COMPRESSIONAL Pc 4 PULSATIONS OBSERVED AT SYNCHRONOUS ORBIT

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***Abstract*:** Magnetic oscillations of Pc 4 type ULF waves in the period range from 40 to 180 s are examined using the ATS-6 magnetometer data during the period from June 1 to August 31, 1974. During this period the satellite was located at a magnetic latitude of 10°. It is found that there are two typical types of waves; compressional (meridionally polarized) and transverse (azimuthally polarized) waves. The transverse waves occur mainly in the early morning hours, while the compressional waves occur in the afternoon hours. The compressional waves exhibit rather shorter periods (40–110 s) than the periods of the transverse waves (90–180 s). The calculation of eigen mode period using the recent GEOS 2 plasma density data shows that the period of compressional waves agrees well with the calculated period of the second harmonic oscillation of the magnetic field line passing through the satellite. The compressional waves occur closely associated with ring current proton flux oscillations. A bounce resonant condition between azimuthally propagating waves and ring current protons is examined. The resonant condition is satisfied when the azimuthal angular wave number is longer than ~ 100. It suggests that these compressional Pc 4 waves can not be observed on the ground due to the ionospheric screening effect.

1. Introduction

Many studies, recently performed using the magnetic field data obtained with synchronous satellites, ATS-1, ATS-6, SMS-1 and SMS-2 have clearly demonstrated that there are different types of oscillation modes in the Pc 3 to 5 period range of pulsations in the magnetosphere (CUMMINGS *et al.*, 1978; BARFIELD *et al.*, 1972; BARFIELD and MCPHERRON, 1972, 1978; ARTHUR *et al.*, 1977; ARTHUR and MCPHERRON, 1981; HUGHES *et al.*, 1978, 1979; KOKUBUN, 1980; TONEGAWA *et al.*, 1980; SAKURAI *et al.*, 1981).

CUMMINGS *et al.* (1969) examined the magnetic field data obtained by ATS-1, which was situated at the magnetic equator, and found that there occurred quasi-sinusoidal oscillations in the period range from 60 to 250 s mainly with magnetic field variations perpendicular to the main magnetic field. The examination of the oscillations in the Pc 4 range was extended by TONEGAWA *et al.* (1980), SAKURAI *et al.* (1981) using the data obtained by ATS-6 located near the magnetic equator, revealing that the quasi-sinusoidal (almost monochromatic) oscillations were observed in magnetically quiet conditions. The radially polarized transverse oscillations of Pc 4 waves are generally observed when the satellite is located near the magnetic equator.

On the other hand, ARTHUR and MCPHERRON (1981) and ARTHUR *et al.* (1977)

statistically examined the magnetic ULF waves in the Pc 3 to 4 ranges obtained at ATS-6, when the satellite was located at 10° above the magnetic equator, and showed that the waves could be classified into two types of oscillations, *i.e.*, azimuthally and radially polarized waves. They named them A class and R class, respectively. KOKUBUN (1980) extended the analysis for oscillations from Pc 1 to Pc 5 ranges.

BARFIELD and MCPHERRON (1972) found in their analysis of ATS-1 data that the compressional type oscillations of Pc 4 to 5 were dominant in the afternoon, especially during magnetically disturbed (storm) conditions. The compressional oscillations of Pc 4 range were also analyzed by HUGHES *et al.* (1978, 1979) using the simultaneous data obtained by three satellites, ATS-6, SMS-1 and SMS-2. They found that compressional waves had a large (angular) azimuthal wave number, *m*, of about 100. This large wave number suggests that waves are excited in a very limited range in longitude.

It has been shown in the study of ULF waves that energetic protons oscillate with a period similar to that of the magnetic ULF waves. Proton ULF waves were reported by SU *et al.* (1977, 1979), KOKUBUN *et al.* (1977), CUMMINGS *et al.* (1978), HUGHES *et al.* (1979) and KOKUBUN *et al.* (1981). By using OGO 5 data KOKUBUN *et al.* (1977) found that quasi-periodic perturbations in the thermal ion, energetic electron and proton fluxes were usually associated with occurrence of Pc 5 waves in the region of $L=6$ to 11. They showed that drift motions of energetic particles can interact strongly with the oscillations of field lines. Although there seems to be a very close relation between the magnetic and proton ULF oscillations, the phase relation appears to be very complicated. Some proton waves occur independently of the proton energy, while the others are shown to be energy dependent (KOKUBUN *et al.*, 1981). In order to interpret the mechanisms of excitation of ULF waves the relation between these two oscillations should be examined in detail.

The present paper is intended to clarify the mechanism for the excitation of ULF waves in the Pc 4 range, especially of the compressional oscillations observed mostly in the afternoon hours, which have a close relation to the oscillations in proton flux. The ULF data used in the present paper are those obtained by the UCLA magnetometer on board ATS-6 during the period from June 1 to August 31, 1974. The general characteristics of compressional oscillations in the Pc 4 range will be discussed in Section 3 by comparing them with the transverse (azimuthally polarized) waves which mainly occur in the morning hours. An oscillation mode of compressional waves will be studied in Section 4 in comparison with the plasma data observed by the GEOS 2 satellite. In Section 5 the resonant condition for excitation of the waves will be examined in relation to the oscillations of energetic protons reported by SU *et al.* (1977).

2. Data and Method of Analysis

Magnetic field data used in the present study were obtained with the UCLA fluxgate magnetometer on board ATS-6 during three months from June to August 1974. A detailed description of UCLA fluxgate magnetometer was given by MCPHERRON *et al.* (1975) and MCPHERRON (1976). ATS-6 was placed in a synchronous orbit at

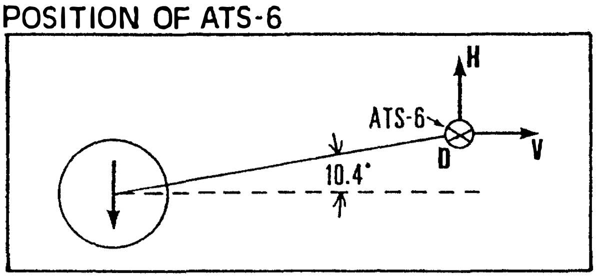

Fig. 1. The dipole coordinate system at the satellite position.

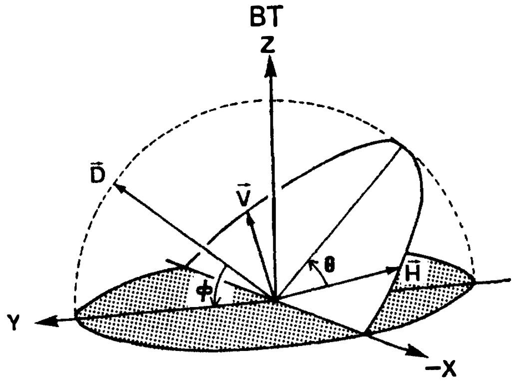

Fig. 2. The relation between the dipole coordinates (V, D, H) and the coordinates of the main magnetic field (X, Y, Z).

a geographic longitude of 96° west. The magnetic latitude of the satellite was about 10° north. The data used here are five second averages plotted in dipole coordinates, ***V***, ***D*** and ***H***. The component antiparallel to the dipole axis is given by ***H***. ***V*** is perpendicular to ***H*** and radially outward and ***D*** is $\boldsymbol{H} \times \boldsymbol{V}$, toward the east. The dipole coordinate system at the satellite position is shown in Fig. 1.

Part of the analog data are analyzed by digitization followed by a calculation of the power spectrum. The polarization of the ULF waves is examined using filtered data. In order to make a hodogram for the polarization analysis, the magnetic field data which are in the dipole coordinate system are transformed into the main magnetic field coordinate system. The transformed magnetic field components are denoted by X, Y and Z. The relation between the two coordinate systems is shown in Fig. 2. The transformation of the coordinates is calculated by using the matrix given below:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ -\sin\varphi\cos\theta & \cos\varphi & -\sin\varphi\cos\theta \\ \cos\varphi\sin\theta & \sin\varphi & \cos\varphi\cos\theta \end{bmatrix} \begin{bmatrix} V \\ D \\ H \end{bmatrix} . \quad (1)$$

The polarization is examined in the planes both parallel $(Z-X)$ and perpendicular $(X-Y)$ to the magnetic field.

3. General Characteristics of Pc 4 at Synchronous Orbit

3.1. Typical examples of wave characteristics

The magnetic pulsations in the period range from 40 to 180 s were examined and divided into two major types based on the wave polarization, *i.e.*, transverse and compressional. The transverse wave oscillates only along the azimuthal component of the magnetic field with little compressional signature. While, the compressional one oscillates mainly in the meridian plane with a small azimuthal component. The typical examples of each type of oscillation are shown in Figs. 3 and 4, respectively.

Figure 3 shows a pure transverse oscillation, which was observed on the morning

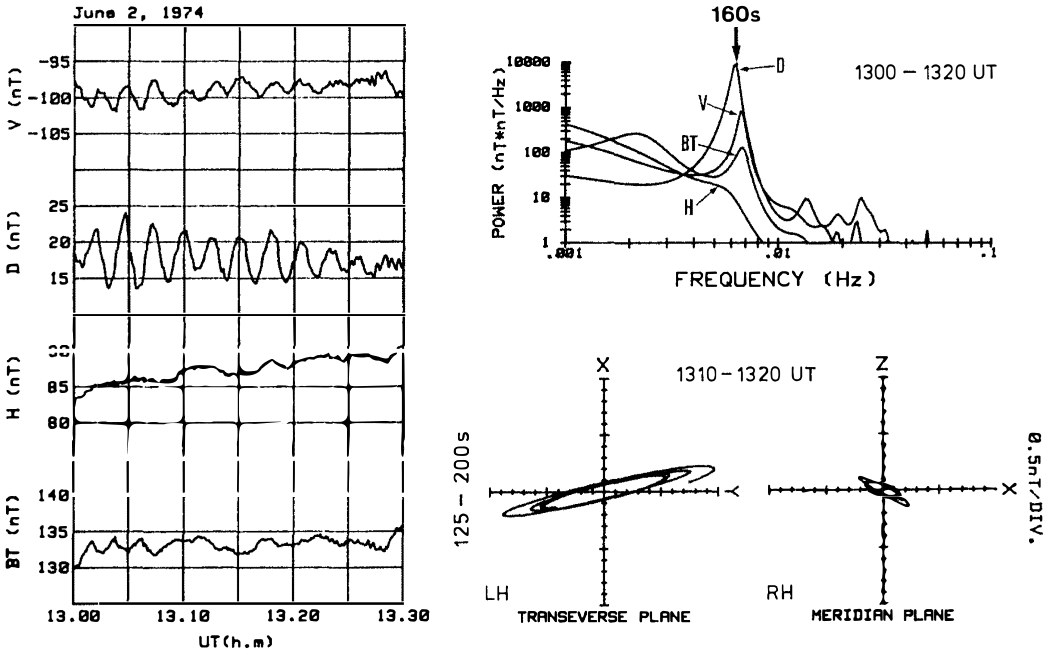

Fig. 3. Left: A typical example of transverse (azimuthally polarized) waves in the early morning hours (LT≃UT-06 h). Right top: Power spectrum for 20 min from 1300 to 1320 UT. Right bottom: The wave polarization is almost azimuthal and is left-handed.

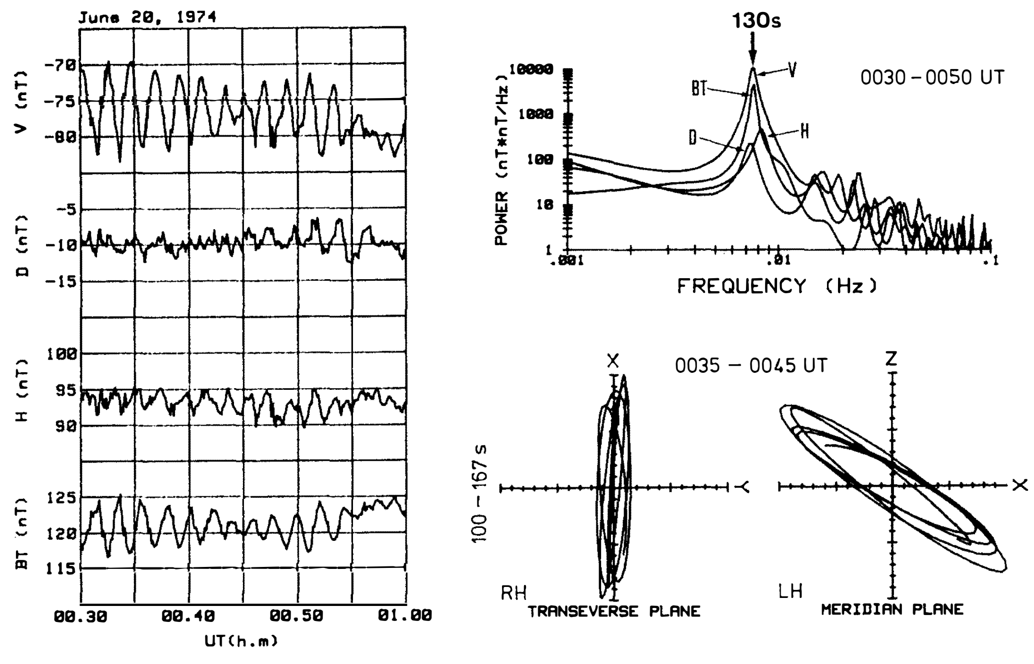

Fig. 4. Left: A typical example of compressional (radially polarized) waves in the afternoon hours. Right top: Power spectrum for 20 min from 0030 to 0050 UT. Right bottom: The wave polarization is almost radial and is right-handed.

side on June 2, 1974. The oscillation of the azimuthal component is found to be larger than those of the other components. The power spectrum calculated for the 20 min time interval from 1300 to 1320 UT is at the upper right and indicates a strong peak at a period of 160 s. The polarization hodograms for the interval from 1310 to 1320 UT in the planes both perpendicular and parallel to the ambient magnetic field are given at the bottom right and indicate that the wave oscillates in the perpendicular plane with its major axis directed towards the azimuthal direction.

On the other hand, Fig. 4 shows a typical example of a compressional oscillation, which was observed on the dusk side on June 20, 1974. The oscillations dominate in the *V*-component of the magnetic field without any indication in the *D*-component. This oscillation is in contrast to the previous example shown in Fig. 3. The power spectrum is shown and indicates a strong peak at a period of 130 s. The polarization hodograms during the period from 0035 to 0045 UT in the planes both perpendicular and parallel to the ambient magnetic field are given at the bottom right side of the figure, and indicate that the wave oscillates dominantly in the meridional plane. Note that the polarization of the wave is opposite to that of the transverse one.

3.2. Local time dependence of occurrence and period

As described in the previous subsection, the magnetic pulsations of Pc 4 in the period range from 40 to 180 s are clearly divided into two types, *i.e.*, transverse and compressional. In this section the occurrence characteristics of local time dependence and of dominant period will be examined for these two types of pulsations.

In the 92 days data we found 65 transverse and 50 compressional wave events. Average periods of the oscillations for an interval of ten minutes were calculated for each event. The periods are plotted against local time in Fig. 5. The magnetic activities are indicated by three different symbols, *i.e.*, circles, triangles and squares, which correspond to $Kp \leq 2+$, $3- \leq Kp \leq 3+$ and $4- \leq Kp$, respectively. The solid and open symbols show compressional and transverse waves, respectively. The local

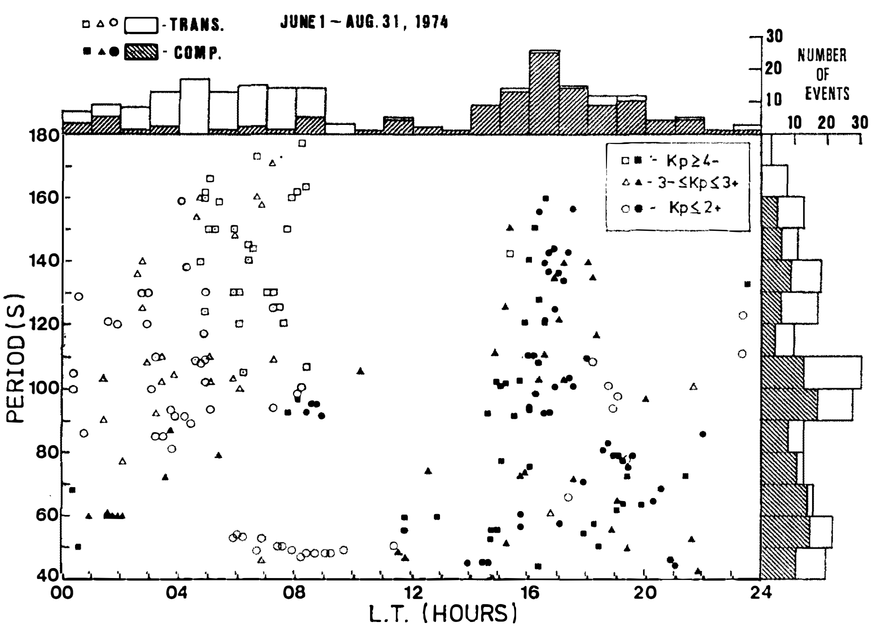

Fig. 5. Local time distribution of period and occurrence for transverse and compressional waves during three months from June 1 to August 31, 1974. Open symbols: Transverse waves. Solid symbols: Compressional waves.

time occurrence is given in the histogram at the top of the figure, and the occurrence of the oscillation periods is shown at the right of the figure. The figure indicates that the compressional waves occur mostly during the afternoon hours from 14 to 20 LT with their periods distributed from 40 to 160 s. The tarnsverse waves occur dominantly in the morning hours, with periods mostly longer than 90 s.

3.3. *Magnetic activity dependence*

The relation between the magnetic activity *Kp*, and occurrence of compressional and transverse magnetic pulsations of Pc 4 will be examined in detail in this subsection. Figure 6 shows percentage occurrence of various values of *Kp* both for the 24 h interval and for each three hours. The top panel illustrates the 24 h percentage occurrences

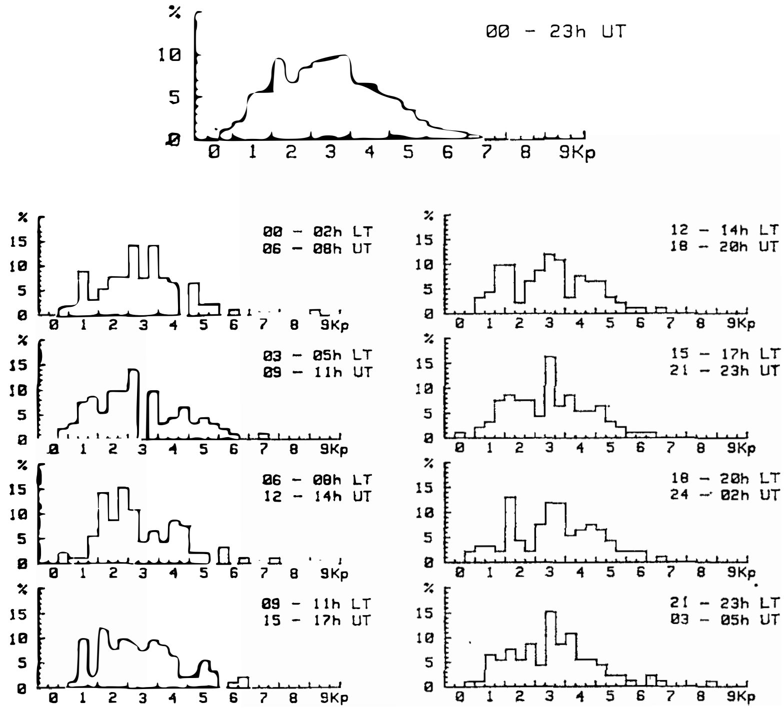

Fig. 6. Occurrence of Kp during the observation period. Top: For the entire period. Bottom: For each three-hour period. The occurrence maximizes around Kp=2 to 3 for the whole period.

of *Kp* for the whole interval from June 1 to August 31, 1974. The *Kp* occurrence maximizes at *Kp*=2 to 3, with a gradual slope to both sides of the peak. On the other hand, the lower eight panels show the percentage occurrence of *Kp* for each three hour interval. These panels indicate that throughout the day there are different distributions of occurrence for *Kp*. In the morning hours local time the occurrence is maximum for *Kp*=2 to 3, while in the evening hours the occurrence is maximum for *Kp*=3 to 4. In order to examine the dependence on the magnetic activity, the percentage occurrences of magnetic waves should be normalized using the occurrence distribution of *Kp* during the same period in which the magnetic waves were observed. Hereafter, the occurrence of the magnetic waves for a certain *Kp* value is normalized to the occurrence during the observation period of that *Kp*.

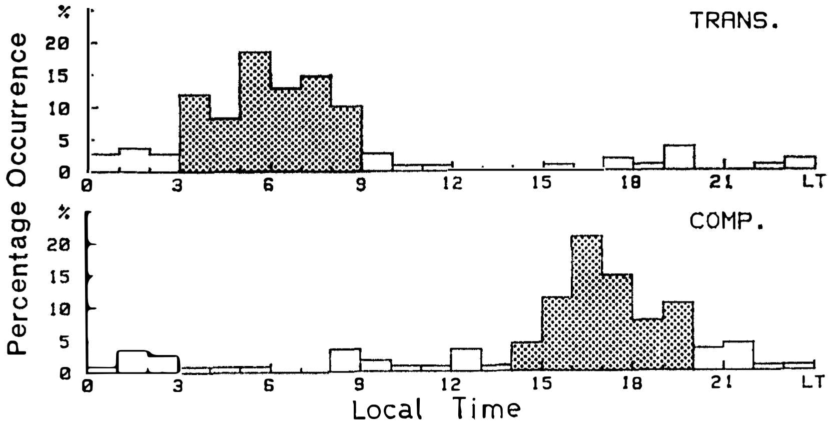

Fig. 7. Local time dependence of occurrence of Pc 4 magnetic pulsations for both compressional and transverse waves. Transverse waves occur dominantly in the dawn, while the compressional ones occur at dusk.

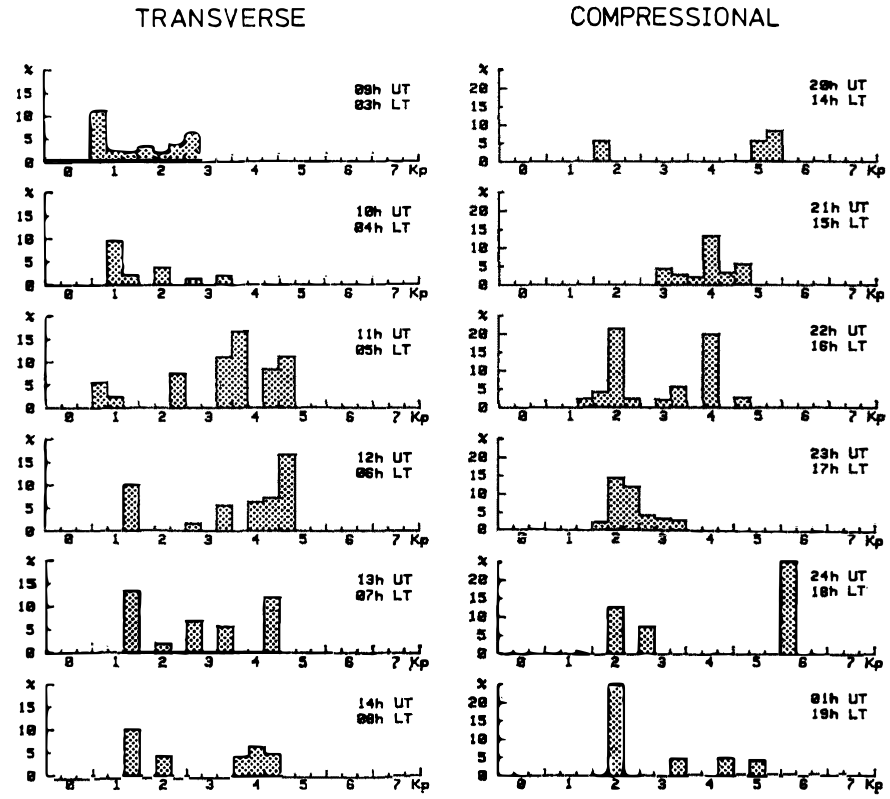

Fig. 8. Kp dependence of occurrence for both compressional and transverse type Pc 4 magnetic pulsations during each one hour interval. The occurrence shows peaks at the lower magnetic activity. The peak occurrences for compressional waves shift toward noon as the magnetic activity increases.

Figure 7 shows the local time dependence of percentage occurrence for transverse and compressional Pc 4 magnetic waves. As shown in the figure the transverse type magnetic waves occur largely in the morning hours from 03 to 09 LT (09 to 15 UT), while the compressional ones dominate in the afternoon hours from 14 to 20 LT (20 to 02 UT). These time intervals are indicated with shaded area. Figure 8 shows the *Kp* dependences of the percentage occurrences of the transverse and compressional waves for each one hour intervals in the morning (03 to 08 LT) and in the afternoon (14 to 19 LT). For the transverse waves the occurrence shows no significant dependence on *Kp*. For the compressional waves the occurrence peaks at the lower magnetic activity, $Kp=2$, throughout late afternoon hours from 16 to 19 LT, and it becomes to be dominant at the higher magnetic activity as local time shifts towards the dayside (16 to 14 LT).

The characteristics of the Pc 4 magnetic pulsations examined here are summarized as follows;

1) The waves can be classified into two typical oscillation types, *i.e.*, compressional and transverse ones.

2) The compressional type polarizes in the meridian plane, while the transverse type polarizes in azimuthal direction.

3) The occurrences of the compressional and transverse waves peak at the dusk and dawn, respectively. The dominant period of these oscillations ranges from 40 to 110 s for the former and from 90 to 180 s for the latter.

4) The peak occurrence for the compressional waves shifts towards noon with increase of magnetic activity.

4. Harmonics of Compressional Magnetic Pulsations Observed at Synchronous Orbit

In this section our discussion is focussed on examining the oscillation mode of compressional Pc 4 waves. The oscillation mode is examined by using both data of the magnetic field and the plasma density. We can refer to the plasma densities observed at the synchronous satellite, GEOS 2, in our examination. On the other hand, the plasma density at synchronous orbit can be estimated from the observed wave period by assuming the wave to be a standing oscillation along magnetic field line. We decide whether the oscillation is a fundamental or second harmonic mode, by comparing the observed and the estimated plasma density.

In order to estimate the plasma density from the wave period, we use a density model of the type $n=n_0(r_0/r)^m$ where n_0 is equatorial plasma density at a geocentric distance r_0, and m is the density index, a parameter which characterizes the variation of plasma density with geocentric distance along a field line. It is appropriate to use the density model of $m=4$ in our case, since a synchronous orbit is usually expected to be outside the plasmapause, where the plasma density varies approximately as r^{-4} along a field line. The eigenperiod of the standing wave for this model is calculated by means of the refined process which was developed by CUMMINGS *et al.* (1969). The plasma density can be estimated by using the relation $n=n_0(T/T_0)^2$, where T is observed wave period and T_0 is the calculated eigenperiod for an equatorial ideal density, n_0. The calculated eigenperiod, T_0, depends on the polarization state, poloidal or toroidal. For the poloidal mode the wave magnetic field is polarized in the meridional plane, while for the toroidal mode it is polarized in the azimuthal direction. We assume the poloidal mode approximation is appropriate for the compressional wave. For convenience, we use the result from CUMMINGS *et al.* (1969) where a list of calculated eigenperiods, T_0, for the poloidal mode corresponding to the first six harmonics is given.

In Fig. 9, the observed and estimated plasma densities are plotted against the magnetic activity index *Kp*, with three different symbols. The plasma densities calculated from the observed wave period by assuming the fundamental and second harmonic for the wave mode are illustrated by solid triangles and circles, respectively. Open squares show plasma densities observed at GEOS 2 during periods both from November 30 to December 21, 1978 and March 20 to 28, 1979. A comparison of the estimated and observed plasma densities is made for a one hour interval from 16 to 17 LT, where the frequency of occurrence of the compressional wave maximizes. From the figure we see that the open squares agree well with the solid circles, but not with the triangles. This means that the distribution of plasma density observed at GEOS 2 agrees with the estimated density assuming a second harmonic mode oscillation for the compressional waves.

Periods for both modes of fundamental and second harmonic oscillations corresponding to the observed plasma density are plotted on the right-hand side of the figure. The periods vary from 200 to 600 s for fundamental oscillations and from 60 to 200 s for the second harmonic. The periods of the observed waves are seen to agree well with those calculated for the second harmonic mode of a standing oscillation.

Therefore, we conclude that the compressional waves are due to second harmonic mode of resonant oscillation of magnetic field line passing through the satellite.

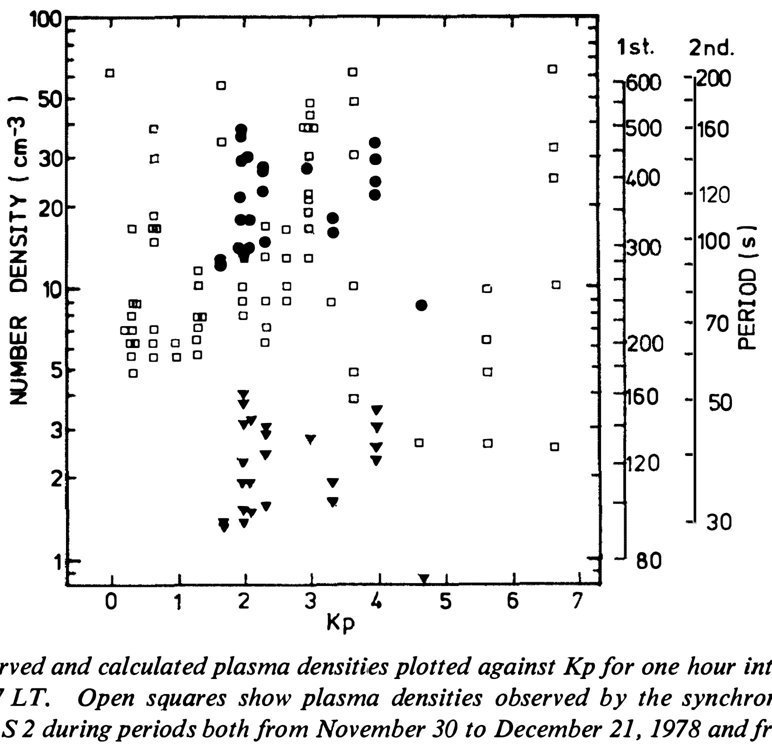

Fig. 9. Observed and calculated plasma densities plotted against Kp for one hour interval from 16 to 17 LT. Open squares show plasma densities observed by the synchronous satellite, GEOS 2 during periods both from November 30 to December 21, 1978 and from March 20 to 28, 1979. Solid triangles and circles illustrate the plasma densities calculated from the period of the compressional wave assuming a fundamental and a second harmonic oscillation, respectively.

5. The Close Relationship of Compressional Magnetic Pulsations to Energetic Proton Flux Oscillations

5.1. Simultaneous occurrence of magnetic pulsations and ring current proton ULF waves

In this section another character of simultaneous oscillations between magnetic and proton flux oscillations will be examined in detail. Local time dependence of the frequency of occurrence both for the magnetic pulsations Pc 4 and proton ULF oscillations, are given in the top and bottom panels of Fig. 10, respectively. The data of the magnetic and proton ULF oscillations were also obtained by ATS-6 during the period from June to August 1974.

The proton ULF oscillation data used here were examined by SU *et al.* (1977) in the energy range from 22.5 to 234 keV. It is clear from the figure that magnetic pulsations Pc 4, and the proton ULF waves show a very similar local time dependence.

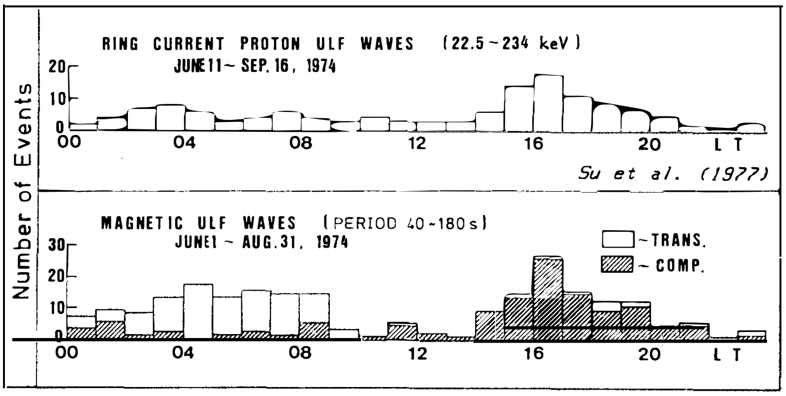

Fig. 10. Local tlme dependence of occurrence of ring current proton ULF waves (top) and magnetic ULF waves (bottom) showed a similar local time dependence.

The proton ULF waves occur most frequently near 16 LT, although they are observed at all local times, and the magnetic pulsations also have a peak in the afternoon around 16 LT, consisting mainly of compressional waves. This statistical character suggests that the compressional magnetic oscillations strongly correlate with proton ULF oscillations.

Some individual supporting evidence is shown in Figs. 11, 12 and 13 by presenting the proton and magnetic ULF oscillations data observed at ATS-6. Figure 11 shows an example of the simultaneous occurrence of the magnetic (top) and proton flux (bottom) ULF oscillations in the evening on June 20, 1974. The proton data obtained by the NOAA low energy proton detectors are shown for three different orientations with respect to the spacecraft, A, B and C. A is directed radially outward, B southward and perpendicular to the A telescope. C is mounted in the plane containing telescopes A and B, and directed northward making an angle of 45° with the A telescope. Each of the detector telescopes is capable of measuring the differential energy number flux for protons with energies from 25.5 to 234 keV in six intervals, $25.5 \leq \Delta E1 < 33.4$ keV, $33.4 \leq \Delta E2 < 47.8$ keV, $47.8 \leq \Delta E3 < 70.8$ keV, $70.8 \leq \Delta E4 < 100.2$ keV, $100.2 \leq \Delta E5 < 150.5$ keV, $150.5 \leq \Delta E6 < 234$ keV. Of these energy ranges three channels

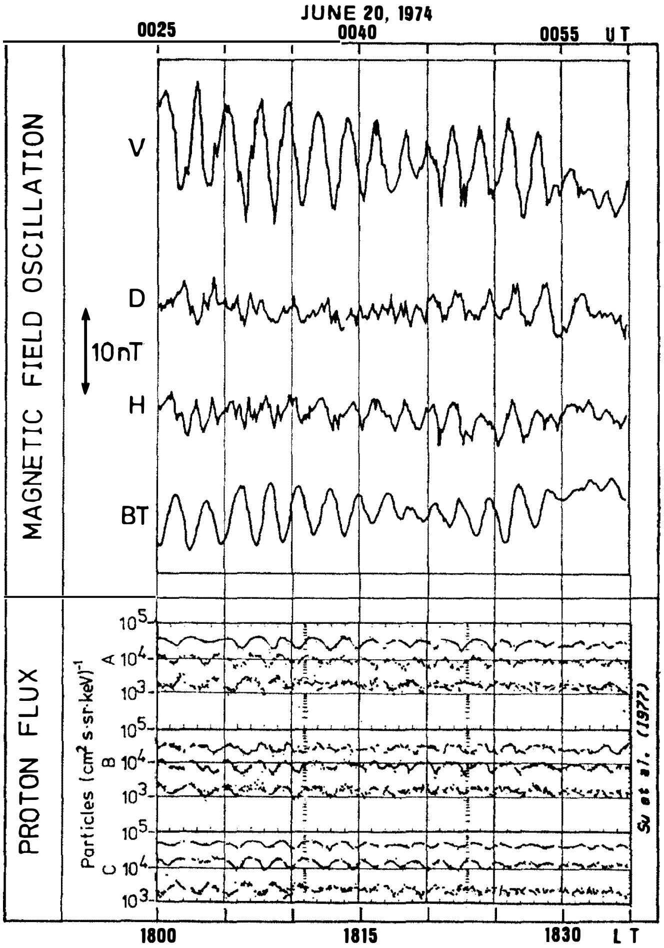

Fig. 11. A typical example of simultaneous Pc 4 oscillations. Top: Magnetic field oscillations. Bottom: Proton flux oscillations (dominant energy).

($\Delta E4$, $\Delta E5$, $\Delta E6$) are plotted in the bottom panel. The dominant period of these proton oscillations peaks around 130 s, which is similar to that of the magnetic ULF oscillations. The phase relation between the proton and magnetic oscillations differs with the orientation of telescope and the energy ranges. The low energy proton data are not shown here, since they did not indicate any significant oscillations. Figure 12 shows a similar example of another case which occurred from 0224 to 0304 UT on July 29, 1974. The magnetic waves in this case also oscillate more strongly in the *V*- and *H*-components of the magnetic field and in the total field BT, with a period of about 68 s. The proton flux shows a similar oscillation period in the energy of the $\Delta E3$, $\Delta E4$ and $\Delta E5$ channels. It is noted here that this event was followed by a substorm onset at 0300 UT. The gradual decrease in the magnitude of *H*-component of the magnetic field during the 30 min from 0230 to 0330 UT indicates that the magnetic field acquires a tail-like configuration just before the substorm onset. Thus, the wave event occurred during the period of this tail-like configuration of the magnetic field. The third example is shown in Fig. 13. The wave event of this proton flux was detected during the interval from 0548 to 0600 UT on June 11, 1974, when the

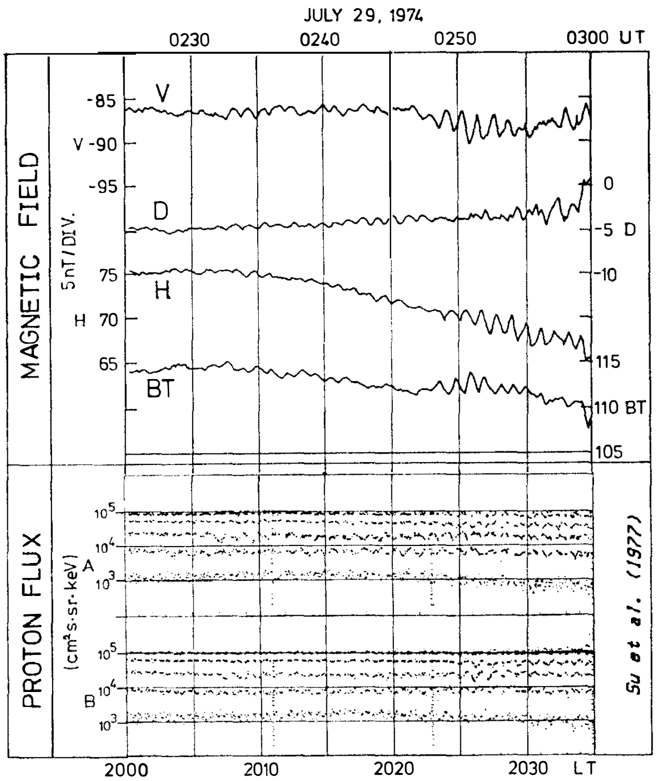

Fig. 12.

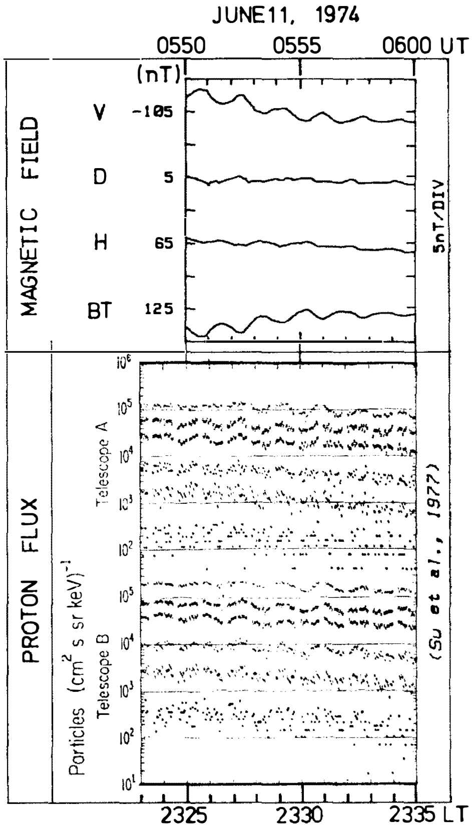

Fig. 13.

Figs. 12 and 13. A typical example of simultaneous Pc 4 oscillations. Top: Magnetic field oscillations. Bottom: Proton flux oscillations (dominant energy).

satellite was located just before the midnight meridian. In this event the flux oscillations are seen in the first three lower-energy channels. In contrast to the previous examples no apparent phase lag was observed in the flux oscillations between the different energy channels or the differently orientated telescopes. The magnetic oscillations are the characteristic compressional one as shown in the previous example. The dominant period of this magnetic ULF event is around 106 s.

These events suggest that the excitation of the magnetic ULF waves may be closely related to the oscillations of proton fluxes. In addition, the amplitude of the proton flux oscillations depends strongly on the range of energy. In Table 1 the wave period, the resonant proton energy and magnetic field configuration for the three events are summarized. In the following subsection the resonant condition for magnetic and

Table 1. Compressional Pc 4 waves with energetic proton oscillations

Event number	Universal time		Period (s)	Resonant energy (keV)	Effective L-value (Re)
	Beginning	Ending			
I	June 19 2226	June 20 0100	130	71–234	7.0
II	June 29 0224	June 29 0304	68	48–150	8.0
III	June 11 0548	June 11 06 00	106	26– 71	8.5

energetic proton waves will be examined in detail.

5.2. Resonant excitation of compressional magnetic waves by energetic ring current protons

In this subsection a resonant mechanism will be examined in detail on a basis of the clear evidence of the simultaneous occurrence of the magnetic and proton ULF waves examined in the previous subsection.

Let us suppose that a charged particle drifting and bouncing with angular frequencies, ωd and ωb, moves into the oscillation field of magnetic waves with frequency ω. In this situation a resonant oscillation for energetic particles will be described as follows (SOUTHWOOD *et al.*, 1969);

$$\omega - m\omega d = N\omega b\,, \qquad N=0,\ \pm 1,\ \pm 2,\ \cdots\,, \tag{2}$$

where m is the angular azimuthal wave number and N is an integer, which expresses the resonant mode. The energy of resonant protons can be obtained for each event, and then ωd and ωb of the resonant protons can be calculated by taking account of the pitch angle and resonant L-shell. An effective L-shell of the magnetic field on which waves are generated must be determined. From configuration of the magnetic field during the interval for each wave event the effective L-shell can be calculated by the method developed by CUMMINGS *et al.* (1978).

To determine the resonant mode of the magnetic field oscillating as a standing oscillation of field line the essential factor is N. If N is assumed to be an odd number, the resonant condition is only satisfied by standing oscillations of the even mode. The oscillations of even mode occur with an antisymmetric displacement of the field line about the equator. On the other hand, if N is taken to be an even number, the resonant condition is satisfied by standing oscillations of the odd mode. The oscillations of the odd mode occur with a symmetric displacement of the field line about the equator. The magnetic waves dealt in the previous section are compressional waves. They are found to oscillate in the second harmonic mode. Thus, the resonant condition should be considered for $N=\pm 1$, where either plus or minus sign is appropriate to this examination. The sign regulates the sign of m, which decides the direction of wave propagation relative to the direction of the drifting protons. For the case of $N=+1$, the azimuthal wave number, m, becomes $|m|<100$ with a minus sign. The minus sign means that the magnetic wave propagates in the direction opposite to the drift motion of protons. For $N=-1$, the azimuthal wave number, m, is $m>100$.

Figure 14 illustrates a relation between the energy of resonant protons and the azimuthal wave number of resonant waves for the oscillation modes of $N=-1$ and $N=0$. They are indicated with solid and dashed lines, respectively. The thick part on each solid line corresponds to each range of energy of observed protons for events I, II and III of Table 1. Once the proton energy is fixed for each wave event, the corresponding azimuthal wave number, m, is determined. As an example, for the case I, the proton flux oscillations correspond to energy from 71 to 234 keV, the azimuthal wave number, m, is determined to be $m=90$ to 180 for the mode of $N=-1$, and $m=13$ to 40 for $N=0$. The mode of $N=0$ means an odd mode oscillation of field line, which is not applicable to the compressional oscillations. The mode of

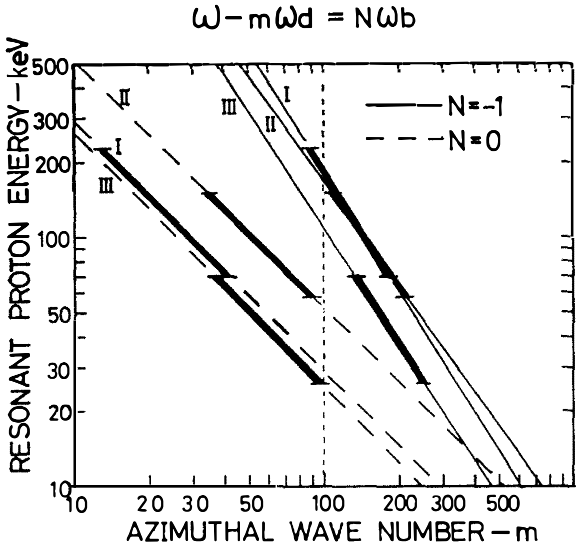

Fig. 14. The resonant condition of magnetic oscillations with energetic protons. The thick lines indicate energies of the observed protons satisfying the conditions for the corresponding wave numbers.

$N=0$ will not be discussed further. For each event the pitch angles of resonant protons are different. They range from 30° to 60°; however, the figure illustrates only protons with a pitch angle of 30°. The results are not so much different for the particles with a pitch angle of 60°.

Although the oscillation period and energy range of resonant protons are different for each wave event, the azimuthal wave number m, is $90<m<280$ for the mode $N=-1$. According to our calculations based only on the resonant conditon it is possible that the resonance occurs in either mode $N=1$ or $N=-1$. For the mode $N=1$, however, the azimuthal wave number is found to be small, $|m|<100$.

Other observational evidences for the compressional waves show that the azimuthal wave number is found to be very large, $m\gtrsim 100$ (HUGHES *et al.*, 1978, 1979; KOKUBUN, 1980). Therefore, $N=-1$ mode of oscillation is more appropriate in our case.

6. Discussion and Conclusions

The present analysis indicates that Pc 4 magnetic pulsations observed at synchronous orbit are classified into two major oscillation types; *i.e.*, radially polarized compressional wave and azimuthally polarized transverse waves. On the other hand, in the previous study another different type of oscillation of Pc 4 has been pointed out (TONEGAWA *et al.*, 1980; SAKURAI *et al.*, 1981; KOKUBUN, 1980). This type of the wave shows a radially polarized transverse oscillation. Characteristics of these three types of oscillations observed at ATS-6 are summarized in Table 2. As indicated in the bottom of the table, different nomenclatures are used for Pc 4 waves by KOKUBUN (1980) and ARTHUR and MCPHERRON (1981). They classify Pc 4 waves to A and R classes. The A and R classes are named principally on the basis of the polarization analysis of the waves, and correspond to azimuthally and radially polarized waves, respectively. It is also shown that R class waves generally have a compressional component and A class waves oscillate in the plane transverse to the ambient magnetic field. Therefore, A and R classes may correspond to the transverse (azimuthally

Table 2. Characteristics of Pc 4 type magnetic pulsations observed at synchronous orbit.

Wave mode	Compressional	Transverse	Transverse
Oscillation component	Radial and total	Azimuthal	Radial
Satellite position	Off equator		Near equator
L. T. Occurence	Evening	Morning	Daytime
Period range	40–160 (s)	80–180 (s)	40–160 (s)
L.T. dependence of period	No significant change		Longer period in late afternoon
Correlation with proton flux oscillation	Good energy dependent (KOKUBUN *et al.*, 1981)	Good energy independent (KOKUBUN *et al.*, 1981)	?
Classification by ARTHUR and MCPHERRON	R class	A class	Not described
Classification by KOKUBUN	R class	A class	R class

polarized) and compressional waves in the present study.

The compressional waves examined in the present paper appear to occur in the afternoon sector around 16 LT during rather quiet magnetic activity, and the occurrence at the higher magnetic activity increases as the local time of occurrence advances toward the dayside as shown in Fig. 8. Figure 15 shows that the equatorward inner boundary of the plasmasheet is found to move earthward with the increase of magnetic activity (GUSSENHOVEN *et al.*, 1980). In this figure the solid curves represent the locations of the earthward boundary of the electron precipitation measurements for different values of Kp. It is reasonable to suppose that the location of ring current protons moves earthward with the movement of the inner boundary of plasmasheet in association with the increase of magnetic activity. These facts suggest that the generation region of the compressional waves have a close relation to the position of ring current protons. The result seems to be consistent with the theoretical expection (SOUTHWOOD, 1976) that the radially polarized compressional waves generally occur in a hot plasma like the ring current.

A generation mechanism of the compressional waves is examined based on the resonant condition with ring current proton waves. The azimuthal wave number, m, is found to be $90<m<280$ for the resonant mode of $N=-1$. This large wave number agrees with other observational evidence obtained in a multi-satellite performed by HUGHES *et al.* (1978, 1979). On the other hand, it is suggested in Section 4 that the compressional waves are second harmonic mode oscillations of the field line. In this situation the resonant mode of $N=-1$ is also suitable for the compressional waves.

It is suggested that the compressional waves in the afternoon sector could not be detected at the ground (KOKUBUN, 1980). HUGHES and SOUTHWOOD (1976a, b) shows from a theoretical approach that a magnetospheric signal having a scale length

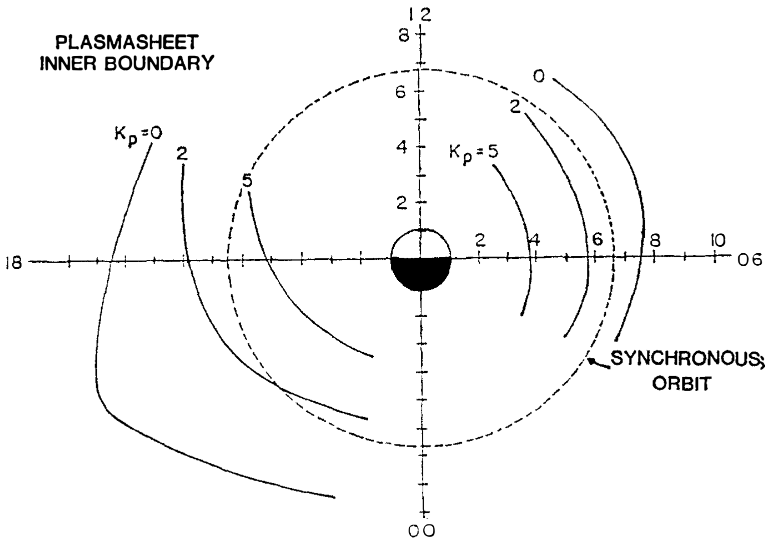

Fig. 15. Inner boundary of the plasmasheet as a function of Kp. The boundary moves earthward and as the magnetic activity Kp increases (after GUSSENHOVEN *et al., 1980).*

of less than 120 km at the ionospheric height could not be observed at the ground. The azimuthal angular wave number corresponding to this scale length at the ionospheric height is expected to be $m > 130$ at synchronous orbit. This value seems to be consistent with our result.

The characteristics of observed Pc 4 waves are summarized in Table 2. In addition to Table 2, the important characters for the compressional waves are as follows:

1) The compressional character is strongly supported by the occurrence of the dominant oscillations in the meridional plane.

2) The occurrence maximizes in the afternoon with an occurrence peak at 16 LT.

3) The waves mainly occur during the rather quiet magnetic condition of $Kp=2$.

4) The occurrence peak shifts towards noon with increase of magnetic activity.

5) The waves are found to be closely correlated with ring current proton waves.

6) A second harmonic mode ($N=-1$) is the most probable oscillation mode for the compressional waves.

7) The azimuthal wave number is found to be very large, which means that the waves can not be observed on the ground due to the ionospheric screening effect.

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