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Relation between low latitude Pc3 magnetic micropulsations and solar wind

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Abstract. Pc3 geomagnetic pulsations are quasi-sinusoidal variations in the earths magnetic field in the period range 10-45 seconds. These pulsations can be observed in a number of ways. However the application of ground based magnetometer arrays has proven to be one of the most successful methods of studying the spatial structure of hydromagnetic waves in the earth's magnetosphere. The solar wind provides the energy for the earth's magnetospheric processes. Pc3-5 geomagnetic pulsations can be generated either externally or internally with respect to the magnetosphere. The spatial and temporal variations observed in Pc3 occurrence are of vital importance because they provide evidence which can be directly related to wave generation mechanisms both inside and external to the magnetosphere. At low latitudes (L $<$ 3) wave energy predominates in the Pc3 band and the spatial characteristics of these pulsations have received little attention in the past. An array of four low latitude induction coil magnetometers was established in south-east Australia over a longitudinal range of 17 degrees at L=1.8 to 2.7 for carrying out the study of the effect of the solar wind velocity on these pulsations. Digital dynamic spectra showing Pc3 pulsation activity over a period of about six months have been used to evaluate Pc3 pulsation occurrence. Pc3 occurrence probability at low latitudes has been found to be dominant for the solar wind velocity in the range 320- 700 Km s^{-1}. The results suggest that solar wind controls Pc3 occurrence through a mechanism in which Pc3 wave energy is convected through the magnetosheath and coupled to the standing oscillations of magnetospheric field lines.

Keywords : Pc3 magnetic pulsations – Pc3 occurrence – solar wind velocity – magnetospheric physics

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1. Introduction

Observations of geomagnetic pulsations at low latitudes (L<3) indicate that significant hydromagnetic wave energy penetrates deep into the magnetosphere and the plasmasphere. Statistical studies carried out in the past show that wave energy at low latitudes is primarily in the Pc3 frequency band (Saito 1969; Jacobs 1970; Orr 1973). However the origin of these waves has not been fully established and it is important to determine whether they are generated within or external to the magnetosphere and to identify their generation mechanism.

It is generally accepted that some of the dayside Pc3 pulsation energy is associated with sources external to the magnetosphere. Statistical studies show that the Pc3 wave period is strongly correlated with the magnitude of the interplanetary magnetic field while the pulsation occurrence rate is dependent on the orientation of the interplanetary magnetic field (Greenstadt et el. 1980). The first direct evidence for the propagation of external Pc3-4 wave energy into the magnetosphere had been presented by Greenstadt et al. (1983). They had shown that similar wave frequencies were observed simultaneously by ISEE-1 and ISEE-2 spacecrafts in the magnetosheath and the outer magnetosphere respectively while lower power was seen within the magnetosphere. In contrast to the external source, waves generated within the magnetosphere must originate from instabilities or free energy sources. Using the data of ISEE1, Cao et al. (1994) have reported that Pc3 waves most frequently occur just outside synchronous orbit and are approximately centred on local noons. Furthermore using the data from GOES-2 satellite, Yumoto et al. (1984) have proposed that Pc3-4 wave energy is convected through the magnetosheath to the magnetopause, transmitted deep into the magnetosphere without significant changes in spectra, and then couple with various hydromagnetic wave modes in the magnetosphere.

There is ample evidence that the solar wind velocity controls some of the properties of Pc3-4 pulsations (Saito 1964; Singer et al. 1977). In addition the direction of IMF also plays an important role in controlling these pulsations (Bolshakova & Troistakaya 1968; Takahashi et al. 1981). Studies of the joint effect of the solar wind velocity (V_{sw}) and the angle of the interplanetary magnetic field from the sun-earth line (θ_{XB}) have shown that the amplitude (occurrence) and energy of Pc3-4 pulsations are positively and negatively correlated with V_{sw} and θ_{XB} respectively (Greenstadt et al. 1979; Wolfe 1982).

The present study describes the dependence of low latitude Pc3 occurrence on V_{sw} over the period range of March 25 to May 11, 1982. Since IMF data was not available, the Pc3 occurrence dependence on θ_{XB} and the frequency dependence on the IMF magnitude could not be studied.

2. Data and analysis

An array of two components Pc3-4 induction coil magnetometers was established in south-east Australia to carry out the study (Ansari et al. 1985). The array is shown

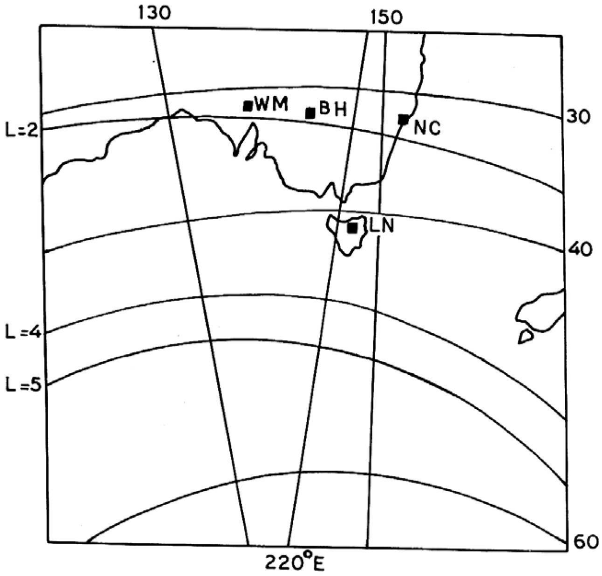

Figure 1. Pc3 recording stations network (WM- Woomera, BH- Broken Hill, NC- Newcastle, LN- Launceston).

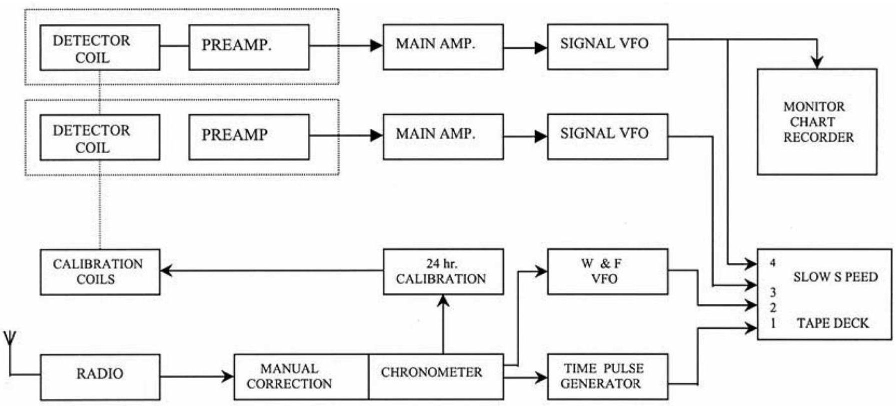

Figure 2. Block diagram of Pc3 recording system.

in Fig. 1. The station locations and interstation distances are listed in Tables 1 and 2 respectively.

It can be seen that a geomagnetic longitude range of 17 degrees is covered at L=1.8 and a latitudinal range of 10 degrees over L=1.8 to 2.7. The geomagnetic north-south (X) and east-west (Y) components of Pc3-4 wave signals in the 5–100 mHz were recorded

Table 1. Coordinate details of four Pc3 recording stations.

	Geographic		Geomagnetic		
Station	$\Phi(^\circ S)$	$\lambda(^\circ E)$	$\Phi(^\circ S)$	$\lambda(^\circ E)$	L value
Newcastle (NC)	32.6	151.7	42.0	226.3	1.81
Broken Hill (BH)	32.0	141.5	42.4	214.5	1.81
Woomera (WM)	31.1	136.7	41.7	209.1	1.79
Launceston (LN)	41.7	147.2	52.4	231.1	2.69

Table 2. Interstation distances of the four Pc3 recording stations in Australia.

Station pair	Interstation distance
WM-NC	425 Km
BH-NC	1065 Km
WM-NC	1485 Km
NC-LN	1120 Km

using slow speed analog magnetic tapes employing frequency modulated recording system (Fig. 2). Data from March 25 to September 21, 1982 were digitized in the laboratory with a 5 sec sample rate using the recorded time channel pulses and providing a Nyquist frequency of 100 mHz. Digital sonagrams from the X (t) and Y (t) time series of all the data for each recording station over little more than one day (25 hour) intervals were constructed using the Maximum Entropy Method (MEM) on 10 minute subsets overlapped by 5 minutes. A detailed analysis of the digital sonagram characteristics was then carried out and the duration of Pc3 occurrence to the nearest five minutes and the signal frequencies were determined for each station. This information was used to calculate the Pc3 occurrence probability and consequently study the control of V_{SW} on Pc3 pulsations.

3. Results

The hourly occurrence probability of Pc3 is defined in Fig. 3 and is based on a method developed by Saito et al. (1979). The daytime intervals from 0500 to 1900 hr AEST (Australian Eastern Standard Time) in the digital sonagrams are divided into fourteen hourly domains to eliminate local time effects. The hourly value of Pc3 occurrence probability, PH, is defined by the formula based on the shaded area AS and hourly area AH in the frequency time domain. The solar wind velocities were taken from IMP-8 data (King 1983). Days on which solar wind velocity data were available and days which showed Pc3 activity at one or more stations are shown in Table 3. There were only 16 out of 48 days which provided common solar wind velocity and Pc3 occurrence.

Table 3. Solar Wind velocity data and Pc3 occurrence over the time interval 0500-1900 hr AEST.

Date	V_{SW}	Pc3	Date	V_{SW}	Pc3
25.3.82	-	A	18.4.82	-	A
26.3.82	-	A	19.4.82	-	A
27.3.82	-	A	20.4.82	-	A
28.3.82	-	A	21.4.82	-	A
29.3.82	A	-	22.4.82	A	A
30.3.82	A	A	23.4.82	A	A
31.3.82	A	A	24.4.82	-	A
01.4.82	A	-	25.4.82	A	A
02.4.82	A	-	26.4.82	A	A
03.4.82	A	-	27.4.82	-	-
04.4.82	A	A	28.4.82	A	A
05.4.82	-	A	29.4.82	-	A
06.4.82	-	A	30.05.82		- A
07.4.82	-	A	01.5.82	-	A
08.4.82	-	-	02.5.82	-	A
09.4.82	-	-	03.5.82	-	A
10.4.82	A	-	04.5.82	A	A
11.4.82	A	-	05.5.82	A	A
12.4.82	A	-	06.5.82	A	-
13.4.82	A	A	07.5.82	A	-
14.4.82	A	A	08.5.82	A	-
15.4.82	A	A	09.5.82	A	-
16.4.82	A	A	10.5.82	A	A
17.4.82	-	A	11.5.82	A	A

A: Solar wind velocity data available or Pc3 occurrence observed.
-: Solar wind velocity data not available or Pc3 occurrence not observed.

The dependence of Pc3 occurrence probability on the solar wind velocity at all the four stations over the 16 days is shown in Fig. 4. The results show a variable pattern with Pc3 occurrence around $V_{SW} = 400$ km s^{-1} followed by a gap between 520 and 610 km/sec and no occurrence over 700 km s^{-1}. Over all velocity ranges, the Pc3 occurrence probability is uniformly high ($\geq$ 50%). The lack of Pc3 activity around $V_{SW} = 600$ km/sec may be due to the low occurrence of V_{SW} in this velocity range as illustrated in the V_{SW} distribution shown in Fig. 5.

4. Discussion and conclusion

The dependence of Pc3 occurrence on V_{SW} found in the present study, based on a small data sample is in general agreement with previous studies on the ground (Greenstadt et al. 1979; 1980) and in space (Takahashi et al. 1981). Greenstadt et al. (1979) examined the

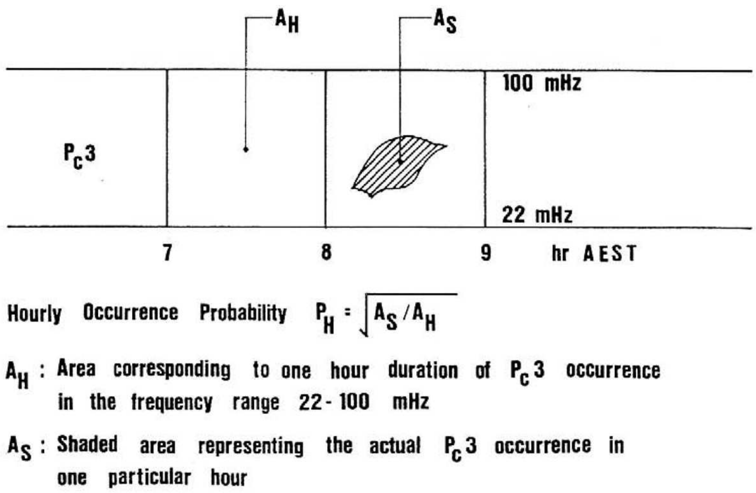

Figure 3. Hourly occurrence probability of Pc3 (after Saito et al. 1979).

maximum amplitude of Pc3 for solar wind parameter correlations, while the definition of occurrence of Pc3 pulsations in this study was based on the shape of the spectra. Gugliel'mi and Potapov (1994) have also reported similar results.

There are two possible locations for the external origin of pulsations, at the magnetopause, and upstream from the magnetopause. Surface waves generated by the K-H instability are important at the magnetopause (Southwood 1968; Boller & Stolov 1973). Upstream from the magnetopause large amplitude waves in the quasi-parallel bow shock are swept back into the magnetosheath and then penetrate the magnetosphere and couple to the standing oscillations of the magnetospheric field lines (Greenstadt 1972). This coupling may occur at all latitudes (Yumoto & Saito 1983). Chi et al. (1998) have explored the statistical relationship between two years of solar wind data recorded by IMP8 spacecraft and Pc3 data from the Mount Clemens magnetometer stations (L $\approx$ 3). They found that Pc3 waves have an energy source in the upstream foreshock. Although the range of solar wind velocity for Pc3 occurrence rate varied between 300 to 700 km s^{-1}, they did not find any apparent threshold for the solar wind velocity that enhances the power of pulsations.

The characteristics of the waves excited by the K-H instability are dependent on the length of the field lines and the plasma density at the magnetopause (Chen & Hasegawa 1974). The association of westward propagation of Pc3 waves with left hand (LH) ellipticity pre noon and eastward propagation with right hand (RH) ellipticity after noon for the azimuthal pair of stations (Ansari & Fraser 1986) are consistent with the waves generated at the magnetopause by the K-H instability. The Pc3 noon peaks in occurrence (Ansari & Fraser 1985), however, cannot be explained by this mechanism. It is also difficult to see how the externally excited evanescent surface waves with large damping

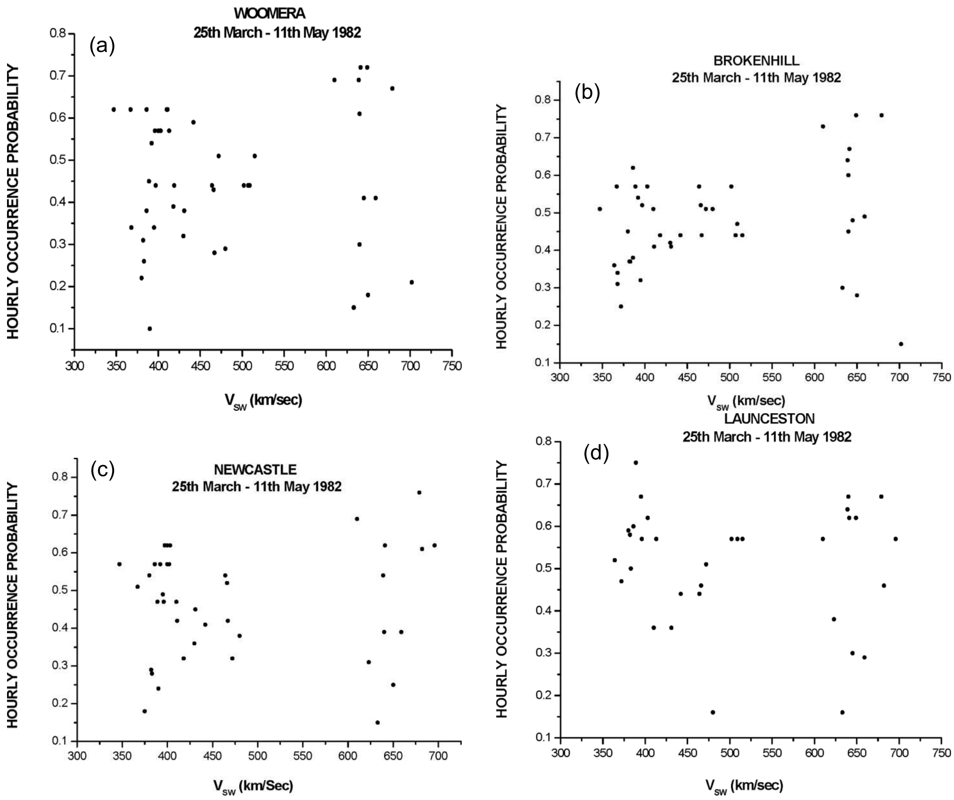

Figure 4. The dependence of Pc3 occurrence probability on the solar wind velocity (VSW) over 16 days in the duration March 25 to May 11, 1982 in the 0500-1900 hr AEST interval at (a) Woomera (b) Broken Hill (c) Newcastle. (d) Launceston.

rates can propagate deep into the magnetosphere and through the plasmapause to couple with the field line resonance at low latitudes. In addition the threshold velocity for the K-H instability involves the angle between the magnetic fields across the magnetopause. Hence on a statistical basis it is likely that the magnetopause is more unstable for higher solar wind velocity, which is consistent with the present results. The contribution of qXB to Pc3 occurrence cannot be interpreted in the absence of IMF data.

The electron density inferred from the upper hybrid frequencies observed by the Plasma Waves and Sounder (PWS) instrument at L $\approx$ 3 is reported to be of the order of 10 per cm (Chi & Russel 2005). Chi et al. (1998) have experimentally verified that for L $\approx$ 3, the threshold solar wind velocity for the onset of Pc3 events is about 300 $\mathrm{km\,s^{-1}}$. However the experimental results of the present study indicate the threshold solar wind velocity of about 320 km/sec for onset of Pc3 occurrence at L $\approx$ 2.

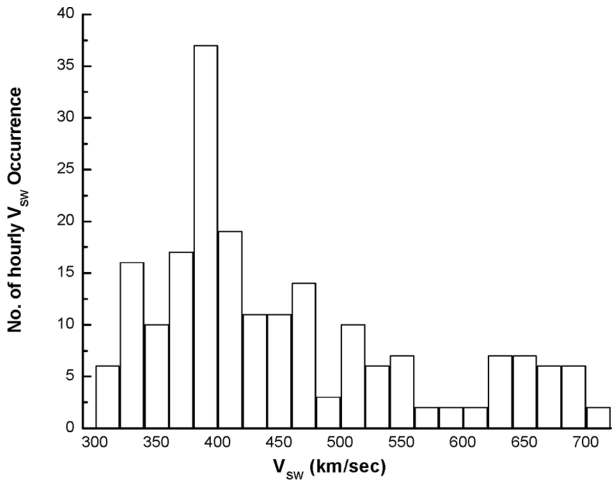

Figure 5. Hourly occurrence of solar wind velocity (VSW) over the period March 25 to May 11, 1982 in the 0500-1900 hr AEST interval.

The quasi-parallel shock transition has been found to be highly turbulent (Greenstadt et al. 1977). Furthermore the amplitude of bow-shock-associated waves seems to be dependent on the magnetosonic Mach Number (Formisano et al. 1973) and therefore on the solar wind velocity. The association of higher probability of Pc3 occurrence at low latitudes with higher solar wind velocity is therefore more likely to be a consequence of bow-shock associated waves. The results of Yumoto et al. (1984) support this mode of Pc3 wave generation and resonance. Using the data of search coil magnetometers from two Antarctic stations (sub-auroral Pc3), Chugunova et al. (2003) have found that the suggested idea about the possibility of two channels of the penetration of primary upstream turbulence, i.e., via the cusp and via the lobe flanks is statistically feasible. More recently Howard & Menk (2005) have undertaken the study of Pc3-4 waves recorded on the ground with the IMAGE magnetometer array at higher geomagnetic latitudes (56°-76°) during January & March 1998. The occurrence and the frequency of these waves have suggested that they are generated by the upstream ion-cyclotron resonance mechanism, with no evidence of generation by the Kelvin-Helmholtz instability. It is however obvious that further studies are needed, which include IMF data, in order to uniquely determine the external and internal contributions to the generation of Pc3 waves observed at low latitudes.

In conclusion it has been demonstrated that the occurrence probability of Pc3 pulsations depends on solar wind velocity with a threshold at about 320 km s^{-1} and ranging up to 700 km s^{-1}. It is likely that an instability originating from the direct interaction between the solar wind and the magnetosphere is exciting Pc3 pulsations through bow-shock associated waves.

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