GENETIC CLASSIFICATION OF Pc3 AND Pc4
GEOMAGNETIC PULSATIONS IN MID-LATITUDES

by

TAI PING NG

A.R.M.I.T., Royal Melbourne Inst. of Technology, 1961
M.Sc., The University of British Columbia, 1966

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We accept this thesis as conforming to the
required standard

THE UNIVERSITY OF BRITISH COLUMBIA
November, 1969
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Department of Geophysics

The University of British Columbia
Vancouver 8, Canada

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ABSTRACT

Dynamic spectra processed from data recorded on magnetic tape at the mid-latitude Ralston station (Alberta) in 1967 have been studied in detail. The Pc3,4 pulsations appear to behave in a much more complicated manner than reported by other observers at low-latitude stations. The variation of the Pc3,4 frequency at Ralston assumes different forms from one day to another, the pattern depending largely upon the general level of magnetic disturbance represented by the $K_p$-index. It appears, however, that most of the Pc3,4 spectra analysed may be classified into one of, or a combination of, four well-defined diurnal patterns under steady magnetospheric conditions. An interpretation is offered to explain the existence as well as the fine structure of these four diurnal patterns. The crux of the present interpretation is that Ralston, under moderate magnetospheric agitation, may pick up micropulsation activities originating from the plasmasphere and/or the plasmatrough depending upon its position relative to the plasmapause. Eigen-oscillations of modified Alfven mode (poloidal oscillation) in these two magnetospheric regions are considered to be the prime sources of the ground observed Pc3,4 magnetic pulsations. Such suggestion is reinforced by observations made simultaneously at other mid- and high-latitude stations. Other morphological properties of Pc3 and Pc4 are discussed in the light of the new interpretation.
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At the 13th General Assembly of the International Union of Geodesy and Geophysics in Berkeley, August 1963, the notation and classification of geomagnetic micropulsations were discussed by Committee 10 of the International Association of Geomagnetism and Aeronomy. From the experimental knowledge obtained since the International Geophysical Year, it has been recognized that micropulsations can be divided into two main classes: those of a regular, and mainly continuous, character and those with an irregular pattern (Jacobs et al, 1964).

The classification scheme then proposed is listed in Table I.1. The research to be presented in this thesis is principally concerned with the $Pc3,4$ band of continuous micropulsations.

Since great advances have been made in the past five years in the field of micropulsation research and in its related fields, this classification can, of course, be improved. In particular, a better understanding of the general physical state of the magnetosphere and of the morphological properties of micropulsations enables one to define more accurately the range of periods for a number of groups. For instance, it is now a well-known fact that
there exist many different types of pulsations within the frequency range defining the Pc1 group. This enables one to subclassify Pc1 accordingly (Saito, 1964a; Troitskaya, 1967; etc.).

### TABLE I.1

CLASSIFICATION OF MICROPULSATIONS

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<th>Type</th>
<th>Range of Periods (Sec)</th>
<th>f (mHz)</th>
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<td><strong>Continuous Pulsations</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pc1</td>
<td>0.2 - 5</td>
<td>200 - 5000</td>
</tr>
<tr>
<td>Pc2</td>
<td>5 - 10</td>
<td>100 - 2000</td>
</tr>
<tr>
<td>Pc3</td>
<td>10 - 45</td>
<td>22 - 100</td>
</tr>
<tr>
<td>Pc4</td>
<td>45 - 150</td>
<td>6.7 - 22</td>
</tr>
<tr>
<td>Pc5</td>
<td>150 - 600</td>
<td>1.7 - 6.7</td>
</tr>
<tr>
<td><strong>Irregular Pulsations</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pi1</td>
<td>1 - 40</td>
<td>25 - 1000</td>
</tr>
<tr>
<td>Pi2</td>
<td>40 - 150</td>
<td>6.7 - 25</td>
</tr>
</tbody>
</table>

The Pc3,4 bands of continuous micropulsations represent one of the oldest and yet the least known field in micropulsation research. Eschenhagen observed pulsations with a period of about 30 seconds at Potsdam, Germany as early as 1896 (Kato and Watanabe, 1957b), but it was not until very recently, mainly due to the research momentum gathered since the IGY, that some of the morphological properties of Pc3,4 became better known. Even today, when nearly a decade has elapsed since the epoch.
of space exploration, some of the important properties of \( \text{Pc}3,4 \) such as the diurnal variation of frequency, latitudinal, longitudinal and \( K_p \)-dependence, etc., remain a matter of controversy. From time to time apparently contradictory results have been reported by different experimenters and there is not yet a consistent model that could explain these differences.

The scarcity of sufficiently high quality data and the inadequacy of the spectral analysis techniques employed have been recognised as two principal reasons for the existence of some of the inconsistencies. Although chart magnetograms have yielded so much information in the past and will continue to do so in the future, scaling of chart-recorded magnetograms may often be misleading particularly when more than one frequency component is involved. Various spectral analysing techniques have been developed recently in micropulsation research, one of the most successful being dynamic spectrum analysis of magnetic tape-recorded data, used, for example, in the discovery of hydromagnetic emissions (Saito, 1960; Tepley and Wentworth, 1962).

In the past three years this new spectral analysing technique has been extended to many other lower frequency regions. Hirasawa and Nagata (1966), and Nagata and Fukunishi (1968) among others, were successful in producing dynamic spectra of \( \text{Pc}3,4 \) and they observed a certain regularity
in the diurnal variation of frequency in each of these bands. Their results, however, are based only on an analysis of magnetic data from low-latitude stations.

As discussed in Chapter III, dynamic spectra processed from magnetic tapes recorded at the mid-latitude Ralston station (Alberta) in 1967 have been studied in detail. More than 500 sonagrams have been studied, and the Kay Electric Sonagraph 7029 with scale expander provides a marked improvement in the quality of these sonagrams. The results indicate that Pc3,4 observed in mid-latitudes behaves in a much more complicated manner than reported by Hirasawa and Nagata (1966) at the low-latitude station. The variation of the Pc3,4 frequency at Ralston assumes different forms from one day to another, the particular pattern depending largely upon the general level of magnetic disturbance represented by the $K_p$-index. It appears, however, that most of the Pc3,4 spectra analysed may be classified into one of, or a combination of, four well-defined diurnal patterns under steady magnetospheric conditions. An interpretation is offered to explain the existence as well as the fine structure of these four diurnal patterns.

As micropulsations are known to be of magnetospheric origin, the morphology of Pc3,4 cannot be understood without a knowledge of the structure and the physical properties of the magnetosphere.
One of the most important findings in the past five years which has had profound influence on micropulsation research is the discovery of the so-called 'knee' boundary in the magnetosphere. Using whistler data, Carpenter (1963) deduced that the equatorial electron number density drops abruptly by two orders of magnitude at a radial distance of several earth radii. This abrupt density decrease, which was designated 'knee' by Carpenter and is now also known as the 'plasmapause', was later found to be a regular three-dimensional feature of the magnetosphere (Carpenter, 1966; Angerami and Carpenter, 1966).

The plasmapause divides the magnetosphere into two regions, namely, the plasmasphere (the inner region), and the plasmatrough bounded by the magnetopause (See Fig.I.1).

The east-west asymmetry of the plasmapause configuration has been reported by Carpenter. It has been found that the dimensions as well as the configuration of the plasmapause depend strongly on the planetary magnetic conditions represented by the value of the $K_p$-index. The general properties of the plasmapause as reported by Carpenter are described in Appendix 1. Carpenter's description of the general physical properties of the magnetosphere has profoundly affected the model to be chosen to interpret observational results reported in this thesis.
Both the Alfvén velocity in the equatorial region and the estimated fundamental eigen-period for each field line oscillation have been calculated using the equatorial electron density distribution that takes into account the presence of the plasmapause. A dipole field is assumed in the present calculation, and the electron density distribution along magnetic field lines of force is taken to be proportional to a certain power $n$ ($n = 1$ is assumed) of the intensity of the local magnetic field of the earth following Watanabe (1965), Wentworth (1965), Brice (1965), and others. The result is summarized by a graph shown in Fig. 1.2.

Under the assumption that micropulsations are due to resonance in the different portions of the Earth's magnetic cavity, one might expect that micropulsations generated and/or propagated inside each cavity bounded by the Alfvén velocity maxima could characterize different physical properties of each of these regions.

The general problem of resonances in a confined plasma magnetized by a dipole field is mathematically ponderous (Dungey, 1954; Carovillano and McClay, 1965). A subset of this general problem, which considers the special case of axisymmetric oscillations has received more attention. It is found that this symmetry requirement produces a significant decoupling of the vector wave
equation into independent toroidal and poloidal modes. The toroidal mode is represented by the azimuthal component of the perturbed velocity, and the poloidal mode is represented by the same component of the perturbed electric field. The principal difference between the two modes is that the energy of the toroidal mode is guided along the field line and so should be strongly latitude-dependent whereas the poloidal mode should not. Many authors have treated the toroidal mode under various assumptions concerning the plasma density (Kato and Watanabe, 1956; Obayashi and Jacobs, 1958; Westphal and Jacobs, 1961; Radoski and Carovillano, 1966). It is not until recently, however, that a theoretical attempt has been made to study the poloidal oscillation in the magnetosphere.

It is widely believed that the Pc3 range of pulsation is caused by a standing wave of modified Alfven mode (poloidal oscillation) existing between the plasmapause and the ionosphere. Experimental evidence based on observations made at a low-latitude station by Hirasawa and Nagata (1966) and Nagata and Fukunishi (1968) provides support to this suggestion.

A theoretical calculation has been performed by Radoski (1967) where he shows that the poloidal wave equation is separable in spherical coordinates under the assumption of an axisymmetric plasma density (i.e. the Alfven speed
increases linearly with radial distance) and ambient dipole field. These simplifying assumptions are considered to represent a reasonable first approximation applicable in the plasmasphere. Radoski's calculation shows that the zero order fundamental period of poloidal oscillation in the plasmasphere is 34.2 seconds with the second order correction less than one second, which is the mean period of Pc3 typical of mid- and low-latitude observations under moderate magnetospheric conditions.

An eigen oscillation of modified Alfvén mode has also been considered to exist in the plasmatrough. A simplified theoretical consideration made by Trussell (1966) suggests this possibility. Indeed, the result of Trussell's calculation not only indicates that periods of the poloidal oscillation in the plasmatrough are in the Pc3,4 range, it also predicts a change of these periods as a function of the degree of magnetospheric disturbance represented by the sum of \( K_p \), i.e. \( \Sigma K_p \). This has been summarized by a graph shown in Fig. I.3 which is to be compared with experimental observations reported in Chapter IV (see Fig. IV.2b).

It has been observed in the present research that if the existence of standing poloidal oscillations set up in both the plasmasphere and the plasmatrough is assumed, some of the experimental observations made at the mid-latitude Ralston station may be explained, namely, the apparent
diversity of morphological properties of Pc3 from one day to another. A qualitative description of how each of the four different diurnal patterns may appear as a function of the $K_p$ index is presented in the last section of Chapter III, and further checking by experimental observation as discussed in Chapter IV. The crux of the present interpretation is that Ralston, which is located near the plasmapause under moderate magnetospheric agitation, may pick up micropulsation activity originating from the plasmasphere and/or the plasmatrough depending upon the relative position of the plasmapause.

Two different approaches have been proposed in this thesis to locate the plasmapause, assuming the existence of eigen oscillation in both the plasmatrough and the plasmasphere. In the first approach, one may take continuous observations over a single station in the mid-latitudes. The movement of the plasmapause will be manifested in the changing dimensions of each or both of the earth's two magnetic resonators, which in turn are represented in the changing eigen period of the ground-observed micropulsation (Pc3 range). The movement of the plasmapause depends on the level of magnetic disturbances in the magnetosphere as well as on the variation of the solar wind parameters represented by the changing value of the $K_p$ index. At certain levels of magnetic activity, represented by different values of $K_p$, boundary effects may be observed at Ralston that will
indicate the approximate location of the plasmapause. The Kp dependence of Pc3 observed at Ralston will be studied in Chapter IV.

The second approach one may take to locate the plasmapause is to have simultaneous observations made over a chosen distribution of stations, a number of which preferably lie along the same meridian. Comparison of these simultaneous records would indicate the latitude dependence of Pc3 frequency which in turn would provide information on the position of the plasmapause.

The second approach is superior to the first, provided the network of stations is well chosen and the stations are operating in an exactly identical manner, for it is possible to pinpoint more accurately the location of the plasmapause at a given instant of time.

In Chapter V, the latitude-dependence as well as the local time dependence of Pc3 are studied using the classification scheme proposed in Chapter III as a guideline. A network of three main stations is chosen for comparison. These stations are so situated that two of them, namely Great Whale River and McGill, lie close to the same geomagnetic meridian whereas Ralston and McGill are at about the same geomagnetic latitude. The telluric sonagrams published in High Latitude Geophysical Data by the Geophysical Institute, College, Alaska over a period from January to March 1967 have also been used for comparison.
The observational results thus obtained provide further support for the postulated model described in the previous chapters.

A preliminary study has been carried out on Pc4 observed at Ralston, the result of which will be reported in Chapter VI.

In the final chapter, we shall propose future experiments so that some of the ideas described in this thesis may be investigated.
FIG. 1.1  THE MAGNETOSPHERIC REGIONS
FIG. 1.2 MAGNETOSPHERIC EQUATORIAL ALFVEN VELOCITIES
FIG. I.3  THEORETICAL ESTIMATION OF DEPENDENCE OF Pc2, 3 and 4 PERIOD IN THE PLASMATROUGH ON MAGNETIC ACTIVITY (AFTER TRUSSEL, 1966)
CHAPTER II

SOURCE OF DATA AND INSTRUMENTATION

II.1 SOURCE OF DATA

Data recorded on charts and recently also on tapes have been made available through the Defence Research Establishment, Pacific. For more than eight years cooperative field work has been carried out between the Radio Science Laboratory, Stanford University, the Pacific Naval Laboratory (now the D.R.E.P.) and the University of British Columbia. One of the main interests has been conjugate point studies at the two stations, Great Whale River and Byrd. A third mid-latitude station at Ralston, Alberta was also established. All stations are installed with identical systems. Magnetograms recorded at McGill for specific days in the earlier years (1963-1965) are also available through the cooperation of the D.R.E.P.

The telluric sonagrams published in High Latitude Geophysical Data by the Geophysical Institute, College, Alaska over a period from January to March 1967 has also been used in this investigation.

In Fig. II.1a, a map is provided showing the relative position of the various stations. The geomagnetic and geographic latitude and longitude of each station are listed in Table II.1.
The available data on the rapid variation of the earth's magnetic field were recorded in three orthogonal field components X, Y, and Z along the geographic east-west, north-south and vertical directions respectively, but if comparisons are to be made among stations, care must be taken to account for any local anomaly that may exist. Weaver (1963) and others have shown that a conductivity discontinuity will materially affect the ratio of the vertical to horizontal components of the magnetic field. However, since even dry earth is a good reflector as far as micropulsation frequencies are concerned the magnitude of the horizontal components should not be greatly affected by the nearness of a conductivity discontinuity. Experimentally, this has been found to within at least a factor of two; see for example Christoffel et al (1961) who show results from Westham Island. The intensity of the horizontal components were only slightly affected by the contrast in conductivity. Lokken (1964) also found that micropulsations in the vertical component, as would be expected, are very much reduced in intensity over Sable Island.

Throughout the course of the study to be reported here therefore, only the horizontal X and Y components are used for investigation. No attempt has been made to deduce any conclusions that include the Z component.
Also, since the X and Y components are very similar, we have processed from Ralston all of the 1967 magnetic tape data for the X component whereas tape recorded data for 3 months only (February, March, and August 1967) have been processed for the Y component.

Only the X component recorded on tape is of sufficiently low noise to signal ratio at Great Whale in the Pc2, 3, and 4 frequency range, and data for three months (February, March, and August 1967) have been processed.

Micropulsation data recorded continuously on chart are available from Ralston, Byrd and Great Whale in both X and Y components. Normally they were recorded with a chart speed of 6 inch/hour, but occasionally, a high chart speed of 3/4 inch/min was used, providing a much higher frequency resolution. High-speed chart-recorded magnetograms are also available from McGill and Westham Island in both X and Y components for specific time intervals.

Of the vast amount of chart recorded data available, a synoptic examination only has been taken. The data are so selected that only those available simultaneously from a maximum number of stations are used. In Table II.2, the different forms of data from various stations used in the present investigation have been tabulated. The designations X, Y, and XY represent the field components examined in that particular time interval. XY means X and Y.
# Table II.1

## The Location and Magnetic Elements of Stations from Which Data Was Made Available

<table>
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<tr>
<th>Station</th>
<th>Geographic</th>
<th>Geomagnetic</th>
<th>Incl. of</th>
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<td>Long (W)</td>
<td>Lat (N)</td>
<td>Long (E)</td>
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<td>119°30'</td>
<td>-70°.6</td>
<td>336°.3</td>
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<tr>
<td>Great Whale River (GW)</td>
<td>55°16'</td>
<td>77°47'</td>
<td>66°.6</td>
<td>347°.4</td>
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<tr>
<td>College (Co)</td>
<td>64°52'</td>
<td>147°50'</td>
<td>64°.6</td>
<td>256°.5</td>
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<tr>
<td>Ralston (RA)</td>
<td>51°12'</td>
<td>111°07'</td>
<td>58°.8</td>
<td>305°.5</td>
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<tr>
<td>Eights (EI)</td>
<td>-75°14'</td>
<td>77°10'</td>
<td>-63°.8</td>
<td>355°.3</td>
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<tr>
<td>McGill (MG)</td>
<td>45°32'</td>
<td>73°09'</td>
<td>57°.0</td>
<td>354°.3</td>
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<tr>
<td>Westham Island (WI)</td>
<td>49°06'</td>
<td>123°11'</td>
<td>54°.7</td>
<td>292°.9</td>
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### TABLE II.2

**SELECTED DATA USED IN THE PRESENT INVESTIGATION**

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<td><strong>La Cour Type</strong></td>
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II.2 RECORDING AND REPRODUCING SYSTEM

The rapid variation of the geomagnetic field has been resolved into three orthogonal components for the purpose of detection. The detecting equipment in the horizontal axes (X in the geographic north-south and Y in the east-west directions) consisted of mumetal cored solenoids. Signals received by these coils were fed to recorders through d.c. chopper amplifiers.

Two types of data recorders were used. One is the Esterline Angus chart recorder, with a chart speed of 6 inch per hour or with a higher speed of 3/4 inch per minute. For analysis, the higher speed was used for Pc2, 3 and 4 micropulsation signals and the slower speed for Pc3, 4 and 5 signals. The higher speed was required to resolve Pc2 while the long period Pc5 could best be observed at the slower speeds.

Data may also be recorded on magnetic tapes. The recording tape speed is 0.025 inch per second (7.5 ft. per hour). This provide 10 days of continuous recording on 1800 feet of 1 mil magnetic tape (7 inch reels, 1/4 inch wide tape). In order to identify events recorded on tapes, simultaneous recordings were made on helicorder charts operating with a chart speed of 3 cm per min.

The frequency domain of interest defined by the D.R.E.P. group (English et al, 1961) who were responsible for the experimental operations, has an upper frequency
limit of 100 Hz and a lower limit of 0.01 Hz. The frequency response curve for the equipment of the D.R.E.P. group, given by English et al (1961), is shown in Fig. II.2a.

A block diagram of the micropulsation recording system is shown in Fig. II.2b, a detailed description of which may be found in the Technical Memoranda published by the Defence Research Board of Canada (Weir, 1966; Lokken 1964; Shand et al, 1959; Gibb, 1968).

The reproduction speed for the tape is 3-3/4 inch per second, giving a frequency multiplication of 150, therefore 10 days of data can be played back in 1.6 hours. The record bandwidth is 0 to 4.0 Hz and the reproduction bandwidth is 0 to 600 Hz.
DETECTOR NO. 15
FILTER "A"
AMPLIFIER NO. 1425
FORT CHURCHILL, MAN. OCT. 2, 1960

FIG. II.2a FREQUENCY RESPONSE OF F. M. RECORDING SYSTEM
FIG. II.2b  MICROPULSATION RECORDING SYSTEM
II.3 TAPE ANALYSING SYSTEM

In order to feed the output of the reproducing unit (which has already been multiplied by 150 times the frequency of the signal) into a sonagraph for spectral analysis of the Pc3 frequency range, the output signal must be further speeded to suit the design of the sonagraph. To achieve this, the output of the reproducing unit has been re-recorded by an eight-channel Sanborn tape recorder with a recording speed of 15/16 inch per second (recording bandwidth is d.c. to 313 Hz). The recorded signal is then played back with a higher speed of 60 inch per second (reproduce bandwidth is d.c. to 20 KHz), thus a resultant speed-up factor of 150 x 64, or 9600, has been achieved. Thus, a micropulsation signal in the 0.01 to 0.1 Hz frequency range has now been speeded up to 96 to 960 Hz, ready to be processed by the sonagraph. The specification and technical data for the Kay Electric sonagraph are tabulated in Appendix 2 for reference.

The visual records which contain the analysis of the recorded micropulsation waves are made on non-photographic, current sensitive, facsimile-type paper. The paper is mounted on a drum whose axis is the same as the turntable on whose periphery the continuous magnetic recording film is deposited. The arrangement provides automatic time synchronization. The record is traced by a stylus which advances upward, and at the same time changes the apparent center frequency of the
analyzing band pass filter. A high-frequency current applied to the stylus is varied in amplitude in proportion to the amount of energy passed by the bandpass filter. The first type of record obtainable displays time on the abscissa, frequency on the ordinate, and intensity as shading between gray and black. The second type of record displays intensity in db vs. frequency at as many as six selected times. This display has a dynamic range in intensity of 35 db. The third type of record displays average available amplitude vs. time within a dynamic range of 34 db maximum.

Only the first type of record, i.e. the frequency-time display, however, has been found useful in our present investigation. In addition, a Kay Electric contour unit has been used to produce contoured sonagrams which are useful in locating the mid-band frequency of a given signal. A scale expander is also available to expand the frequency scale so that, coupled with a correct choice of recording speed, any portion of a given spectrogram may be expanded to show a finer detail.

The telluric sonagrams published in High Latitude Geophysical Data by the Geophysical Institute, College, Alaska and used in this thesis for comparison purposes is a continuous frequency-time display of telluric current activity in the period range of 9 to 500 sec. The telluric system has the advantage of larger low frequency response
than an induction loop system and a better signal to noise ratio because of the millivolts available from the telluric electrodes in comparison with the microvolt signal of the induction loop.

The amplifier is a Medistor microvoltmeter set at 10 mv range and logarithmic scale. The logarithmic response makes it possible to accommodate the wide dynamic range of activity which occurs at College in the frequency range under investigation. Thus with constant gain settings the low amplitude Pc3 daytime activity can be brought out clearly on the sonagrams, and with no overloading of the instrumentation due to the powerful nighttime Pi activity.

The tape recorder is a Knight 4000A direct record instrument which has been modified to record at 1-1/6 inch per hour. The frequency response of the playback amplifier and Vibralyzer are shaped such that average activity at the bottom of sonagram is not too black and average activity at the top is not too faint. To accomplish this, the response was made to increase monotonically toward higher frequencies. If a flat response had been used, the upper part of the sonagrams would usually be blank when a reasonable level was present at the bottom. The departure from flatness is not sufficient to significantly distort the Pc3-5 activity.
CHAPTER III

SUBCLASSIFICATION OF Pc3 IN MID-LATITUDE-DIURNAL VARIATION OF Pc3 FREQUENCY AT RALSTON

III.1 INTRODUCTION

Recently, various authors have shown from satellite data that there is a definite connection between the period of continuous pulsation (Pc 2, 3, and 4) and the changes of magnetospheric dimension (Bolshakova and Troitskaya, 1964; Bolshakova, 1965a; Nagata et al, 1966). The same authors have indicated also that the variation in period of continuous pulsations may be able to serve as a new characteristic of the solar wind (Bolshakova, 1965a; Nagata et al, 1966; Troitskaya, 1967). Since a Pc3 event takes place every day, if the period of a Pc3 micropulsation is indeed a manifestation of the general physical condition of the magnetosphere and beyond, micropulsation research could provide us continuously with a most economic 'window' to the exosphere.

Research in the diurnal behaviour of the continuous micropulsation period is a topic which is nearly as old as the subject itself. E.R.R. Holmberg (1951, 1953) noticed the systematic change of Pc3 and Pc4 periods and produced the well-known scatter diagram of period against time using data obtained by an induction loop at Eskdalemuir as early as 1926 and 1927. Since then many workers have reported results of their
observations, and yet this particular subject remains a matter of controversy even today. Many authors concluded from scaling magnetograms that the frequency of Pc3 behaves as a U-type (inverted U-type in period) diurnal variation (Kato and Saito, 1959; Yanagihara, 1959; Pope et al, 1962; Holmberg, 1953), that is to say the frequency of Pc3 is lower in the afternoon than that in the morning. More recent observations made by several researchers using data recorded on charts as well as on slow speed magnetic tapes demonstrates the contrary. Using slow speed magnetic tape data recorded at Kakioka Field Station in Japan (26.0° in geomagnetic latitude), Hirasawa and Nagata (1966) reported that the frequency of Pc3 appears to be higher early in the morning and then decreases to the lowest point late in the afternoon. This report agrees with the result shown earlier by Duncan (1961) using also slow speed tape recorded data and charts from Hobart (φ = 52°), Camden (φ = 43°), Adelaide (φ = 45°) and Townsville (φ = 29°) in Australia.

Other authors, noticeably Stuart and Usher (1966) observed a similar trend at Lerwick (φ = 62.6°), but different at Eskdalemuir (φ = 58.5°) and Hartland (φ = 55.1°). At Eskdalemuir, the diurnal variation of frequency is very slight whereas an inverted U-type of diurnal variation in frequency is apparent at Hartland. Nagata and Fukunishi (1968) also found inverted U-type diurnal variation in frequency at Kakioka, Japan.
Each of the above mentioned types of diurnal variation in frequency has been identified at Ralston ($\varpi = 58.8^\circ$). Some occur more frequently than others. The U-type is found to be the least frequent. Out of the data under study in 1967 only two such cases were found, and these occurred only under irregular magnetospheric conditions. The U-type may therefore be taken as an exceptional case rather than a persistent phenomenon.

On the other hand numerous examples were found having diurnal variation resembling that reported by Hirasawa and Nagata, Duncan, Stuart and Usher, and Nagata and Fukunishi. Furthermore, the types reported by these authors may be shown to be particular cases of an enlarged classification scheme (or subclassification scheme) that we are about to propose in this chapter.

Scrutiny of displays of sonagrams (dynamic spectra) processed from slow speed recorded data recorded at Ralston suggests that there are four basic types of diurnal variation of frequency apparent under steady magnetospheric conditions. The majority of events under study could be classified into one of, or the combination of, these four basic types. This, however, does not imply that exceptions may not take place, but the exception will rarely occur. Moreover, these exceptions may be shown to take place only under rapidly changing magnetospheric conditions represented by the $K_p$ index. An inverse relation between $K_p$ and the radius of the
magnetosphere was documented by Cahill and Amazeen (1963). Some of the exceptional cases will be presented in Section III.6. In the following sections the four proposed sub-categories of Pc3 continuous pulsation will be described in detail with examples given wherever possible.
III.2 MULTI-BAND STRUCTURED CONTINUOUS PULSATION

One of the most interesting findings that justifies our proposal for reclassification or subclassification of continuous pulsation is the existence of multi-band structure in frequency. Experimental evidence indicates that two or three frequency bands may often be identified within the framework of Berkeley resolution (Jacobs et al, 1964) defining the boundary of Pc3 micropulsation (Mainstone, 1967). Occurrence of these distinct Pc3 frequency sub-bands may not be unusual at Ralston. Rather they usually occur only for a brief interval of time. Or, when the frequency bands overlap, the ordinary sonagraph fails to provide sufficient resolution to reveal them. It has been evident to us for some time that scrutiny of rapid-run magnetograms (3/4 inch per minute chart speed) obtained at mid-latitude stations may often identify double periodicity. Further, the periods of the two waves superimposing each other are within the Pc3 frequency range (see Fig. III.2a). But analysis by scaling magnetograms has often proved to be misleading. No definite conclusions may be drawn until further evidence becomes available. It is rather fortunate that a sample of 13 days in total of multi-band structured Pc3 has been identified out of the slow speed tape recorded data obtained at Ralston in 1967. Each of these multi-band structured Pc3 events identified last for at least three hours.
In Table III.1, we have listed all the days of high quality multi-band structured Pc3 at Ralston in 1967. We have listed also the mid-frequency of each band for comparison. With an only exception of \( f_1 \) which is in the Pc4 range, the other three bands \( f_2, f_3 \), and \( f_4 \) are inside the boundary of Pc3 defined by the Berkeley resolution. In order to locate the mid-frequency of each individual sub-band accurately, contoured sonagrams are made which have been found to be most efficient. We have also listed the time intervals during which multi-band structure has been observed on each of these days. It is evident from Table III.1 that the multi-band effect is strongest around or just after local noon. Only on the days of moderately disturbed magnetic conditions do we find strong multi-band characteristics in the morning (noticeably on November 24, December 6, 7, and 8, 1967), and it is again on these moderately disturbed days that the fourth band \( f_4 \) becomes noticeable.

The association of Pc4 with the occurrence of multi-band Pc3 should not be taken as purely incidental. Further discussion will be given in the later sections.

In Fig.III.2b one of the most demonstrative examples of multi-band structured Pc3 is shown. The multi-band structure is only vaguely seen earlier in the day. The frequency of all bands decreases as the day proceeds towards the afternoon. There is an enhancement of Pc3 activity observed at 1100 L.T. The enhancement of both Pc3 bands
<table>
<thead>
<tr>
<th>Date</th>
<th>Kp</th>
<th>Mid $f_1$</th>
<th>Mid $f_2$</th>
<th>Mid $f_3$</th>
<th>Mid $f_4$</th>
<th>Time of Occurrence</th>
<th>Maximum Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb 5</td>
<td>22</td>
<td>0.010</td>
<td>0.025</td>
<td>0.040</td>
<td>0.065?</td>
<td>10 - 12 LT</td>
<td>11 - 12 LT</td>
</tr>
<tr>
<td>Feb 11</td>
<td>19</td>
<td>0.010</td>
<td>0.022</td>
<td>0.038</td>
<td>--</td>
<td>Daytime</td>
<td>Noon</td>
</tr>
<tr>
<td>Feb 12</td>
<td>4</td>
<td>0.010</td>
<td>0.022</td>
<td>0.035</td>
<td>--</td>
<td>8 - 16 LT</td>
<td>Noon</td>
</tr>
<tr>
<td>Mar 3</td>
<td>15</td>
<td>0.010</td>
<td>0.020</td>
<td>0.030</td>
<td>--</td>
<td>Daytime</td>
<td>15 - 16 LT</td>
</tr>
<tr>
<td>Jul 12</td>
<td>17</td>
<td>0.012</td>
<td>0.025</td>
<td>0.035</td>
<td>--</td>
<td>10 - 16 LT</td>
<td>13 LT</td>
</tr>
<tr>
<td>Aug 23</td>
<td>10</td>
<td>0.010</td>
<td>0.025</td>
<td>0.040</td>
<td>--</td>
<td>Daytime</td>
<td>12 - 14 LT</td>
</tr>
<tr>
<td>Sep 3</td>
<td>12</td>
<td>0.012</td>
<td>0.025</td>
<td>0.040</td>
<td>--</td>
<td>Daytime</td>
<td>15 - 18 LT</td>
</tr>
<tr>
<td>Sep 4</td>
<td>13</td>
<td>0.012</td>
<td>0.025</td>
<td>0.035</td>
<td>--</td>
<td>4 - 21 LT</td>
<td>16 - 19 LT</td>
</tr>
<tr>
<td>Oct 13</td>
<td>17</td>
<td>0.010</td>
<td>0.025</td>
<td>0.038</td>
<td>--</td>
<td>Daytime</td>
<td>11 - 16 LT</td>
</tr>
<tr>
<td>Oct 23</td>
<td>15</td>
<td>0.008</td>
<td>0.020</td>
<td>0.030</td>
<td>--</td>
<td>Daytime</td>
<td>12 - 14 LT</td>
</tr>
<tr>
<td>Nov 16</td>
<td>17</td>
<td>0.015</td>
<td>0.025</td>
<td>0.038</td>
<td>0.060</td>
<td>5 - 18 LT</td>
<td>9 - 13 LT</td>
</tr>
<tr>
<td>Nov 23</td>
<td>16</td>
<td>0.010</td>
<td>0.028</td>
<td>0.045</td>
<td>0.070?</td>
<td>Daytime</td>
<td>13 - 15 LT</td>
</tr>
<tr>
<td>Nov 24</td>
<td>27</td>
<td>0.010</td>
<td>0.025</td>
<td>0.040</td>
<td>0.070</td>
<td>5 - 17 LT</td>
<td>9 - 11 LT</td>
</tr>
<tr>
<td>Dec 4</td>
<td>14</td>
<td>0.010</td>
<td>0.022</td>
<td>0.038</td>
<td>--</td>
<td>6 - 21 LT</td>
<td>12 - 14 LT</td>
</tr>
<tr>
<td>Dec 6</td>
<td>28</td>
<td>0.015</td>
<td>0.030</td>
<td>0.045</td>
<td>0.070</td>
<td>5 - 19 LT</td>
<td>10 - 17 LT</td>
</tr>
<tr>
<td>Dec 7</td>
<td>27</td>
<td>0.010</td>
<td>0.028</td>
<td>0.042</td>
<td>0.065</td>
<td>6 - 18 LT</td>
<td>9 - 15 LT</td>
</tr>
<tr>
<td>Dec 8</td>
<td>31</td>
<td>0.010</td>
<td>0.025</td>
<td>0.040</td>
<td>0.070</td>
<td>4 - 16 LT</td>
<td>7 - 8 LT</td>
</tr>
<tr>
<td>Dec 12</td>
<td>12</td>
<td>0.008</td>
<td>0.020</td>
<td>0.035</td>
<td>--</td>
<td>8 - 18 LT</td>
<td>17 - 18 LT</td>
</tr>
</tbody>
</table>

Average 0.011 0.024 0.038
takes place simultaneously. This is different from the
Pc\textsuperscript{4} band whose intensity has been enhanced earlier in the
morning. Maximum intensity takes place around noon for all
three bands.

Notice also in this example the irregular pulsation
P12 occurring just before and after the local midnight.

The majority of multi-band events are observed around
noon or early in the afternoon. The frequency of these types
of Pc3 is either constant or decreasing. This is different
from the types that are observed in the morning. The morning
type occurs only rarely, and those observed display an
increasing frequency trend toward noon. Two examples, shown
in Fig.III.2c and Fig.III.2d, illustrate the case of multi-
band Pc3 with constant frequency occurring in the afternoon,
and the case of multi-band Pc3 with increasing frequency
occurring in the morning.

In Fig.III.2e, one example of distinct 4 band structure
has been demonstrated. This occurs on a day when the general
disturbance level is high. But the magnetic activity takes
place fairly steadily as indicated by the steady value of the
K\textsubscript{p} index. It is interesting to note the spike-like discrete
appearance of the spectrogram which is most apparent after
1500 L.T. This is contrary to the generally continuous and
diffused appearance, such as occurred on February 12, 1967,
Fig.III.2c.
FIG III.2a  September 18, 1965
MULTI-PERIODICITY OF Pc3
FIG III.2b RALSTON Y  11 FEB 67

MULTI-BAND Pc3 WITH DECREASING FREQUENCY FROM DAWN TO DUSK
FIG III.2c RALSTON Y 12 FEB67

MULTI-BAND Pc3 WITH CONSTANT FREQUENCY
FIG III.2d  RALSTON X  15 NOV67

MULTI-BAND Pc3 IN THE EARLY MORNING
FIG III.2e  RALSTON X  6 DEC 67

4 BANDS STRUCTURED Pc3,4
III.3 NORMAL TYPE WITH MORNING AND AFTERNOON SEPARATION

Very often, Pc3 observed in the morning behaves differently from that observed in the afternoon or in the evening. The morning type Pc3 is usually of lower frequency than its counterpart in the afternoon.

The morning type Pc3 behaves as an inverted U-type daily variation in frequency with maximum frequency occurring around 0600 L.T. This train usually begins around 0200 or 0300 L.T. with low frequency which would then increase towards dawn. After going through the maximum frequency near dawn, the frequency begins to take a downward trend until it reaches the lowest point early in the afternoon.

Towards noon, a new train begins to take place which is of higher frequency than the one that existed in the morning. Sudden enhancement of activity of this new train occurs early in the afternoon and then its frequency diminishes rapidly toward dusk (1800 L.T.). This is demonstrated profoundly by an example shown in Fig. III.3a.

The boundary between the morning and the afternoon type is usually well defined. However there are occasions when the boundary is difficult to locate. This happens when the two bands overlap each other at the boundary.

There is strong Kp dependence on the occurrence time of the boundary between the morning and the afternoon type.
Pc3. Under moderately disturbed conditions corresponding to $K_p = 3 \rightarrow 4$, the boundary effect takes place earlier in the morning. On the other hand, when the magnetic condition is reasonably quiet ($K_p \sim 0 \rightarrow 2$), the boundary effect takes place later in the afternoon.

In Fig.III.3b an example is shown where the afternoon type of Pc3 begins in the morning. This occurs when the level of magnetic disturbance is reasonably high ($\Sigma K_p > 25$ say). Its frequency then decreases as the day proceeds towards the afternoon. The morning type of Pc3 is only vaguely recognizable, and the separation between the morning type Pc3 and Pc4 is not too clear. It is this type of diurnal variation of frequency that Hirasawa and Nagata (1966) reported from Kakioka, Japan (see Fig.III.1). Because the morning type of Pc3 observed at high and mid-latitudes become very weak at the lower latitude, observers at low-latitude stations would tend to average out the difference between this type of Pc3 with the much stronger signal of Pc4. We shall leave further discussion of this topic to the later chapter on the comparative study of continuous pulsations at stations of different latitudes and different longitudes.

The example given in Fig.III.3c is a typical observation at Ralston under quiet magnetic conditions ($\Sigma K_p = 3$ in this case.). As shown in the spectrogram, Pc3 shows an inverted U-type diurnal variation with a maximum
frequency occurring around noon. The diffused structure is typical for a quiet day under steady conditions. At 1530 L.T. the boundary between the morning and afternoon type of Pc3 may be identified. Soon after 1600 L.T. the second train of higher frequency takes over. There is some overlapping of frequency between the two trains as is clearly shown in the contoured sonagram in the lower portion of Fig.III.3c.

Pc4 is observed only rarely at Ralston under very quiet and steady magnetic conditions.

The particular case where we do not observe Pc3 in the morning may occasionally take place at Ralston. An example given in Fig.III.3d contains most important features reported by Hirasawa and Nagata. The occurrence of this type is very rare at Ralston. It occurs only when the magnetosphere is expanding rapidly (see the Appendix 1 for the table of Kp index).

There is another feature which is very interesting and common to most spectrograms observed at Ralston. It has been noticed that even for the most continuous events observed, a 'blank' of 20 to 60 minute interval may often take place. This 'pause' of micropulsation activity takes place abruptly, and it does not affect the continuity of the pulsation event in other time intervals. Under mildly disturbed conditions this abrupt pause of activity usually occurred early in the afternoon, but there are cases where the pause is found earlier in the morning.
In Fig.III.3b, the pause was at 1230 L.T. and lasted for about half an hour. The pause of the February 10 event occurred at 1345 L.T. and lasted only about ten minutes (see Fig.III.3c).

The March 19 event shown in Fig.III.3e took place under disturbed conditions ($\sum K_p = 29$). The pause of this particular event occurred in the morning. It is noted that in all the cases shown, the pause took place only in the Pc3 frequency range. The Pc4 in both examples shown in Fig.III.3b and Fig.III.3e are not affected.
FIG III.3a RALSTON X 18 OCT 67

NORMAL TYPE WITH MORNING AND AFTERNOON SEPARATION
FIG III.3b RALSTON X 7 DEC 67
NORMAL TYPE UNDER DISTURBED CONDITIONS
FIG III.3c  RALSTON X  FEB 10, 67

NORMAL TYPE UNDER QUIET CONDITIONS
FIG III.3d  RALSTON X  30 OCT 67

AFTERNOON TYPE OF Pc3
FIG III.3e  RALSTON X  MAR 19, 67

THE 'PAUSE' THAT OBSERVED IN THE MORNING
THE INVERTED U-TYPE WITH DISCRETE STRUCTURE

Very often, Pc3 observed at Ralston under moderately quiet conditions ($K_p < 2$) behaves as an inverted U-type of diurnal variation in frequency. Further, unlike anything that has been so far reported by other workers, the dynamic spectrum of Pc3 may often take a spike-like discrete appearance. The time interval between successive spikes is usually about half to one hour although they do not occur at regular time intervals. The width of each spike is of the order of ten to twenty minutes. The spike of maximum frequency appears around local noon, but no definite rule has been observed governing the occurrence of such spikes.

Two examples are given in Fig. III.4a and Fig. III.4b. Both events shown occur under quiet but not too steady magnetic conditions indicated by the low but fluctuating values of the $K_p$ index.

The spike-like structured Pc3 is not restricted to the inverted U-type of diurnal behaviour. All the other types mentioned in the previous three sections may also take a discrete appearance. We prefer to consider them as a mixture of the type mentioned in this section and their own type. We are well aware that this classification is not unique. Only when the physical nature of these spikes becomes better understood can one classify them in a strict manner.
FIG III.4a RALSTON X 26 MAR 67

INVERTED U-TYPE WITH DISCRETE STRUCTURE
FIG III.4b  RALSTON X  28 DEC 67

INVERTED U-TYPE WITH DISCRETE STRUCTURE
III.5 THE DIFFUSED INVERTED U-TYPE

There is another type of Pc3 activity observed at Ralston which also displays an inverted U-form of daily variation in frequency. A sonagram of this type shows a continuous trend with no particular preference for a maximum intensity at any particular time interval. We therefore called this type of activity a 'diffused' inverted U-type in contrast to the 'discrete' inverted U-type described in the last section.

The diffused inverted U-type occurs only under steady and reasonably quiet magnetic conditions. The word 'steady' should be emphasized, because it is only when the value of the Kp index does not fluctuate over a certain level from the mean value that we may observe the diffused inverted U-type, whereas the discrete inverted U-type of diurnal variation takes place only when the magnetic condition is reasonably fluctuating. Of course, one may also think of this diffused type as only a particular case of the discrete type with the spikes crowded together.

In Table III.2, we have listed 8 clear days of diffused inverted U-type Pc3. All the events listed in Table III.2 have $\Sigma K_p$ less than 15 because we have not been able to find any good example of this type where the value of $\Sigma K_p$ is greater.

The average frequency of events listed is 30 mHz, with very small variance, and the most probable time for maximum
frequency to take place is around 1300 L.T. Most cases under study have maximum frequency occurring one hour before or after 1300 L.T.

TABLE III.2

DATES OF DIFFUSED INVERTED U-TYPE DIURNAL VARIATION OF FREQUENCY

<table>
<thead>
<tr>
<th>Date</th>
<th>$\Sigma K_p$</th>
<th>$f$ mHz</th>
<th>L.T. max$f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov 17, 1967</td>
<td>3?</td>
<td>30</td>
<td>1200</td>
</tr>
<tr>
<td>Nov 18, 1967</td>
<td>5?</td>
<td>29</td>
<td>1200</td>
</tr>
<tr>
<td>Oct 20, 1967</td>
<td>6+</td>
<td>29</td>
<td>1330</td>
</tr>
<tr>
<td>Nov 19, 1967</td>
<td>6+</td>
<td>30</td>
<td>1430</td>
</tr>
<tr>
<td>Mar 17, 1967</td>
<td>9+</td>
<td>30</td>
<td>1230</td>
</tr>
<tr>
<td>Oct 16, 1967</td>
<td>10+</td>
<td>30</td>
<td>1230</td>
</tr>
<tr>
<td>Mar 28, 1967</td>
<td>15?</td>
<td>35</td>
<td>1400</td>
</tr>
</tbody>
</table>

Two examples of the D.I.U. type of diurnal variation are shown in Fig. III.5a and Fig. III.5b where the inverted U-shape is most clear. However, some of the diffused structure Pc3 listed may behave somewhat differently. Besides the main peak in frequency obvious in all cases there are events that have secondary peaks occurring near dawn or before dusk. One such example is illustrated in Fig. III.5c where two secondary peaks are shown, one at 0600 L.T. and the
other at 1600 L.T. The occurrence of a secondary peak around dawn or dusk is not uncommon at Ralston.
FIG III.5a RALSTON X 16 OCT 67

INVERTED U-TYPE WITH DIFFUSED STRUCTURE
FIG III.5b  RALSTON X  19 NOV 67

DIFFUSED TYPE OF DIURNAL STRUCTURE
FIG III.5c RALSTON X 17 NOV 67

DIFFUSED INVERTED U-TYPE WITH SECONDARY MAXIMA
III.6 MIXED CASES OF THE FOUR BASIC TYPES

It has been observed that the great majority of $\text{Pc3}$ events occurring at Ralston may be subclassified into one of, or the combination of, the four basic types of diurnal variation of frequency described in the previous four sections. A table has been prepared where spectrograms over a period of three months in 1967 have been subclassified according to this scheme (see Table III.3).

In order to show the level of magnetic disturbance, a sketch has been prepared for each day in the third column of Table III.3. These sketches may provide us with a rough idea as to how steady the planetary magnetic disturbance is. But one must bear in mind the limitation of $K_p$ index, and care must be taken before one draws further conclusions.

The designations $x^1$, $x^2$, and $x^3$ signify the quality of each individual event with respect to each particular basic type. For example, $x^1$ shown under Type 1 would mean that the appearance of the spectrogram for this particular observation is best approximated to Type 1 diurnal variation. On the other hand, $x^2$ and $x^3$ shown under Type 2 and Type 4 respectively, indicate that this event appears to behave as a combination of Type 2 and Type 4 diurnal variation with Type 2 dominating.

Examples are given in Fig. III.6a-e to demonstrate the existence of some of the possible combinations.
In Fig.III.6a, an example is shown whose diurnal variation may be taken as a combination of the discrete inverted U-type and the morning and afternoon type. The boundary between the morning and afternoon types takes place around noon and the spike-like structure is apparent throughout most of the day.

In Fig.III.6b the inverted U-type has discrete structure early in the morning, but the appearance of the spectrogram is of the diffused type after 1100 L.T. and in the afternoon. A similar example is shown in Fig.III.6c where the diffused structure appears in the morning rather than in the afternoon.

Combination of the diffused inverted U-type with the normal type is demonstrated in yet another example shown in Fig.III.6d. In Fig.III.6e the spectral pattern shown is so complicated that each of the four basic types of diurnal behaviour may be identified.
### TABLE III.3

**SUB-CLASSIFICATION OF SOME Pc3 EVENTS**

<table>
<thead>
<tr>
<th>Date</th>
<th>( \Sigma K_p )</th>
<th>K(_p) Variation</th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
<th>Type 4</th>
<th>Misc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct 1</td>
<td>17(^+)</td>
<td>( \sim )</td>
<td>( x_3 )</td>
<td>( x_3 )</td>
<td>( x_3 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct 2</td>
<td>9(^+)</td>
<td>( \sim )</td>
<td>( x_2 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct 3</td>
<td>15(^-)</td>
<td>( \sim )</td>
<td></td>
<td>( x_2 )</td>
<td>( x_3 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct 4</td>
<td>8(_0)</td>
<td>( \sim )</td>
<td></td>
<td>( x_2 )</td>
<td>( x_2 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct 5</td>
<td>15(^-)</td>
<td>( \sim )</td>
<td>( x_2 )</td>
<td>( x_2 )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct 6</td>
<td>12(_0)</td>
<td>( \sim )</td>
<td>( x_3 )</td>
<td></td>
<td>( x_3 )</td>
<td></td>
<td></td>
</tr>
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<td>Oct 12</td>
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FIG III.6a RALSTON X 7 SEPT 67

COMBINATION OF THE DISCRETE INVERTED U-TYPE AND THE MORNING AND AFTERNOON TYPE
FIG III.6b  RALSTON X  4 OCT 67

MIXED INVERTED U-TYPE OF DISCRETE AND DIFFUSED STRUCTURE
FIG III.6c  RALSTON X  26 OCT 67

MIXED INVERTED U-TYPE OF DISCRETE AND DIFFUSED STRUCTURE
FIG III.6d  RALSTON X  OCT 25.67

MIXED INVERTED U-TYPE AND NORMAL TYPE
FIG III.6e  RALSTON X  1 SEPT 67

MIXTURE OF ALL 4 BASIC TYPES
III.7 MISCELLANEOUS TYPES

The diurnal variation of Pc3 at Ralston becomes very complicated when the planetary magnetic conditions are unsteady or when the condition is very disturbed.

However, the research undertaken in this thesis is concerned only with Pc3 that behaves under quiet to mildly disturbed conditions. No attempt has been made to study the continuous pulsation when the disturbance level is high.

In the following, there are four examples given in Fig.III.7a, b, c, and d that could not be classified into any of that described in the previous section. There are, of course, many other examples. We have noticed that their values of $K_p$ index are either too high or they are very fluctuating.
FIG III.7a   RALSTON X   FEB 23, 67

MISCELLANEOUS TYPES
FIG III.7b  RALSTON X  12 OCT 67

MISCELLANEOUS TYPES
FIG III.7c  RALSTON X  MAR 18, 67

MISCELLANEOUS TYPES
FIG III.7d  RALSTON X  29 OCT 67

MISCELLANEOUS TYPES
III.8 INTERPRETATION OF RESULTS AND DISCUSSION

Many researchers believe that the Pc4 range of pulsation is caused by a hydromagnetic wave, and that this hydromagnetic wave propagates along the field line at the plasmapause discovered by Carpenter (1966), whereas the Pc3 range of pulsation is thought of as a standing wave of modified Alfven mode (poloidal oscillation) existing between the plasmapause and the ionosphere.

Experimental evidence provided by Hirasawa and Nagata (1966) and Nagata and Fukunishi (1968) gives further support to the above postulations. By studying the diurnal variation of Pc3 and Pc4 frequency, these authors found agreement between experimental results obtained at Japanese stations with theoretical prediction. The theoretical calculation is based on general diurnal behaviour of the plasmapause configuration reported by Carpenter (1966) using whistler data. As Carpenter has shown, the geocentric distance of the plasmapause is largest at about 2000 L.T. and the shortest at about 0600 L.T. when the geomagnetic field is moderately disturbed ($K_p = 2 \rightarrow 4$). If the Pc3 range of pulsation is indeed a standing wave set up between the plasmapause and the ionosphere, it should behave as a diurnal variation that has maximum period around 2000 L.T. and minimum period at about 0600 L.T. This is exactly the case found experimentally by Hirasawa and Nagata (1966). It may also explain the existence of one of the two Pc3 bands observed at Ralston.
The frequency band that has period closest to that observed by Hirasawa and Nagata (35 mHz) is the 38 mHz band shown in Table III.1. It remains for us to explain why there are two Pc3 bands, and why the Pc4 band is always observed simultaneously with the two Pc3 bands.

Stuart and Usher (1966), and Holmberg (1953), found that the Pc spectra at Eskdalemuir (\(\phi = 58.4^\circ\)) show peaks of micropulsation occurrence at 60 sec (Pc4) and 25 sec (Pc3) period, and they attribute this to the different harmonics of a fundamental frequency which shows preference at Eskdalemuir.

One would then begin to wonder whether the multi-band structure of continuous pulsation events observed at Ralston could in turn be explained by the presence of different harmonics involved. However, it may be demonstrated that the theory offered by Stuart and Usher fails to explain some of the observational facts found, although the existence of multi-band structure as a result of different harmonics can not be disproved altogether as a theory (Derivation of this result is shown in Appendix 3). Therefore, we have to look for a more favourable theory.

So far, we have postulated only the existence of a standing wave along the field line at the plasmapause and also between the plasmapause and the ionosphere. If we extend this postulation to include the possible existence of another standing wave, set up in the plasma-trough outside
the plasmapause, then the following must be considered.

The position of Ralston is situated very close to the foot of the field line defining the average equatorial position of the plasmapause. Suppose there is a time when Ralston is at the plasmapause which is very probable under moderately disturbed conditions, and at that particular interval of time, there is standing wave of poloidal mode existing in the plasmasphere, and in the plasmatrough. Let eigen-frequency of these standing waves for the two regions be $f_3$ and $f_4$ respectively. Both $f_3$ and $f_4$ are in Pc3 frequency range. As a result, superposition of these two waves would produce an oscillation of the magnetic field observed at Ralston that upon spectral analysis should yield two distinct frequencies $f_3$ and $f_4$. Furthermore, if the configuration of the plasmapause on that particular day is such that Ralston remains in the vicinity of the knee boundary for a certain long interval of time, and this is possible because the plasmapause is a continuous three dimensional boundary, one would expect to find in that particular time interval a two-band structure with frequencies $f_3$ and $f_4$. The variation of $f_3$ and $f_4$ would manifest the different dimension of the plasmasphere and the plasmatrough.

To see whether this is indeed the situation that leads to the occurrence of multi-band structured Pc3 observed in mid-latitude stations, one has to take simultaneous observations at the high as well as at the low latitude stations.
We shall report the result of some of these observations in a later chapter.

It has been widely recognised that Pc4 is a localised phenomenon that is caused by a standing hydromagnetic wave set up along the field line at the plasmapause. If this is to be accepted, then the simultaneous occurrence of the Pc4 \(f_1\) band with the other two Pc3 bands may also be explained in the light of the above postulation that Ralston is at the plasmapause when multi-band structure takes place.

Fig. III. 8 is an attempt to represent graphically the periodic expansion and contraction of both the plasmasphere and the plasmatrough of \(f_3\) and \(f_4\) frequency respectively (poloidal oscillations). Pc4 \(f_1\) frequency) is also shown.

![EIGEN OSCILLATIONS IN THE MAGNETOSPHERE](image)

The occurrence of the normal type diurnal variation with morning and afternoon separation may also be explained using the same model after taking into account the dawn-dusk asymmetry of the plasmaspheric configuration (Carpenter 1966). On the day that this type of Pc3 diurnal variation takes place,
Ralston is outside the plasmasphere in the morning. The boundary between the morning and afternoon type of Pc3 would therefore be taken as evidence of boundary crossing when Ralston is going from outside to the inside of the plasmasphere. The overlapping of frequencies at the boundary between the morning and the afternoon type may be understood with the same reasoning we offer to explain the occurrence of multi-band Pc3.

After crossing the boundary into the plasmasphere, the morning type begins to give way to the new afternoon type as is apparent at Ralston. The frequency of Pc3 observed at Ralston would now depend on the dimension of the inside of the plasmasphere. Therefore, the frequency of the afternoon type Pc3 would decrease rapidly with time. This agrees with experimental results reported earlier in this chapter.

The inverted U-pattern of the morning type Pc3 with maximum frequency occurring around 0600 L.T. could be explained too if the region outside the plasmapause also has an east-west asymmetry.

Recently, Siscoe et al (1969), using data obtained from the M.I.T. plasma experiment on Pioneer 6, found that an east-west asymmetry may exist in the solar wind velocity. The asymmetry is introduced by the influence of the sun's rotation on the interaction between fast and slow plasma streams. The fast stream would tend to come from the west
and the slow one from the east with respect to the average solar wind direction. The existence of an eastward component of solar wind velocity would produce an east-west asymmetry of the magnetosphere. As the magnetosphere is subjected to compression by solar wind with an eastward velocity component, the dimension on the dawn side of the magnetosphere outside the plasmasphere would be smaller than that on the afternoon side. The region outside the plasmapause is more sensitive to compression because of its low particle density, and this result gives further experimental support to the theory we offered to explain the diurnal behaviour of the normal type with morning and afternoon separation.

The inverted U-type of daily variation of frequency of Pc3 with both diffused and discrete structure occurred only under magnetically quiet conditions. Carpenter (1967) observed that during very quiet planetary magnetic conditions, the plasmapause appears to assume a more nearly circular configuration at its larger radius. According to this report the dimension of the plasmasphere becomes so large under these quiet conditions that Ralston would be found inside the plasmasphere throughout the day. That is to say, no boundary crossing should be observed. To explain the inverted U-type diurnal behaviour, one has to go back to the theory of the formation of the plasmapause.
The formation of plasmapause has been theoretically interpreted (Nishida, 1966) as due to a superposition of the two different kinds of dynamic motion of the magnetospheric plasma, namely the co-rotation with the Earth and the convective motion in the magnetosphere driven by solar wind. The mechanism that provides a driving force to maintain the convective motion in the magnetosphere is best described in terms of Dungey's model (1961). It has been shown by Nagata (1967) that the polar SP-field which is considered as caused by the magnetospheric convection becomes practically null when the $K_p$ index approaches zero. This result suggests that during the quietest condition there may be no interaction between the solar wind and the magnetospheric plasma, whence the solar wind pressure causes simply a compression of the magnetosphere including the plasmapause on the noon side, thus making the eigen frequency of the standing hydromagnetic wave of modified Alfven mode inside the plasmasphere largest around noon, that is, an inverted U-type of daily variation.

The dawn side shift of the maximum frequency and also of the boundary between morning and afternoon type of Pc3 could also be explained by Nishida's theory of the plasmapause when the value of the $K_p$ index becomes larger. As Nishida has already shown, the local time corresponding to the minimum geocentric distance of the plasmasphere shifts towards the dawn side as the convective motion is intensified.
This again agrees with experimental results mentioned in the previous sections.
K_p-DEPENDENCE OF Pc3 IN MID-LATITUDE

IV.1 INTRODUCTION

By comparison of the position of the magnetospheric boundary, as directly observed by the Explorer 12 satellite, with corresponding K_p indices, Cahill and Amazeen (1963) observed an inverse relation between K_p and the radius of the magnetosphere. If the Pc3 range of pulsation is caused by standing waves of modified Alfven mode existing in the magnetospheric resonators, since the eigen frequency of the poloidal oscillation depends on the dimension of its resonators, one would expect to find dependence of the frequency of Pc3 pulsation on the K_p index (Bolshakova and Troitskaya, 1964; Bolshakova, 1965a; Nagata et al, 1966).

The research to be reported in this chapter has been motivated by a desire to find the precise condition under which the different types of diurnal variation of Pc3 frequency subclassified in the last chapter may be expected to occur. Further, if the physical nature of the mechanism responsible for the existence of each of the Pc3 bands observed at Ralston is to be better understood, a precise knowledge must be obtained of how different levels of magnetic activity could affect each of the individual bands.
Correlation between the frequency of \( \text{Pc3} \) pulsation and the \( K_p \) index has been found experimentally by many researchers (McNicol and Mainstone, 1963; Nagata and Fukunishi, 1968; Bolshakova, 1965). Bolshakova (1965) observed an inverse dependence of the \( \text{Pc} \) periods (\( \text{Pc2}, \text{Pc3} \) and \( \text{Pc4} \)) on \( K_p \) which is given by an empirical expression.

\[
T_{\text{Pc}} = 58.3 - 8.25 \, K_p
\]

Nagata and Fukunishi (1968) also found an approximately linear relation between the eigen frequency of magnetic pulsation and the average value of \( K_p \) (\( \bar{K}_p \)) as well as \( \sum K_p \) and they derived empirically a numerical expression for the maximum central frequency (\( f_m \)) of \( \text{Pc3} \) and \( \text{Pc4} \) pulsations which is given by

- \( f_m \) (mHz) = 11 + 4.5 \( \bar{K}_p \) for the 15 mHz \( \text{Pc4} \) band
- \( f_m \) (mHz) = 20 + 7 \( \bar{K}_p \) for the 35 mHz \( \text{Pc3} \) band

Both equations will be plotted in Fig. IV.2a in the next section.

A similar linear relationship between the maximum central frequency of each of the \( \text{Pc3} \) bands observed at Ralston and \( \bar{K}_p \) has been obtained. Each of the three \( \text{Pc3} \) bands described in the last chapter has been found to behave differently subject to different levels of magnetic disturbances. Such differences have been studied in the light of results reported earlier by other authors.
Different types of diurnal variation of Pc3 frequency have been found to occur under different magnetic conditions. The result of this observation will be presented in the next section.

Experimental evidence gathered in section IV.3 has shown that sudden enhancement of Pc3 activity may occur with an abrupt increase in the value of the $K_p$ index. An interpretation of observational facts is offered in the last section.
In order to investigate how the mean frequency of each of the three Pc3 bands $f_2$, $f_3$ and $f_4$ would respond to different magnetospheric conditions represented by different values of $K_p$, extreme care must be taken to ensure reliable identification of each of these bands under consideration. Such identification is made only after the type of diurnal pattern in Pc3 spectral structure is determined and Pc3 signals are properly interpreted with the help of the model in Chapter III. Thus, the variation of Pc3 frequencies with $K_p$ is meaningful only if days with a constant $K_p$ are investigated and only with such a careful preliminary selection may definite and reliable evidence of systematic behaviour be obtained.

In this chapter, we shall select only those days that have approximately constant value of $K_p$ for our basic data. The working criterion is such that fluctuation of the value of the $K_p$ index within an individual day should not exceed one, that is, for a day labelled $K_p = 1$, the value of $K_p$ within that particular day must be within the range of $K_p = 0$ to $K_p = 2$. Further, each of the extreme cases must not occur more than twice a day.

Data compiled with the above mentioned criterion are listed in Table IV.1, where the values of $K_p$ as well as the values of $\Sigma K_p$ for each individual day selected are tabulated, along with the mean frequency of each Pc3 band observed.
TABLE IV.1

Kp DEPENDENCE OF DIURNAL VARIATION OF Pc3

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<th>ΣKp</th>
<th>f3</th>
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It has been noticed that no Pc3 activity is observed during extremely quiet conditions. July 31, 1967 is one of those extremely quiet days where the zero value of the $K_p$ index has been persistent throughout most of the twenty-four hours. Such extremely quiet conditions occur only rarely.

As the value of $\overline{K}_p$ increases, the mean frequency of the Pc3 band also increases. It has been found that at least for the value $\overline{K}_p$ less than or equal to 4, the mean frequency is directly proportional to $\overline{K}_p$. This agrees with what has been reported by Nagata and Fukunishi (1968). To demonstrate the dependence of the daily mean frequency of Pc3 on $\sum K_p$, an example is shown in Fig. IV.2a where a continuous sonagram has been displayed covering a seven and one-half day period from December 4, 1967 to December 12, 1967. A graph of $\sum K_p$ against Universal Time has been plotted in the upper portion of the same diagram. $\sum K_p$ is useful in this case for it provides a rough indication of the long range movement of the magnetospheric boundary. As suggested by Fig. IV.2a, inward movement of the magnetospheric boundary appears to be taking place from December 4 to December 6 causing the eigen frequency of magnetic pulsation to increase. The condition becomes fairly steady in the following three days and eventually assumes a reverse trend and expands rapidly from December 9 onward. The variation of the daily mean period of Pc3 follows
closely the variation of the value of \( \Sigma K_p \). The type of
diurnal variation of Pc3 frequency also appears to change
with changing level of magnetic disturbance. The changes
that take place ranging from the normal type with morning
and afternoon separation of December 7 to the diffused
inverted U-type that appears on December 10 correspond to
moderately disturbed to quiet conditions.

The multi-periodicity of Pc3 described in the last
chapter plays an important role in our study of the \( K_p \)
dependence of frequency of magnetic pulsation to be
presented in this section. It has been observed at Ralston
that for \( K_p \) greater than or equal to 2, the multi-band
characteristics of Pc3 begin to be significant. The result
of this observation has been tabulated in Table IV.1. The
frequencies \( f_3 \) and \( f_4 \) obtained by scaling the contoured
sonagrams show clearly an upward increase trend as the
value of \( K_p \) increases. Scaling of the mean frequency from
a sonagram has been found often to be difficult particularly
when overlap between two Pc3 bands has taken place. In some
cases one of the two bands occurs over a very brief interval
only and it may be of such lower signal strength that one
begins to doubt its real existence.

The \( f_4 \) band is usually much weaker in signal strength
than the \( f_3 \) band under moderately disturbed conditions (\( K_p < 3 \)).
As the magnetospheric conditions become more disturbed, the
\( f_4 \) band becomes stronger. For the value of \( K_p \) greater than
4, the signal strength of the \( f_4 \) band is much greater than
the \( f_3 \) band.
There is also another band of Pc3 observed under moderately disturbed conditions. It is the 25 mHz Pc3 band that was reported in the last chapter (Table III.1). Unlike the other two bands, the frequency of the $f_2$ band does not show clear $K_p$ dependence, although the maximum intensity of the $f_2$ band has been found to occur when $\overline{K_p}$ is at approximately 2.

A graph of $\overline{K_p}$ dependence of the mean frequency observed at Ralston has been plotted for all three bands of Pc3, namely $f_2$, $f_3$, and $f_4$ (Fig. IV.2b). A similar relationship reported by Nagata and Fukunishi from Kakioka ($\phi = 26^\circ 0$), and Bolshakova from Borok ($\phi = 53^\circ 0$) has also been plotted on the same diagram for comparison.

It is most interesting to find that of all the graphs plotted in Fig. IV.3b, only the $f_3$ band observed at Ralston is approximately parallel to the 15 mHz Pc4 band, and not the 35 mHz Pc3 band reported by Nagata and Fukunishi. That is to say, the $f_3$ band of pulsation observed at Ralston behaves the same way as the Pc4 at Kakioka would behave under different magnetospheric conditions. A similar trend has also been observed for the Pc3 band recorded by Bolshakova when the value of $K_p$ is smaller than 3 (see Fig. IV.3b). This finding has profound implication as it may reveal locations within the magnetosphere where the different bands of Pc3 observed at Ralston could have originated.
It has been noticed also that if the mean value of \( f_m \) is to be plotted from the two \( f_3 \) and \( f_4 \) curves for each value of \( K_p \), the resultant curve would appear to be parallel to the \( \text{Pc3} \) curve given by Nagata and Fukunishi.

In the last three columns of Table IV.1, the diurnal variation of \( \text{Pc3} \) frequency for steady days has been classified into four types according to the classification scheme proposed in the last chapter. The designations \( X_1 \), \( X_2 \) and \( X_3 \) used in Table III.3 in the last chapter are again used in Table IV.1 to signify the quality of each individual event with respect to each particular basic type. It is evident from the Table that the diffused inverted U-type (Type 3) of diurnal variation of \( \text{Pc3} \) frequency appears to occur when the planetary magnetic condition is both quiet and steady \((K_p < 2)\), whereas one of or a mixture of the other types is to be observed during moderately disturbed conditions \((2 \leq K_p \leq 4)\). For \( K_p > 4 \), the condition becomes so disturbed that the diurnal variation of \( \text{Pc3} \) frequency could not be simply classified.

To further illustrate Table IV.1, particular examples are given in Fig. IV.2c to Fig. IV.2g. One example has been given for each different value of \( K_p \) from 0 to 4.

The general appearance of the examples given in Fig. IV.2c and Fig. IV.2d is very similar. They both behave as diffused U-type diurnal variation.
The example given in Fig. IV.2e for $K_p = 2$ displays clear multi-band structure with spike-like discrete appearance. The discrete appearance is a feature common to all cases under moderately quiet conditions ($K_p$ is between 2 and 3) or when the condition is quiet and unsteady (see Section III.4).

The March 27 event shown in Fig. IV.2f for $K_p = 3$ shows a normal type of diurnal variation of frequency. The separation between the morning and afternoon type of $Pc3$ is not at all clear on the ordinary sonagram because the two bands overlap around and after 1400 L.T. causing confusion. However, the contoured sonagram displayed in the lower portion of the diagram reveals the two-band nature of this particular event.

Another example of the normal type of daily variation of $Pc3$ frequency which has morning and afternoon separation is clearly illustrated in Fig. IV.2g. However, care should be taken if one is to compare this example with the example given in Fig. III.3a in the last chapter. Unlike the event of October 18, 1967 which occurred under moderately quiet conditions, the event shown in Fig. IV.2g took place when the magnetic condition was reasonably disturbed. Further, the December 26, 1966 event displays double periodicity in the morning as well as in the afternoon, contrary to that observed on October 18, 1967.
FIG. IV.2a $\Sigma K_p$ Dependence of the Pc3 Mean Frequency
FIG. IV. 2b

Kp Dependence at
Ralston $\Phi = 58.8$
FIG. IV.2c    RALSTON X_b    NOVEMBER 18, 1967    $K_p = 0$
FIG. IV.2e  RALSTON Xb  October 5, 1967  $K_p = 2$
FIG. IV. 2f    RALSTON Xb    March 27, 1967    $K_p = 3$
FIG. IV. 2g  RALSTON X_b  December 26, 1966  \bar{K}_p = 4
IV.3 SUDDEN ENHANCEMENT OF Pc3 ACTIVITY

Dependence of the amplitude of Pc3 pulsation on the Kp index has been reported by many authors (Maple, 1959; Campbell, 1959; Munch, 1964; McNicol and Mainstone, 1963). These authors observed that the amplitude of Pc3 oscillation increases with a rise in the Kp indices. A similar trend of Kp dependence of the amplitude of Pc3 is generally evident at Ralston. The amplitude of Pc3 oscillation usually increases with a rise in the level of magnetic disturbance as may be illustrated in Fig. IV.2a of the last section. But the Kp index, or in this case the value of \( \Sigma K_p \), could offer indication of long range movement of the magnetospheric boundary and the general disturbance level within the magnetosphere; any short range movement in the value of the Kp index would not usually result in a corresponding change of the amplitude of Pc3.

An example is shown in Fig. IV.3a where the Kp index has increased from the value of 1 to the value of 3 in the afternoon and yet, no significant increase in Pc3 activity has been observed.

However, there are a few occasions when sudden enhancement of Pc3 activity has been observed to take place following a similar rise in the value of the Kp index. Two examples are independently displayed in Fig. IV.3b and Fig. IV.3c to demonstrate the working of the phenomenon.
In Fig. IV.3b, an abrupt increase of Pc3 amplitude, indicated by an increase in darkness of the sonagram, has been observed at approximately 2100 U.T. May 21, 1967 which is the time within the three hour interval when the Kp index has risen from a value of 1 to 3+. Notice also that the sudden enhancement of micropulsation activity takes place in the Pc3 band only (25-60 mHz in the case of the May 21 event).

In Fig. IV.3c, another example of sudden enhancement of Pc3 activity corresponding to an increase in the Kp index is shown where two Pc3 bands have been initiated. Notice that an enhancement of Pc4 activity occurs prior to the enhancement of both of the Pc3 bands which takes place at approximately 1830 U.T. Two calibration marks appear on the sonagram before and at 1723 U.T.
FIG. IV.3a
RALSTON Xₖ
AUGUST 9, 1967
FIG. IV.3b
RALSTON Xb
MAY 22, 1969
SUDDEN ENHANCEMENT OF Pc 3
FIG. IV.3c  
RALSTON Xb  AUGUST 23, 1967  
SUDDEN ENHANCEMENT OF Pc3 & Pc4
IV.4 DISCUSSION

Based on data obtained on board Mariner 2, Snyder et al (1963) have derived an empirical expression demonstrating the linear relationship between $\sum K_p$ and the velocity of the solar wind. Wilcox et al (1964) also have derived from the IMP-1 observation that there is an approximately linear relation between $V$ and $K_p$. Since it is not inconceivable that the plasmasphere or magnetosphere more compressed by the stronger solar wind, corresponding to an increase in the $K_p$ indices, may result in a shorter period of hydromagnetic eigen oscillation as indicated for the case of $Pc5$ oscillation (Hirasawa et al, 1966), a direct correlation between $\Pi_p$ and the frequency of $Pc$ type of magnetic pulsation has been anticipated. Experimental observation has so far confirmed this theoretical speculation.

Further, if the existence of the multi-band structured $Pc3$ is indeed due to the eigen oscillation of the modified Alfvén mode set up in the earth magnetic resonators both inside the plasmasphere and in the plasmatrough, one would expect the eigen oscillations in the two different resonators to respond differently to any change in magnetospheric conditions. As the plasmatrough is more susceptible to the compression of the solar wind because of its low particle density, one may anticipate
that the Pc3 originating in the plasmatrough would be more sensitive to any change of the $K_p$ index than its counterpart in the plasmasphere. The above consideration leads us to believe that the $f_4$ sub-band of Pc3 pulsation originates in the plasmatrough outside the plasmapause whereas the $f_3$ sub-band originates inside the plasmasphere.

The observational fact that the $f_3$ curve shown in Fig. IV.2b is parallel to the Pc4 curve given by Nagata et al provides further support for our speculation that the $f_3$ sub-band of Pc3 originated from the inside of the plasmapause. If Pc4 is caused by a hydromagnetic wave propagating along the field line at the plasmapause, the frequency of this eigen oscillation would reflect the dimension of the plasmasphere which is bounded by the plasmapause. As the dimensions of the plasmapause, and in turn the plasmasphere, change subject to different degrees of compression by the solar streams, it is only logical to expect close correlation between the change of the frequency of the Pc4 ($f_1$) band and the change of the frequency of the $f_3$ band of Pc3 under different levels of magnetic activity.

Also, the $f_4$ band is found to be significant only when the magnetic condition is reasonably disturbed ($K_p \sim 3$), that is, when Ralston is well outside the plasmapause. On the other hand, when the magnetic condition
is quiet Ralston would be inside the plasmasphere and the only dominating pulsation observed would be in the $f_3$ band. This observation again is consistent with our proposed model.

The $f_2$ band of Pc3 described in Section III.2 of the last chapter has not demonstrated clear $K_p$-dependence. This property may be vital in our ultimate understanding of the exact nature of the $f_2$ band of Pc3.

The present author believes, as many others do, that a $K_p$ index is a measure of polar substorm activity. Its enhancement is thought to accompany an injection of particles into the magnetosphere which cause an instability of the plasmapause, giving rise to a hydromagnetic oscillation in the dayside magnetosphere.

Thus, an enhancement of Pc3 activity may then be taking place. The example given in Fig. IV.3c suggests this possibility. The sudden enhancement of activity for the August 23 event took place first in the Pc4 frequency range which is then followed by an excitation of the two Pc3 bands. This may suggest that this kind of sudden enhancement begins with excitation of the plasmapause. Obviously, the result so far obtained is not sufficient for us to draw any conclusions, and future research should look into the possibility of simultaneous observations.
being made at two stations approximately 180° apart in geomagnetic longitude.
CHAPTER V

COMPARATIVE STUDIES OF Pc3 IN HIGH AND MID-LATITUDES

V.1 INTRODUCTION

In order to understand the origin of micropulsation, it is of prime importance to determine accurately any regularities that govern the changes of micropulsation amplitude and period with latitude, and the distribution of pulsations observed on the earth's surface. Although a tremendous amount of work has been done by numerous researchers on this subject since the IGY, and undoubtedly great advances have been made in the past decade through use of better spectral analysing techniques, there is not yet a consistent picture that could explain the apparent controversy among different results reported by different workers.

Theoretical attempts to formulate the nature of a latitude dependence, based on hydromagnetic resonances of the magnetosphere, were made by Dungey (1954) and Kato and Watanabe (1956a). Dungey's calculations have been extended by Westphal and Jacobs (1962) to include more recent knowledge of the magnetosphere. Each of these and some later calculations were based on certain assumptions about the density distribution in the magnetosphere. These calculations have all predicted a steady increase in the period of micropulsation with an increase in geomagnetic latitude.
Indeed, earlier experimental observations made by various authors have also provided support for the theoretical prediction that the periods of $Pc2$, $Pc3$, and $Pc4$ types of continuous pulsation increase with an increase in latitude. By studying simultaneous records around the world, Obayashi and Jacobs (1958) first reported the systematic increase of micropulsation period with latitude $\phi$ and concluded that the period is inversely proportional to $\cos^2 \phi$. A similar correlation with latitude was found by Bolshakova and Zybin upon studying the periods of the most stable pulsations at each of the five stations within the latitude range $23^\circ N \rightarrow 64^\circ N$ (Troitskaya, 1967). However, the result reported by Obayashi and Jacobs was derived from data obtained from the nighttime as well as from the daytime side of the earth, and it may not hold for the purely daytime $Pc3$ events that we assume today.

More recent observations created more confusion than they originally planned to resolve. Investigations on the latitude dependence of the $Pc3$ period made by Duncan (1961) and Ellis (1960) with the same data from three stations in latitude range $29^\circ S \rightarrow 52^\circ S$ gave contradictory results, while other authors, notably Herron and Heitzler (1966), Usher and Stuart (1966), and Troitskaya (1967) failed to obtain a clear picture of the dependence of $Pc3$ period on latitude. They have reported that instances when somewhat longer periods are observed at high latitude occur just as often as instances when the reverse applies.
Scrutiny of micropulsation events simultaneously recorded on rapid-run magnetograms at Great Whale River ($\phi = 66.6^\circ, \theta = 347.4^\circ$), McGill ($\phi = 57.0^\circ, \theta = 354.3^\circ$), and Ralston ($\phi = 58.0^\circ, \theta = 305.5^\circ$) also indicate that in some instances the period of Pc3 may be observed to be longer at Great Whale, while in other instances the period of Pc3 is the same for all stations. On some occasions the period of Pc's in the high latitude has even been found to be shorter than that observed in the mid-latitude. We shall describe these results in Section V.2 as a prelude to further investigation to be made in the later sections.

It has been recognised that two main causes may be responsible for the apparently contradictory results obtained from experimental observations. The lack of sufficient high quality data may be taken as one of the principal reasons. Indeed, it has always been realized that unless data obtained from different stations are recorded simultaneously with identical equipment and with standardized techniques and calibrations, it would be very difficult for one to compare these data in an exact manner.

Because of the scarcity of good quality data presently available, many researchers have to resort to a statistical approach as a principal means to research in the field. Statistical analyses undoubtedly have yielded much information of various types of geomagnetic perturbation phenomena, yet, statistical results may often be found to be very misleading, particularly when more than one parameter is
involved in the study.

The second major cause of the apparent inconsistency of the observational results is the present lack of precise knowledge in other related fields or in other related topics within the same field. It should be noted that, even in the comparison of simultaneous events, correlations may not always be meaningful. In the study of the latitude dependence of pulsation frequency, for instance, comparison of any statistically obtained mean periods or frequencies may be very misleading indeed where no account has been taken of magnetic activity, diurnal variations, etc. Thus the lack of precise knowledge of the diurnal behaviour or $K_p$ - dependence of $Pc3$ at any single station would also hamper research on its latitude dependence.

The three main stations that we have chosen for comparison are situated in such a position that Great Whale River and McGill lie closely on the same geomagnetic meridian whereas Ralston and McGill are at about the same geomagnetic latitude. The telluric sonagrams published in High Latitude Geophysical Data by the Geophysical Institute, College, Alaska ($\phi = 64.65^\circ N$, $\theta = 256.56^\circ E$) over a period from January to March 1967 have also been used for comparison.

Our present emphasis is on the detailed study of typical events selected according to the classification scheme proposed in Chapter III. Observations made at Ralston are taken as a base for comparison with other stations
because of the high quality of its tape recorded data. Examples displayed for illustrative purposes are so selected that only data available from the maximum possible number of stations are used. Unfortunately only very few tape recorded data from Great Whale River are of sufficiently low noise to signal ratio, and no magnetic tape recorded data are available from McGill, so except for the few available tape recorded data from Great Whale River and College, Alaska, comparison can be made only on chart records.

In Section V.4 the latitude dependence of Pc3 frequency will be studied in the light of the recently acquired knowledge on the diurnal variation of frequency at Ralston (Chapter III) and at Great Whale River (Section V.3), and also on the Kp-dependence of Pc3 reported in the last chapter. It has been found that some of the apparent inconsistency in the previous as well as in the present observational results may be resolved in the present study under the new perspective. This is to be summarized in Section V.6.

In Section V.5, conjugacy of Pc3 of both the high and mid-latitude pair (Great Whale-Byrd and McGill-Eights respectively) has been studied. Preliminary results indicate that Pc3 is conjugate in general except under very disturbed magnetic conditions.
V.2 LATITUDE DEPENDENCE OF Pc3 FREQUENCY - Preliminary Observations on Rapid-Run Magnetograms

Scrutiny of rapid-run magnetograms (3/4 inch per minute recording speed) from Great Whale River, Ralston and McGill has indicated that under different conditions the frequency of the Pc type of magnetic pulsation at the high latitude station may be found to be higher than, or lower than, or the same as, the frequency of the pulsation activity observed at the mid-latitude stations. Each of these cases has been reported by other researchers from other observatories. However, it has been observed at the three Canadian stations that certain regularities could be found governing the existence of each of the different behaviours. Some of the preliminary results obtained by study of rapid-run magnetograms simultaneously recorded at different stations is to be reported in this section as an introduction to deeper investigation to be presented in the future sections.

No clear latitude dependence of Pc3 frequency has been observed under very quiet magnetic conditions; the frequency of Pc3 is comparable at Great Whale, McGill as well as at Ralston. In Fig. V.2a, the constancy of Pc3 frequency with respect to different latitudes is illustrated where peak to peak correlation is observed for that particular Pc3 event simultaneously occurring at Great Whale,
Ralston and McGill under very quiet magnetic conditions ($K_p = 0^+_1$).

As the magnetic condition becomes more disturbed, the latitude dependence of Pc3 frequency becomes noticeable at Great Whale and McGill, particularly so in the afternoon, but the Pc3 frequency remains comparable between the two stations in the morning. An example given in Fig. V.2b shows a clear latitude dependence of frequency of Pc3 where the event observed at Great Whale ($20 \rightarrow 25$ mHz) is of much lower frequency than that observed at McGill ($35 \rightarrow 40$ mHz). It is very interesting to note that at Ralston before 1843 U.T. and after 1846 U.T., the Pc3 is observed with approximately 20 -- 25 mHz in frequency comparable to Great Whale, whereas in the interval between 1843 U.T. and 1846 U.T. the frequency of Pc3 is comparable to that at McGill rather than at Great Whale. In fact, even peak to peak correlation could be identified for the right pairs of stations. A statistical average of the Pc3 frequency over each of these stations would surely suggest that the mean frequency of Pc3 decreases as latitude increases. It is the author's opinion that such a conclusion is, to say the least, very misleading. On the other hand, if the model postulated in Chapter III and reinforced by Chapter IV that there exists eigen oscillation in the Pc3 frequency range in both the plasmatrough and the plasmasphere is to be accepted, the outcome of the observation made and shown in Fig. V.2b may even be predicted. It is only logical that if Great Whale
is in the plasmatrough while McGill is in the plasmasphere, the frequency of Pc3 observed at the two stations would be different, being higher at McGill in this particular case. Suppose the plasmapause is at such a position relative to Ralston that Ralston may at one time be found inside the plasmapause and at other time outside the plasmapause in the plasmatrough, then the frequency of Pc3 observed at Ralston would surely be changed accordingly. This is what has been observed in Fig. V.2b.

To provide further support for our postulation that eigen oscillation may exist in the plasmatrough, the following experimental observation is considered.

There is another class of micropulsation known as Pcl with frequency range from 0.2 Hz to 5 Hz. These micropulsations appear in polar regions (including the auroral zones) as well as in the mid- and low-latitudes. In mid- and low-latitudes they are more likely to appear during night time than during the day. This type of activity is known to be a hydromagnetic wave that originates in the plasmatrough several to fourteen earth's radii distant and is propagated to one (or more) limited area(s) in the polar region along magnetic lines of force (Jacobs and Watanabe, 1964; Obayashi, 1964; Wentworth, 1966). It has been realized that if a correlation could be found between this type of Pcl and the Pc3, whose intensity is also greater than at mid latitude stations, then one could infer that the Pc3
observed in the high latitude also originated in the plasmatrough.

It is well known that Pcl recorded on helicorder charts running at a speed of 3 cm/min often appear in bundles (pearls). Furthermore, the envelope of the Pcl observed in the daytime at Great Whale is often found to be of 20-30 sec period. It has been observed for this particular type of Pcl that correlation between the period of its envelopes and the corresponding Pc3 event recorded simultaneously at the same station is extremely good (Fig. V.2c). This cannot be explained purely as a beating effect because the frequency observed is much lower than the beating frequency calculated theoretically and observed experimentally on the sonagram (which has a bandwidth $\Delta f = 0.2$ Hz i.e. $T_{\text{Beat}} = 5$ sec). This may suggest that Pc3 is at least partly responsible for the modulation of the amplitude of Pcl. If this is indeed the case, the Pc3 observed must also originate outside the knee boundary.
GW

RA

MG

1440  1445

FIG V. 2a  December 17, 1965  Kp = 0+

1.82 \gamma AT 0.5 Hz

0.07 \gamma AT 0.5 Hz

0.05 \gamma AT 0.5 Hz
FIG. 2b  $X_b$, February 17, 1967  $K_p = 3$
GREAT WHALE, AUGUST 22, 1966

Pc 1 Envelope

FIG V.2c Pc 3 Modulated Pc 1
DIURNAL VARIATION OF Pc3 AT A HIGH LATITUDE STATION - GREAT WHALE RIVER (GEOMAGNETIC $\phi = 66.6^\circ$, $L = 7.5$)

During moderate to mildly disturbed conditions ($K_p = 2$ to 4), the diurnal variation of micropulsation activity may be roughly classified into four regions dividing the whole 24 hours. The pattern of activity on a typical day has been drawn in Fig.V.3a which is similar to the one given by Jacobs and Wright (1965) for Byrd Station.

From 1700 L.T. to 2000 L.T. (i.e. 2200 U.T. to 0100 U.T.) is the dusk region. This is the region where positive bay is usually very active. It is extremely interesting to note that for every event of positive bay observed there has always been regular micropulsation of 10 to 20 sec period (Pc2 and Pc3) associated with it. Pc5 also is very often observed simultaneously. Positive bays occur very often in the auroral zone; from data studied in a ten day period in September 1965 alone, there are 7 cases of such events being observed. One typical example of this dusk type Pc2 - 3 association with positive bay is shown in Fig. V.3b. In the upper portion of the diagram there is a part of a high speed recorded magnetogram showing a typical Pc2 - 3 event near dusk, and there is a La Cour type of magnetogram of the same event shown in the lower portion which is recorded at relatively slower speed and has much poorer frequency response. The
Pc2 - 3 event shown takes place first around 2208 U.T. and it is interesting to note that this is the very moment that a positive bay begins to be observable. Another feature that should be noted is that after 2240 U.T., the period of the same event begins to decrease continuously. This reminds us of another type of geomagnetic pulsation called IPDP which when observed, usually occurs around this particular local time and is always identified by its decreasing period. However, IPDP is usually of higher frequency.

In the absence of positive bay, the dusk region is usually quiet. The only activity that may still be observed is Pc5 which has not appeared in Fig. V.3b.

The second region extends from 2100 L.T. to 0100 L.T. (0200 U.T. to 0600 U.T.). This is the region where pulsation of the impulsive type usually occurs. A typical example of a Pi2 event is presented in Fig.V.3d. As may be seen in this example, Pc2 and Pc3 are often found superimposed on these impulsive micropulsation events. The condition is generally quiet in the absence of these impulsive events although traces of shorter period (∼ 10 sec) pulsation activity may sometimes be identified.

The early morning region before or near dawn (0100 L.T. - 0600 L.T. or 0600 U.T. - 1100 U.T.) is a region often invaded by negative bays. Similar to the first region mentioned above, there have also been Pc2 and Pc3 events
associated with every negative bay that we observed in this region. The amplitude of the bay associated \( \text{Pc2 - 3} \) has maximum at the recovery stage of the bay then eventually dies down towards dawn. Before or at 0600 L.T., a quiet condition usually prevails until the onset of day time \( \text{Pc3} \) activity. One of the events observed is illustrated in Fig. V.3c where both negative bay and \( \text{Pc2 and Pc3} \) (10 → 20 sec) pulsation events occurs simultaneously around 0650 U.T. Pulsation of longer period may occasionally be present in the same event which by itself is often fluctuating in period. Notice also that the intensity of the micropulsation event has been significantly enhanced only after the bay enters its recovery phase at around 0725 U.T. and then dies down toward dawn. In the absence of bay activity, a longer period \( \text{Pc3} \) with smaller amplitude is usually detected with or without \( \text{Pc5} \) occurrence.

The day region (0600 L.T. to 1700 L.T.) is very active in continuous pulsation events with frequency ranging from 25 Hz to 70 Hz. The frequency is usually at its highest just after dawn and at its lowest in the afternoon. Such a change in frequency does not seem to take place continuously. The daytime \( \text{Pc3} \) appears to be very sensitive to the change in the dimension of the magnetosphere. This effect is manifested in the frequency fluctuation often observed before and around local noon. \( \text{Pc3} \) events are
generally a little more regular between 0700 L.T. and 0900 L.T. when there seems to be a maximum in intensity, continuity and regularity of period. A secondary maximum is often found around 1400 L.T. or 1500 L.T. In fact, cases of very regular Pc2 of 10 to 20 sec period have been found on many occasions in the afternoon (1300 to 1600 L.T.) instead of longer period Pc's (the August 19, 1966 event is one of the typical examples). Also, it does not seem that there is a definite boundary between Pc2 and Pc3 as suggested by the IAGA committee, 1964. In general, the frequency of Pc2 - 3 in the high latitudes fluctuates throughout the day except under very quiet conditions.

At times when the geomagnetic disturbance is found to be at its minimum ($K_p = 0 \rightarrow 1$), very regular Pc3 - 4 pulsation is often observed for most of the day (0300 to 1700 L.T.). Diurnal variation in frequency does not seem to be very significant. The intensity of these Pc3 - 4 pulsations appears to be at its maximum in the local morning and then decreases towards afternoon. A typical event has been reproduced in Fig. 7.3a where nearly peak to peak correlation has been shown to occur between high- and mid-latitude stations for these types of Pc3 - 4 activities.

Pc2 may also be found to occur in the afternoon under extremely quiet conditions, (the November 14, 1966 event is one of such examples) but it occurs at a less frequent rate. The impulsive type of P12 micropulsation
usually observed around midnight also occurs less frequently. Conditions are generally very quiet from dusk to after midnight although less regular pulsation in the \( \text{Pc2 -3} \) frequency range may still be detected in association with bay.

Unfortunately, good data obtained during stormy conditions are rarely available at Great Whale River, as they are usually recorded off scale. However, information extracted from the available data indicates that during stormy conditions, the diurnal variation observed under moderately disturbed conditions described above not only remains true but becomes more pronounced. The frequency of the pulsation activity is much higher in general. The night time pulsation events appear to be more violent during stormy conditions (e.g. the June 16, 1965 event). Large amplitude Pc5 may be observed continuously all day, particularly so in the morning and in the late afternoon. One example is shown in Fig. V.3f where Pc5 is observed at both high and mid latitude stations, all with Pc3 riders.
FIG. V.3a  DIURNAL REGIONS OF MICROPULSATION ACTIVITIES AT THE HIGH AND MID-LATITUDES
FIG V.3d  September 18, 1965

IMPULSIVE EVENTS
FIG V.3e January 21, 1964

LATITUDE DEPENDENCE OF \( \text{Pc3,4} \)

- GW
  - \( Y_b \)
  - 1.2 \( \gamma \) at 0.5 Hz

- RA
  - \( Y_b \)
  - 0.16 \( \gamma \) at 0.5 Hz

- MG
  - \( Y_b \)
  - 0.32 \( \gamma \) at 0.5 Hz

- WI
  - \( Y_b \)
  - 0.22 \( \gamma \) at 0.5 Hz
FIG V.3f   APRIL 18, 1964

Pc5 WITH Pc3 RIDERS
The classification scheme proposed in Chapter III provides a general guideline for research on latitude and local time dependence of Pc3 frequency, further results of which are to be presented in this section. Observations made at Ralston are again chosen as a base for comparison with observations made at other stations.

The multi-band structured Pc3 event observed at Ralston and described in detail in Section III.2 has been displayed alongside the dynamic spectrum of the same event simultaneously observed at College, Alaska ($\delta = 64.7^\circ$). The display is shown in the lower portion of Fig. V.4a. Simultaneity of occurrence and general appearance of Pc3 observed at these two stations is most remarkably demonstrated on the diagram. This is particularly so in the lower frequency bands where no latitude or local time dependence of frequency is observed in the day regime. The nighttime pulsation activity observed at around 03 U.T. is definitely more violent at the higher latitude.

It is very important to note that the multi-band structure so apparent at Ralston from 1700 U.T. to 2100 U.T. (i.e. around local noon) is only barely in existence at College. The 40 mHz band observed at Ralston becomes very weak in the higher latitude. This band becomes significant at College only after 2300 U.T. From 2300 U.T. to 0100 U.T.
the frequency of the band is comparable at the two stations.

The same event recorded on magnetograms operating at chart speed of 6 inches per hour has also been observed at Great Whale which is located at an even higher geomagnetic latitude than College. This has been compared with magnetograms recorded with the same recording speed at Ralston. Part of the magnetogram (from 1400 U.T. to midnight U.T.) is illustrated in the upper portion of Fig. V.4a. Scaling of these two magnetograms recorded at the two stations indicates that the high frequency component observed at Ralston is constantly of higher frequency than that observed at Great Whale. The highest frequency component observed at Ralston is approximately 46 mHz occurring around 1700 U.T., whereas the highest frequency observed at Great Whale is only about 25 mHz within the same time interval. The frequency of the pulsation activity at Ralston decreases from 46 mHz at 1700 U.T. to 35 mHz at 2100 U.T. with multi-periodicity apparent throughout this time interval. The frequency of the corresponding activity observed at Great Whale in the same interval is obviously of much lower frequency and its frequency changes only 4 mHz from 25 mHz at 1700 U.T. to 21 mHz at 2100 U.T. Unlike Ralston, scrutiny of the same event observed at Great Whale shows no clear evidence of multi-periodicity in the Pc3 frequency range. The diurnal variation of amplitude of micropulsation takes place at both Ralston and Great Whale. Note, for example, that the
amplitude of the wave packet occurring around 1815 U.T. at Great Whale is approximately 3.15 $\gamma$ (at 25 mHz) whereas the corresponding wave packet observed at Ralston is only 1.7 $\gamma$ in amplitude (at 40 mHz). Maximum intensity occurs around 1900 U.T. at both stations and diminishes from then on to reach its lowest value at approximately 2200 U.T.

The beautiful Pc3 event of approximately 30 mHz in frequency that appears after 2300 U.T. at Ralston is very interesting because it is of much greater intensity ($\sim 1.6 \gamma$) than the corresponding event observed at Great Whale ($\sim 0.5 \gamma$). This may be partly due to the local time dependence.

Another example similar to the one described above is shown in Fig. V.4b. In the lower portion of the diagram, sonagrams produced from data recorded at College and Ralston have been displayed for comparison. The higher frequency component (35 mHz) observed at Ralston is again found to be much stronger in signal strength than the corresponding component observed at College. The other frequency components are comparable in frequency, time of occurrence and in signal strength between the two stations. A similar trend of diurnal and latitude dependence of Pc3 observed by scaling magnetograms is also evident at Great Whale and Ralston.

In Fig. V.4c, magnetograms from Great Whale (the upper magnetogram) and from Ralston have been shown side by side for comparison. This particular event has already been
described in detail in Section III.3 where the dynamic spectrum of the same event is displayed in Fig. III.3a for Ralston. However, as it has been clearly demonstrated in Fig. V.3c, Pc3 behaves differently at Great Whale. Close correlation between high and mid-latitude Pc3 is found only in the morning (1200 U.T. to 1830 U.T. in the October 18 event shown). The frequency, on the other hand, is slightly higher at the mid-latitudes. The frequency as well as the amplitude of the Pc3 activity decrease from 1300 U.T. (0600 L.T. at Ralston) to around 1900 U.T. at both Great Whale and Ralston. But the rate of decrease in both amplitude and frequency is much greater at Great Whale than at Ralston.

The afternoon type of Pc3 pulsation, which is of higher frequency (40 mHz), is very active at the mid-latitude Ralston station. This is contrary to what has been observed at Great Whale where Pc3 activity is found to be at its minimum. The pulsation activity observed at Great Whale in the afternoon is usually of smaller amplitude and is less regular. However, very regular Pc2 of 10 sec to 20 sec periods may often be found to occur in the afternoon, which have no counterpart in the mid latitudes (see Fig. V.4d).

The inverted U-type of diurnal variation of Pc3 frequency observed usually at Ralston under moderately to very quiet conditions has a counterpart at the higher latitudes. In Fig. V.4e, an event taking place on February 26, 1967 and observed simultaneously at both Ralston and College has been displayed for comparison. No latitude
dependence of Pc3 frequency has been observed between the two stations. The mean frequency of Pc3 events is found to be the same at both stations.

The wide band of activity (Pi2) invading College at 1200 U.T. and 1600 U.T. (i.e. 0200 L.T. and 0600 L.T. at College) was not observed at Ralston. This may be due to local time dependence. Because Ralston is three hours in time ahead of College, it may not occur at Ralston where it is already early in the day regime.

Another interesting feature to be noted on Fig.V.4e is the trace of Pc4 activity (10 mHz) observed at College. No distinct Pc4 has been observed at Ralston.

The close correspondence of the frequency of the Pc3 activity between Ralston and College under moderately quiet conditions could not be found at Great Whale which is of even higher latitude and is two hours in local time ahead of Ralston. The two sonagrams obtained from data recorded at Great Whale and Ralston are shown in Fig.V.4f covering two days in time interval (Feb. 26 and 27, 1967). A latitude dependence of mean frequency of Pc3 is found to be considerable between the two stations. At Great Whale, the separation between the Pc3 and Pc4 bands is not at all clear (the existence of which is doubtful at the high latitudes). An average over the two bands would result in a lower value of the mean pulsation frequency. Thus the mean frequency observed at Great Whale is much lower than
that observed at Ralston. Also, the amplitude of Pc3 at the high latitude station appears to be a maximum early in the morning (0600 L.T.), contrary to the noon maximum observed at both Ralston and College for this type of diurnal variation of Pc3 frequency.

The local time dependence as well as the latitude dependence have a profound effect on the Pc3 cut-off. The Pc3 range of micropulsation cuts off at around 1800 U.T. February 26, 1967 at Great Whale and nearly terminates at midnight U.T. at Ralston (Fig. V.4f), while the same event lingers on until after 0400 U.T. on February 27, 1967 at College.
FIG.V.4b  Multi-Band Structured  Pc3
LATITUDE DEPENDENCE OF NORMAL TYPE OF Pc3
FIG V.4d  
September 19 1965
Pc3 AT THE MID-LATITUDES
SIMULTANEITY OF THE INVERTED U-TYPE OF Pc3 AT MID- AND HIGH-LATITUDES
FIG V.4f  Latitude Dependence of Pc3

GREAT WHALE Xb

RALSTON Xb

f (MHz)

TIME

U.T.

FEB 26.67

FEB 27.67
V.5 CONJUGACY OF Pc3 AT HIGH AND MIDDLE LATITUDES

Conjugate studies of the continuous pulsation are made in the present research mainly at the pair of stations Byrd, Antarctica and Great Whale River, Canada. Only two weeks' data in one component (total field $F$) are available from Eights, Antarctica ($\phi = 63.8^\circ$, $\theta = 355.3^\circ$ geomagnetic). It is found however that in most cases under study pulsation activity on the $X$ or $Y$ field component recorded at McGill are similar in appearance to the signals at Eights recorded on the total field component. McGill and Eights are near conjugate pair of stations in the mid latitudes.

During extremely quiet conditions ($K_p = 0 \rightarrow 1$) longer period Pc3's (sometimes Pc4) are observed at both Byrd and Great Whale. This type of activity shows very good peak to peak conjugacy and is observed mainly when the stations are on the daylight side of the earth. Three examples are shown in Fig. V.5a where peak to peak conjugacy is observed for the very regular waves, both in the morning and in the afternoon. Only the nearly sinusoidal waves are to be taken into consideration. Unfortunately, no data have been available from Eights under very quiet conditions. But good, if not better, conjugacy of Pc3 is to be expected for the mid-latitude pairs. In fact, even when the magnetic condition becomes moderately disturbed, but not violently disturbed, the conjugacy of Pc3 remains good in the mid-
latitudes. One example of such is shown at the bottom of Fig. V.5a where peak to peak conjugacy has been observed for the mid-latitude pairs.

Conjugacy of the dawn and dusk type Pc2,3 observed at the Byrd-Great Whale pair is apparent in overall activity. Occasionally peak to peak correspondence is seen, however. An example is shown on Fig. V.5b for each of these two cases.

When the general level of magnetic disturbance is reasonably high \((K_p = 4)\), Pc3 activity observed at the mid-latitude pair displays more peak to peak correspondence than at the high-latitude pair. The September 16, 1965 event shown in Fig. V.5c is one such example. In general, Pc3 activities observed in the local morning are found to show closer conjugacy than those occurring in the afternoon.

When the magnetic level of disturbance becomes very high \((K_p = 6)\), Pc3 activities are no longer conjugate at the Great Whale-Byrd pair. Fig. V.5d shows one such example. The Pc3 activity is conjugate, and occasionally peak to peak conjugate, around 0600 U.T. on June 15, 1965 when \(K_p = 1\). In the lower portion of Fig. V.5d, it is seen that conjugacy becomes poorer as \(K_p\) increases further (0500 U.T. June 16, 1965), and finally activities are no longer conjugate. When \(K_p\) increases substantially in the afternoon (around 1830 U.T.), the conjugacy is apparent in the overall level of activity; however, individual oscillations cannot necessarily be correlated.
FIG V.5a CONJUGACY OF Pc 3
FIG V.5b CONJUGACY OF DAWN AND DUSK TYPE Pc2,3
FIG V.5c  Sept 16, 1965  CONJUGACY OF Pc3 AT HIGH AND MID LATITUDES
FIG. V.5d  CONJUGACY UNDER DISTURBED CONDITIONS
V.6 DISCUSSIONS

In Chapter III, the existence of eigen oscillations of modified Alfven mode outside the plasmapause in the plasmatrough has been postulated, in addition to the eigen oscillation already widely believed to exist inside the plasmasphere. This model has been used to explain the existence of different types of diurnal variation of Pc3 frequency experimentally observed at Ralston. The same model has been used also to interpret results on $K_p$ dependence of Pc3 frequency studied in Chapter IV. It has been found that experimental results obtained so far agree with theoretical predictions implied by the proposed model. In this section, the same model will again be employed to interpret results reported in the earlier sections.

The $f_4$ band of Pc3 pulsation identified in Section III.2 and in Chapter IV has been considered to be a high-latitude phenomenon originating in the plasmatrough, whereas the $f_3$ band of Pc3 is considered to originate in the plasmasphere bounded by the plasmapause. Occurrence of the multi-band structured Pc3 at Ralston has been thought of as a boundary effect which takes place when Ralston is situated close to the plasmapause. If this is indeed the case, stations of higher latitude than Ralston should observe Pc3 that has frequency comparable to the $f_4$ band observed simultaneously at Ralston under moderately disturbed
conditions. On the other hand, the frequency of Pc3 events observed at stations of lower latitude than Ralston would be dominated by the $f_3$ band. Close examination of magnetograms simultaneously obtained from Ralston, College and Great Whale have indicated that Pc3 in the higher latitudes indeed behaves as predicted by the proposed model. The two examples given in Fig. V.4a and Fig. V.4b are only two of many examples that could show the $f_3$ band to be very weak in the higher latitudes before noon.

The lower frequency component ($\sim 25$ to $30$ mHz) of Pc3 has been observed simultaneously at both high and mid latitude stations with comparable intensity. This observational fact could not be interpreted correctly without a prior knowledge of the simultaneous behaviour of this particular frequency band at the lower latitudes.

The event observed simultaneously at Ralston and College in the afternoon is of particular interest. This may be taken as further evidence of the east-west asymmetry of the plasmapause configuration. Under moderately disturbed conditions, as in the February 11, 1967 event shown (Fig.V.4a), Ralston usually is very close to the plasmapause. College, being at a higher geomagnetic latitude than Ralston, is usually well outside the plasmapause. This is particularly so in the morning when the geocentric distance of the plasmapause is at its minimum (Carpenter, 1966). As the geocentric distance of the plasmapause increases to its
maximum later in the afternoon, both Ralston and College may be found inside the plasmapause, in which case the $f_3$ band of Pc3 would be observed at Ralston as well as at College instead of the other Pc3 band that was observed earlier in the day. This is the phenomenon responsible for the occurrence of the event simultaneously observed at Ralston and College around midnight U.T. February 11, 1967 shown in Fig. V.4a. The same event was observed only vaguely at Great Whale because the latitude is so high that no boundary crossing took place.

Unfortunately, no data simultaneously recorded at a lower latitude station have been available for comparison. However, various workers have reported results of their observations, both in the low and in the mid-latitude stations. These results have been tabulated in Table V.1 to show the mean frequency of Pc3 observed by different authors at different latitudes.

It may be seen from Table V.1 that the mean frequency of Pc3 observed by most workers at geomagnetic latitudes lower than 60° is around 30 to 45 mHz. Allowing for the different scaling methods used by different authors, and also bearing in mind the limitation of the statistical methods employed, the result is in very good agreement with the $f_3$ band of Pc3 that has been observed at Ralston. This is consistent with our speculation that the $f_3$ band of Pc3 is a mid- and lower-latitude phenomenon originating from the inside of the plasmasphere.
In Chapter III, the morning type of Pc3 observed at Ralston on October 18, 1967 under moderately disturbed conditions has been speculated to be a high-latitude phenomenon taking place when Ralston is in the plasmatrough, whereas the afternoon type of Pc3 occurring on the same day is considered to originate inside the plasmasphere and is observed only after boundary crossing took place early in the afternoon. This is consistent with results reported in Section V.4 where the same event recorded simultaneously on charts at Ralston and Great Whale has been compared. It was found that close correlation between Pc3 observed at Ralston and that observed at Great Whale exists only in the morning when the intensity of the Pc3 activity is much greater at Great Whale than at Ralston. This is a clear evidence that the morning type of Pc3 observed at Ralston is a high-latitude phenomenon.

The afternoon type of Pc3 observed at Ralston in the afternoon, however, has no counterpart in the high latitudes. This again is consistent with the speculation that the afternoon type of Pc3 observed at Ralston may have originated from the inside of the plasmasphere.

Since under quiet conditions, the plasmapause expands radially, it is not surprising to find the close correlation between the inverted U-type of diurnal variation of frequency observed at Ralston and that observed at College,
as both of them are expected to be found inside the plasmapause. When the conditions become extremely quiet, then the Pc3 at Great Whale too would have the same frequency and the same diurnal behaviour as at the other stations in the lower latitudes.

The local time dependence of the Pc3 cut-off may also be explained after the asymmetry of the plasmapause configuration has been taken into account. The boundary crossing should take place three hours earlier at Ralston than at College.
<table>
<thead>
<tr>
<th>Observer</th>
<th>Data</th>
<th>Observatory</th>
<th>Geomag. Lat.</th>
<th>Period (Sec)</th>
<th>Frequency (mHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nagata and Fukunishi 1968</td>
<td>Chart and Tapes</td>
<td>Kakioka</td>
<td>26°</td>
<td>28</td>
<td>35</td>
</tr>
<tr>
<td>Hirasawa and Nagata 1966</td>
<td>Chart and Tapes</td>
<td>Kakioka</td>
<td>26°</td>
<td>28</td>
<td>35</td>
</tr>
<tr>
<td>Kato and Saito 1959 (During SSC)</td>
<td>Chart</td>
<td>Onagawa</td>
<td>28°</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>Duncan 1961</td>
<td>Chart</td>
<td>Townsville</td>
<td>29°</td>
<td>19</td>
<td>52</td>
</tr>
<tr>
<td>Campbell 1959</td>
<td>Chart</td>
<td>Borrego</td>
<td>39°</td>
<td>22</td>
<td>45</td>
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<tr>
<td>Maple 1959</td>
<td>Chart</td>
<td>Tucson</td>
<td>40°</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>Berthod, Harris and Hope 1960</td>
<td>Chart</td>
<td>Arizona</td>
<td>41°</td>
<td>35</td>
<td>29</td>
</tr>
<tr>
<td>Duncan 1961</td>
<td>Chart and Tapes</td>
<td>Adelaide</td>
<td>45°</td>
<td>23</td>
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<tr>
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<td>Chart and Tapes</td>
<td>Hobart</td>
<td>52°</td>
<td>27</td>
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</tr>
<tr>
<td>Scholte and Veldkamp 1955</td>
<td>Chart</td>
<td>Witteveen</td>
<td>54°</td>
<td>45</td>
<td>22</td>
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<tr>
<td>Stuart and Usher 1966</td>
<td>Chart</td>
<td>Hartland</td>
<td>55°</td>
<td>40</td>
<td>25</td>
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<tr>
<td>Stuart and Usher 1966</td>
<td>Chart</td>
<td>Eskdalemuir</td>
<td>59°</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td>Holmberg 1953</td>
<td>Chart</td>
<td>Eskdalemuir</td>
<td>59°</td>
<td>25</td>
<td>40</td>
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<tr>
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<td>Chart</td>
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</table>
CHAPTER VI

GENERAL STUDIES OF Pc4

VI.1 INTRODUCTION

Although the exact morphological properties of Pc4 is not yet understood and there remains controversy to be resolved in both experimental observations and the theoretical considerations reported by various researchers since the IGY, many authors believe that the Pc3 and Pc4 types of continuous pulsations are closely correlated. In fact, it has been common practice by some authors to use Pc3, 4, or simply Pc, as a unifying notation to denote both the Pc3 and Pc4 types of micropulsations (Voelker, 1967; Siebert, 1964). On the other hand, Saito (1966) regarded Pc4 as essentially an extension of Pc5 because Pc4 has so many morphological characteristics similar to Pc5. The precise frequency boundary, if there is any, of Pc4 can be located only after the exact nature of its generating and propagating mechanism becomes understood. For this purpose, the morphological properties of Pc4 must first be studied in detail.

The diurnal variation of Pc4 frequency has been observed by Kato and Saito to behave as an inverted U-type in frequency (U-type in period) with minimum frequency occurring just before the noon hour (Kato and Saito, 1959, 1962; Saito, 1962, 1964a). This is contrary to the later report of Hirasawa and Nagata (1966) and Nagata and Fukunishi (1968) who
observed that the Pc4 (15 mHz) band of pulsation appears throughout almost a day, being most active around 0900 L.T. with minimum at about 19 L.T.

Using data obtained during the quiet sun period, 1964 and 1965, Hirasawa and Nagata (1966) have shown that the frequency of the 15 mHz band increases with increasing geomagnetic activity represented by $\Sigma K_p$. Nagata and Fukunishi (1968) even derived an empirical relation expressing the linear relation between the maximum central frequency of Pc4, i.e. the mean frequency of Pc4 scaled at the time of maximum daily frequency occurrence, and the average value of $K_p$ ($\overline{K_p}$) or the sum of $K_p$ ($\Sigma K_p$). These findings have profoundly affected the theoretical model one may use to interpret experimental observations reported in the previous chapters.

The latitudinal dependence of Pc4 amplitude has been studied by a few researchers. Kato and Saito (1962) reported that the maximum amplitude of Pc4 seems to be in the auroral latitude and there seems to be a secondary maximum existing in the sub-auroral zone ($\phi \sim 50^\circ$). Earlier, Vledkamp (1960) collected data from a wider distribution of stations than that used by Kato and Saito and found that there is a prominent maximum in the spatial distribution of Pc4 amplitude near the sub-auroral zones.

These observations are in agreement with those of Obayashi and Jacobs (1958) who, using about 80 days of records
in sunspot-minimum years from 1949 to 1953, observed that there is a concentration of Pc4 range of pulsation near the sub-auroral zone.

In this chapter, we shall report preliminary results based on a detailed study of the few limited data available in the Pc4 frequency range. The records are mainly in the form of rapid-run Esterline Angus charts. The available tape records are those from Ralston and to a lesser extent from Great Whale River. Ralston records are usually of better quality and are used as a basis of comparison with other stations. Only from the Ralston data is the Y field component available for comparison.

The rapid-run magnetograms recorded in one field component F are available from Eights over a period of two weeks in September, 1965. This enables us to make a preliminary investigation into the conjugate behaviour of Pc4 in the mid-latitudes. As for the high latitudes, earlier observation made by Jacobs and Wright (1965) have yielded some results. They suggest that oscillations in the Pc4 range in amplitude and period appear simultaneously at the conjugate stations of Byrd and Great Whale River. This agrees with our observations of more recent data also from the Byrd-Great Whale pair.
VI.2 DIURNAL VARIATION OF Pc4 AT THE MID-LATITUDE RALSTON STATION

Within the frequency boundary of Pc4 defined by the IAGA resolution 1964, there are two different types of pulsation activities that may often be identified at Ralston. Both types are observed mainly in the daytime.

The first type of pulsation activity observed at Ralston under moderately disturbed conditions ($K_p = 3 - 4$) is called 'Giant pulsation' or simply Pg in this thesis, after Sucksdorff (1939) who first discovered this type of phenomenon in an auroral region. The term 'Pg' is used presently in a broader sense, however. As far as the frequency is concerned, Pg is Pc4, but a Pg is known to be a very local phenomenon.

The focus of the present research is mainly on the usual type of Pc4 that occurs under moderately quiet conditions ($K_p \sim 1-2$). This type of Pc4 may be observed simultaneously over a wide area.

The diurnal variation of Pc4 observed at Ralston appears to have a maximum in frequency around 0600 L.T. and a minimum around noon or early in the afternoon. Pc4 occurs at a less frequent rate in the afternoon than in the morning, and the afternoon Pc4, when observed, is usually much lower in signal strength than that in the morning. There are occasions, however, when the signal strength of Pc4 has been found to be greater in the early afternoon. Events that
occur in the afternoon with great intensity are observed at Ralston only when the value of the $K_p$ index is relatively high.

In Fig. VI.2a, an example is shown where Pc4 had been active at Ralston throughout the day, particularly so in the morning. The maximum frequency of Pc4 ($\sim 20$ mHz) occurred just around 0600 L.T. to reach its lowest value of approximately 5 mHz at 1500 L.T. The maximum amplitude of this particular Pc4 event is found to occur around 1000 L.T. which is the time when the $f_3$ band of Pc3 becomes significant.

The correspondence between the occurrence of Pc4 and the occurrence of the $f_3$ band of Pc3 at Ralston has been found to be extremely good. One example of such is illustrated in Fig. VI.2b where the diurnal variation of Pc4 corresponds closely to the diurnal pattern of the $f_3$ band of Pc3. The maximum frequencies of both the Pc4 and the $f_3$ bands are found to occur around 0800 L.T. in the morning whereas the minimum frequencies are observed around local noon. Both Pc4 and the $f_3$ band of Pc3 were observed to be in bundles, each bundle representing a packet of waves. Further, the corresponding packets of waves of the two different bands appear to be strikingly similar. Such correspondence continues, although less easily recognized, even after 1400 L.T. when the $f_4$ band rather than the $f_3$ band of Pc3 dominates (in the sense that it is of much greater intensity).
There are cases where a relatively strong Pc4 signal is observed early in the afternoon, but this occurs only under moderately disturbed conditions. The November 13 event shown in Fig. VI.2c is one such example where a strong Pc4 pulsation signal of 10 mHz in frequency is observed around 1300 L.T. soon after the f₃ band of Pc3 becomes noticeable.

Preliminary results indicate that the amplitudes of the X and Y components of Pc4 are comparable in most cases, but when the general level of magnetic disturbances is high, they may differ, the Y component usually being much larger than the X component.

In Fig. VI.2d, both the X and Y components of the February 9, 1967 event have been displayed for comparison. This example clearly demonstrates that the amplitude of the Y component of Pc4 is much greater than its X component; in fact, the amplitude of the X component is so small that one finds difficulty in identifying it, particularly in the afternoon.
FIG VI.2a  February 24, 1967

DIURNAL VARIATION OF $Pc_4$. 

**Ralston - $X_b$**

TYPE 9/45 SONAGRAM  RAY ELECTRIC CO.  PINE BROOK, N.J.
SIMULTANEOUS OCCURRENCE OF Pc3 AND Pc4
FIG VI.2c  RALSTON X  NOV 13,67

Pc4 IN THE AFTERNOON
FIG VI.2d  COMPARISON OF THE X & Y FIELD COMPONENTS
VI.3 LATITUDE DEPENDENCE OF Pc4

The so-called 'Giant Pulsation' (Pg) described by various authors and reviewed by Kato (1964) has also been observed at Ralston under moderately disturbed conditions. Pg is known to be a local phenomenon which occurs at high latitudes or in the auroral zone. Fig. VI.3a shows a Pg event of approximately 100 sec period observed at McGill and not at the other stations. The Pg activity took place during most of the day of August 17, 1967 but only a small portion of the particular event is shown on the diagram for illustrative purpose.

As for the usual type of Pc4 that occurs under moderately quiet magnetic conditions, it has been widely recognized that this type of Pc4 may be observed simultaneously over a wide area. Indeed, simultaneous observations made at Great Whale, Ralston and McGill not only indicate this trend, but further, the Pc4 observations are found to be of the same frequency.

One typical Pc4 event simultaneously observed at Great Whale, Byrd, Ralston, McGill and Eights is shown in Fig. VI.3b for comparison. The frequency of Pc4 was observed to be the same at all stations. The amplitude, however, is slightly greater at Ralston and McGill, but not to a significant extent.

The conjugacy of Pc4 for both the Byrd-Great Whale
pair in the high latitude region and the Eights-McGill pair in the mid-latitudes has been found to be extremely good. Even peak to peak correspondence has been observed between corresponding pair of stations.

It is rather unfortunate that only a very few of the slow speed magnetic tape data recorded at Great Whale are of sufficiently low noise to signal ratio. This does not allow us to make a detailed comparison of Pc4 observed at the high and the mid-latitude stations. Preliminary observations using the available data, however, have yielded some interesting information. Sonagrams produced from slow speed tape data recorded at Great Whale have shown no distinct separation between the Pc3 and the Pc4 bands, contrary to what is usually observed at the lower latitudes. Often at Ralston, and less often, at College, Pc4 when observed has been found to be a distinct band separated from the Pc3. No separation is observed when the level of magnetic disturbance is high, for example, in the event of a magnetic storm.

The February 24, 1967 event shown in Fig. VI.3c clearly illustrates the phenomenon described above. One may see on the diagram that no separation between the Pc4 and the Pc3 bands has taken place at Great Whale contrary to the clear two-band structure observed at Ralston. The February 23, 1967 event, which occurred under moderately disturbed conditions, did not show clear band structure at
both Great Whale and Ralston, but there is a low-frequency cut-off at approximately 10 mHz observed at Ralston, and not at Great Whale.
FIG VI.3a  Pg ACTIVITY AT McGill
FIG VI.3b CONJUGACY & LATITUDE DEPENDENCE OF Pc4
FIG VI.3c  LATITUDE DEPENDENCE OF Pc's
VI.4 DISCUSSION

The concentration of the Pc4 range of pulsation near the sub-auroral zone observed by various authors (Obayashi and Jacobs, 1958; Veldkamp, 1960; Kato and Saito, 1962) has suggested that Pc4 may originate at the plasmapause. Such a speculation has been reinforced by the observation made recently by a research group reporting from Japan (Hirasawa and Nagata, 1966; Nagata and Fukunishi, 1968) that the daily variation curve of the 15 mHz band frequency (Pc4) on moderately disturbed days (11 ≤ ΣKp ≤ 20) is in good agreement with a daily variation curve of the eigen frequency of a standing Alfven wave along the field lines on the plasmapause, theoretically derived from Carpenter's model of the plasmapause (Wilson, 1963). A similar trend of diurnal and latitude behaviour has been observed at the mid-latitude Canadian stations reported in this chapter. Insofar as the Pc4 band is concerned, therefore, the standing Alfven wave on the plasmapause may be considered as the most probable resonator.

If this is indeed the case, since the eigen frequency of a hydromagnetic oscillation depends heavily on the dimension of the magnetic resonator, and the dimensions of the plasmapause and of the plasmasphere are closely related, it would not be too surprising to find the close correspondence between the occurrence as well as the diurnal behaviour of Pc4 and that of the f3 band of Pc3 observed at
Ralston. The similarity between the $K_p$ dependence of the $f_3$ band of Pc3 and that of Pc4 has already been described in detail in the last chapter.

One example (Fig. VI.3b) has been given where the Pc4 activity observed at both mid- and high-latitude stations are comparable in amplitude as well as in period. This type of 'Pc4' could not be interpreted simply as a result of a hydromagnetic oscillation originating at the plasmapause. Rather, this may be taken as evidence that the eigen frequency of the poloidal oscillation described in the previous chapters may sometimes be found to be very low, so low that it has passed the lower frequency boundary of Pc3 defined by the Berkeley resolution. Such an ultra-low frequency Pc3 is observed only under very quiet magnetic conditions.
CHAPTER VII

POSTSCRIPT: DISCUSSION AND FUTURE EXPERIMENTS

The different forms of diurnal variation of the $\text{Pc}_3$ frequency observed at Ralston in the year 1967 have been studied in detail. It has been found and reported in Chapter III that the majority of them may be classified into four or a combination of four basic types. In order to explain the occurrence of different basic types of diurnal variation of $\text{Pc}_3$, the existence of an eigen oscillation of the modified Alfven mode in the plasmatrough was proposed in addition to the eigen oscillation inside the plasmasphere already widely believed to exist.

Using the proposed classification scheme as a guideline for further research in Chapter IV, the dependence of the four basic types of diurnal variation on the $K_p$ index has been investigated. The experimental result thus obtained further reinforces the idea that eigen oscillation may indeed exist in the plasmatrough. In fact, the research reported in Chapter IV enables one to identify the frequency component of $\text{Pc}_3$ observed at Ralston as having originated in the plasmatrough.

A comparative study of simultaneous observations made at both high and mid-latitude stations provides further support for the proposed model in that the frequency component believed to originate in the plasmatrough was found to be
stronger in the higher latitudes. This is contrary to the observation of another component of Pc3 believed to originate inside the plasmasphere, which was only vaguely seen to exist at the higher latitudes. Thus, all experimental results on Pc3 micropulsation reported in the previous chapters has, up to now, been consistent with the model proposed. It is regrettable, however, that no data simultaneously recorded at a lower latitude station have been available in the course of this investigation. Further experiments must be performed to determine whether the model proposed in this thesis is valid in the low latitudes, or whether it is a phenomenon applicable only in the high- and mid-latitudes.

Future investigation should be planned to look at simultaneous whistler data, as well as any satellite data that may be available, so that the exact position of the plasmapause may be located. So far, whistler observations have been the most successful in locating the plasmapause. If the dimension as well as the configuration of the plasmapause can be accurately determined, then the dimension of the plasmasphere and to a less extent the plasmatrough may be estimated. Further, if the particle density distribution in the magnetosphere which again may be estimated from the whistler data is also known, a simple order of magnitude calculation based on the standing poloidal oscillation in both hydro-magnetic resonators would
enable one to estimate the diurnal variation of micropulsation frequency to be observed at a given station. This, in turn, could be compared with experimental observation.

If the validity of the model may indeed be established, since a Pc3 is observed every day, continuous observation over a network of stations selected along a geomagnetic meridian could provide continuous information on the dimension and the configuration of the dayside plasmapause, the plasmasphere and the plasmatrough. Furthermore, the particle density distribution inside the magnetosphere may be estimated.

The existence of eigen oscillations in the magnetosphere has been assumed throughout this thesis. No serious attempt, however, has been made to study the generation mechanism responsible for the excitation of such oscillations. Atkinson and Watanabe (1966) have suggested that hydromagnetic instability of the Kelvin Helmholtz type may generate surface waves in the magnetopause which may be responsible for the excitation of eigen oscillations in the outer magnetosphere, which in turn are responsible for the Pc5 pulsation observed at ground stations. Since the plasmapause is a boundary between two 'fluids' of different particle density, it would not be too surprising if hydromagnetic instability were responsible for the excitation of surface waves at the plasmapause, which in turn could produce oscillations in the plasmasphere and the plasmatrough.
The sudden enhancement of the two bands of Pc3 activity following an increase in Pc4 intensity, reported in Chapter IV, may be taken as experimental observation that supports the theoretical consideration given in the last paragraph. Undoubtedly future experiments must be planned to look more closely into the validity of such a suggestion.

A future investigation should also give priority to a detailed study of Pc4 to see whether Pc4 may indeed be caused by a hydromagnetic wave propagated along the field line at the plasmapause. In particular, the polarization of Pc4 should be examined more closely.

A close examination of the polarization of each of the three Pc3 bands observed in mid-latitudes should also be very rewarding, particularly when a mid-latitude conjugate pair of stations can be established for comparison. Only with precise knowledge of the polarization of each of the Pc3 and Pc4 bands, can the generation mechanism of these pulsation activities be understood. Such precise knowledge would allow one to pinpoint the particular mode, or combination of different modes, of hydromagnetic oscillation responsible for their excitation.
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SUPPLEMENT TO BIBLIOGRAPHY


APPENDIX 1

CHARACTERISTICS OF THE PLASMAPAUSE

Using whistler data obtained at Eights and Byrd during July and part of August 1963, Carpenter (1966) was able to deduce the following basic features of the knee. Observation of knee effects by satellite has also been made by various observers (Gringduz et al, 1960; Taglar et al, 1965; Lawrence et al, 1965). Results obtained by satellite observations were found to be in good agreement with results obtained using whistler data.

a. The knee is a permanent feature of the magnetosphere.

b. For conditions of moderate magnetic agitation with $K_p = 2 - 4$, the configuration of the plasmapause in the equatorial plane is displayed in Fig. I.2 after Carpenter (1966). The principal feature of this curve are as follows:

(i) A relatively broad minimum in geocentric distance, centered roughly on 0600 L.T., the minimum distance is about $3 - 3.5 \, R_e$.

(ii) A maximum geocentric distance at about 2000 L.T., the maximum being about $5 - 5.55 \, R_e$.

(iii) Following the maximum near 2000 L.T., there is a decrease in the radial distance of the plasmapause on the night side of the earth.
The decrease is roughly $1.6 \, R_e$ over a period of the order of 10 hours.

(iv) A rapid increase in radial distance near 1300 L.T. involving a variation of about $1 \, R_e$ in a period of about 1 hour. This effect may occur several hours before or after 1300 L.T. with roughly half of the cases falling within an hour or two of 1800 L.T.

(v) A gradual increase in radial distance on the day side from about 0600 L.T. to mid-afternoon. The total range of this variation is of the order of $0.5 \, R_e$ and within the period there appears to be a secondary maximum around 1200 L.T., followed by a secondary minimum around 1400 or 1500 L.T.

c. During very quiet planetary magnetic conditions ($K_p = 0 \rightarrow 1$) the above mentioned diurnal curve of the plasmapause moves outward and assumes a more nearly circular configuration at its larger radius. (The high-latitude position of Byrd station becomes favourable for knee observation (Binsack, 1967)).

d. Under stormy conditions the plasmapause moves inward and the degree of asymmetry with respect to the earth may become more pronounced (Corcuff and Delaroche, 1964; Carpenter, 1962).
APPENDIX 2

SPECIFICATION OF KAY ELECTRIC SONAGRAPH 7029A

FREQUENCY RANGE: 5 to 16000 Hz in six ranges:

- 5 - 500 Hz
- 10 - 1000 Hz
- 20 - 2000 Hz
- 40 - 4000 Hz
- 80 - 8000 Hz
- 160 - 16000 Hz

DISPLAYS AVAILABLE: Frequency-vs-amplitude-vs-time (conventional)
Frequency-vs-amplitude-vs-time (contour)
Amplitude-vs-frequency
Amplitude-vs-time

ANALYSIS TIME: 1.3 Minutes

EFFECTIVE RESOLUTION:

- 5 - 500 Hz  2.8 and 19.0 Hz
- 10 - 1000 Hz  5.6 and 37.5 Hz
- 20 - 2000 Hz  11.2 and 75 Hz
- 40 - 4000 Hz  22.5 and 150 Hz
- 80 - 8000 Hz  45 and 300 Hz
- 160 - 16000 Hz  90 and 600 Hz

AGC RANGE: Variable 20 to 40 DB down to 10.

FREQUENCY CALIBRATION: Switchable at 50, 500, or 1000 Hz intervals.

RESPONSE: +2 DB over entire range.

RECORDING TIME:

- 5 - 500 Hz  38.4 sec
- 10 - 1000 Hz  19.2 sec
- 20 - 2000 Hz  9.6 sec
- 40 - 4000 Hz  4.8 sec
- 80 - 8000 Hz  2.4 sec
- 160 - 16000 Hz  1.2 sec

AMPLIFIER CHARACTERISTICS: Flat or 13 DB high-frequency pre-emphasis.

INPUT IMPEDANCE: 200, 600, or 10,000 Ohm, switchable.
APPENDIX  3

POSSIBILITY OF MULTI-BAND \textit{Pc3} CAUSED BY HARMONICS

Stuart and Usher (1966) found that the Pc spectra at the three British stations show peaks of micropulsation occurrence at 30 sec at Lerwick, 60 sec at Eskdalemuir and 40 sec at Hartland. A secondary peak at 25 sec period is also observed at Eskdalemuir. Two possible ways were offered to reconcile the differences:

(a) There may be no latitude dependence of the fundamental period of micropulsations occurring in this range, and the differences may then be due to different harmonics appearing at each station. In this way a fundamental period might be 120 second of which Lerwick was the fourth harmonic, Hartland the third, and Eskdalemuir the second and fifth.

(b) A latitude dependence of fundamental period may exist, being 40 sec at Hartland, 60 sec at Eskdalemuir and 90 sec at Lerwick. In this case the observed Lerwick activity may be the third harmonic, and the secondary peak at Eskdalemuir may be second or third harmonic.

No example, however, has been given in Stuart and Usher's paper to show the diurnal patterns observed at different stations.
To consider whether the multi-band structured Pc3 observed at Ralston too may be caused by higher harmonics of a particular fundamental frequency, as suggested by Stuart and Usher (1966) mentioned above or by Mainstone (1966), we have considered the following:

Let \( F_t \) be the fundamental frequency of a given station at a given time \( t \).

Suppose that only the \( n^{th} \) and the \( n+m^{th} \) harmonics are observed at that station at time \( t \) of a given day, that is

\[
\begin{align*}
f_{n,t} &= n \cdot F_t \\
f_{n+m,t} &= (n+m) \cdot F_t
\end{align*}
\]

Then the separation between the two harmonics observed at time \( t \) is

\[
f_{n+m,n} = f_{n+m,t} - f_{n,t} = m \cdot F_t
\]

At a later time \( T \), if the fundamental frequency of the given station changes to \( F_{t+T} \), since only a continuous event is to be considered, the harmonics observed would be

\[
\begin{align*}
f_{n,t+T} &= n \cdot F_{t+T} \\
f_{n+m,t+T} &= (n+m) \cdot F_{t+T}
\end{align*}
\]

and

\[
f_{n+m,n}^{t+T} = m \cdot F_{t+T}
\]

and the ratio

\[
\frac{f_{n+m}^{t+T}}{f_{n}^{t}} = \frac{F_{t+T}}{F_t}
\]
which implies that as the fundamental frequency increases (or decreases), the separation between two harmonic bands should also increase (or decrease).

If the multi-band structured Pc3 observed at Ralston is caused by harmonics, it should behave as predicted above. However, observations of February 11 (Feb. III.2b), September 3, and October, 1967, for example, indicate that this is not the case. Thus the effect of higher harmonics alone cannot be responsible for the existence of the multi-band Pc3 observed.
## APPENDIX 4

### TABLE OF THE Kp INDEX FOR DATES ILLUSTRATED IN FIGURES

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