294.3	6.7
Fort McMurray	Mcmu	56.7	248.8	64.2	303.5	5.3
Syowa Station	SYO	−69.0	39.6	−66.7	72.5	6.4
ATS-6(Sep. 1974)		0.0	264.0	10.4	332.5	6.8
ATS-6(Aug. 1975)		0.0	35.0	−2.8	103.7	6.6

During the occurrence of these Pc4 giant pulsations at the Alberta chain stations there was a clear evidence of the simultaneous occurrence of the similar Pc4 type pulsations at the synchronous orbit. During this period the ATS-6 satellite was situated at 96° west in longitude, very close to the longitude of the Alberta chain stations. The longitudinal difference between the satellite and the Alberta chain stations was with 30°. Locations of the satellite and the ground stations used in the present paper are tabulated in Table 2.

As described above, the satellite observed the Pc4 type pulsations in the same intervals as observed on the ground. Those pulsations observed aboard the satellite are shown in the bottom panel of Fig. 7, which are similar to those observed on the ground. The Pc4 waves observed aboard the satellite oscillate dominantly in the radial direction, which implies that the waves in the magnetosphere belong to the poloidal oscillations. While, the corresponding waves observed on the ground at the Alberta chain stations oscillate dominantly in the east-west component. These facts observed both on the ground and the satellite indicate that the principal axis of the waves at the satellite seems to rotate about 90° during the propagation through the ionosphere. The fact seems to be consistent with the theoretical prediction by HUGHES (1974).

Although the longitudinal difference between the satellite and the Alberta chain stations was about 30° in these wave events, the similar type Pc4 magnetic pulsations were simultaneously observed on the ground and in space. This observational fact indicates that the longitudinal extention of these waves attains at least about 42000 km at the synchronous orbit. This longitudinal extention of waves seems to be consistent with those obtained with multiple satellite studies by HUGHES *et al.* (1979).

As noted in the preceding sections, the highly monochromatic sinusoidal oscillations in the period range of Pc4 type pulsations were frequently observed by ATS-6 in August 1975, when the satellite was located at 35° east longitude, not far away from Syowa Station (φ=39.6° east, λ=69.0° south in the geographic coordinate). We have checked whether these Pc4 type oscillations occurred simultaneously at Syowa

Station or not. However, there was no indication of appearance of these waves at Syowa Station. The longitudinal difference in the corrected geomagnetic coordinate was about 30°, which was similar to that in the previous case between the satellite and the Alberta chain stations. One of the possibilities of the absence of the simultaneous appearance of the waves at Syowa Station may be attributed to the coarse network of the observation sites on the ground. If many wave data were obtained with a denser network, we could have similar results as obtained in the first examination of wave event discussed previously. A detailed examination will be required in the future.

6. Discussion and Conclusion

As described in the preceding sections, highly monochromatic transverse oscillations have been frequently observed by ATS-6 in August 1975, when the satellite was located within 2.8° of the geomagnetic equatorial plane. The observations by the satellite indicate that the oscillations of the Pc4 type magnetic pulsations are probably even harmonics, since the magnetic wave amplitude is zero at the equatorial plane for the odd harmonics (LANZEROTTI and FUKUNISHI, 1974). Another observed fact, *i.e.* the diurnal variation in the period of the Pc4 type oscillations, supports the evidence of oscillation mode of even harmonics. The calculated period variation of the standing Alfvén wave at the synchronous orbit is consistent with the observed oscillation mode. The calculation is based on the assumption that the plasma density at the equatorial plane is accumulated by supplying the cold plasma with a constant upward flux of 3×10^8 ions/cm^2·s at a height of 1000 km. The calculated plasma density corresponds to that in the dayside plasma trough region.

During the period of the magnetically quiet condition the satellite seems frequently to pass through the region just outside the plasmapause. Therefore, it is reasonable to assume that the density just outside of the plasmapause is distributed with a collisionless model. In addition, almost all the wave events mentioned in the present paper have been observed under the magnetically quiet conditions. The quiet day values of magnetic field intensity are adopted in this calculation. The result indicates that the calculated period variation is almost coincident with the observed one except that in the evening quadrant, where the calculated period with such an assumed model differs from the observed one.

Note that in the evening quadrant the long period waves occur under the extremely quiet condition. The period of these waves is longer than the calculated one. This may be due to the fact that the plasmapause in the evening moves outward beyond the synchronous orbit under such a magnetic condition. The period of the waves in the evening has been reexamined by taking another density model into account which corresponds to the density in the plasma bulge. The calculated period becomes coincident fairly well with the observed values of the wave period. These results indicate that the waves dealt with in the present paper are supposed to have been generated as the second harmonic resonance oscillations at the synchronous orbit.

It is interesting to note that the power in the radial component of the magnetic field oscillations is larger than that in the other field components. Such a large radial perturbation in the magnetosphere suggests that a significant portion of the perturbation on the ground happens to be in the east-west component. These perturbations of the magnetic field may be related to the Pc4 type giant pulsations (ROSTOKER *et al.*, 1979), which are typical oscillations observed near the auroral zone latitudes and occurred during the period of magnetically quiet conditions. ROSTOKER *et al.* (1979) show that giant pulsations on the ground exhibit the larger power in the east-west component than that in the other components of perturbations.

It should be argued that the waves oscillate with some typical features of monochromatic frequency and long-lived wavetrains. These features suggest that the waves may be generated with some stable energy source confined in a radially narrow region near the synchronous orbit. One of the candidates for such a resonance region in the magnetosphere might be the plasmapause, which shows a rather stable structure during the daylight hours and especially during a magnetically quiet period. During the day the synchronous satellite may traverse near the plasmapause and enter into the bulge region of the plasmapause in the evening quadrant. Thus, our interpretations described above may satisfy the wave characteristics observed at the synchronous orbit.

In conclusion, we can summarize the characteristics of resonant oscillations observed by ATS-6 in August 1975 at the synchronous orbit as follows:

1) The oscillations are nearly monochromatic and sinusoidal wave forms.

2) The oscillations dominate in a transverse component, especially in the radial direction.

3) The oscillations do not show compressional character.

4) The oscillations are detected almost in the local time from 07 to 21h LT.

5) The period of the oscillations shows a local time variation, becomes longer with increasing local time.

6) The period of oscillations ranges from 40 to 170 s, which coincides with the period of Pc4 range pulsations, and the peak-to-peak amplitude attains from 1 to 20 nT.

7) From the above results combined with our theoretical calculation, the observed oscillation is the second harmonic of a standing Alfvén wave.

8) The ground and satellite observations show that the principal axis of the oscillations in the magnetosphere rotates about 90° with the propagation through the ionosphere.

Our present study suggests that there is a resonance region of standing oscillations of Alfvén mode near the synchronous orbit. A more extensive study based on the data of the magnetic field and particle density variations would make clear a generation mechanism of such resonant oscillations.

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