THE CONTROL AND GENERATION OF MAGNETIC PULSATIONS ON THE GROUND AND IN INTERPLANETARY SPACE BY PARAMETERS OF THE SOLAR WIND

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DECLARATION

I hereby declare that the work presented in this thesis is my own and has not been presented for a degree in any other University; and that the thesis has been composed by myself.
There is evidence to suggest that some Pc 3, 4 pulsations are controlled by solar wind parameters. The waves have been thought to originate as low-frequency waves generated within the solar wind. Data from five ground stations and the ISEE-2 satellite have been used in an investigation of the problems of the control by solar wind parameters of the generation of low-frequency (10 - 80 mHz) waves in the solar wind and their relationship to Pc 3, 4 pulsations on the ground.

The five ground stations form part of the IGS array of rubidium magnetometers operated during the International Magnetospheric Studies (IMS). The ground data have been correlated with the 1-hourly values of the solar wind velocity ($V_{sw}$), the IMF magnitude ($B$) and the IMF cone angle ($\theta_{xB}$).

Results from statistical analysis of the ground data indicate that (a) the energy level of Pc 3, 4 pulsations on the ground increases with the increase in $V_{sw}$ (b) the energy level rises with the decrease in $\theta_{xB}$ (c) the Pc 3 pulsation is better related to the IMF cone angle than the Pc 4 pulsation and (d) the frequency of Pc 3, 4 pulsations depends on the IMF magnitude. The quality of the last relationship is found to be improved when the same frequency of Pc 3, 4 activity is observed over a large area of the Earth's surface.

Data from the ISEE-2 satellite have been used to study the characteristics of low-frequency upstream waves. Three classes of waves have been identified. These are (a) continuous pulsations similar in type to Pc, (b) quasi-periodic incoherent oscillations, distinguished by mixed period fluctuations which often last for several hours, and (c) relatively isolated wave 'bundles'.
The upstream waves are observed preferentially when the IMF direction is sunwards, and the waves are found to be most common when the cone angle is 15° - 45°.

For a set of selected events the dependence of the frequency of the upstream waves on the IMF magnitude has been tested, and a functional relationship \( F = C_0 + C_1B \), between their frequency and the IMF magnitude has been found to be a statistically better fit to the data than the form \( F = CB \) which is in common use.

The upstream waves aboard the ISEE-2 spacecraft and the Pc 3, 4 pulsations recorded simultaneously on the ground stations \((L = 1.8 - 4.3)\) have been compared. It is found that similarity of the spectra of the waves in the solar wind and the ground is very rare and that correspondence between the events in space and on the ground is extremely low. It is implied that the pulsations in the two media are generated by two different mechanisms.

It is concluded that both satellite and ground pulsations are influenced by the parameters of the solar wind; but that the waves in the solar wind are not transmitted through the magnetosheath and magnetosphere directly to appear as Pc 3, 4 pulsations observed on the ground.
# LIST OF CONTENTS

| Title page | i |
| Declaration | ii |
| Abstract | iii |
| List of contents | v |
| List of tables | ix |
| List of captions | xi |

## CHAPTER 1 GENERAL INTRODUCTORY NOTES

1:1 Introduction 1
1:2 Importance of geomagnetic pulsations 2
1:3 This work 4
1:4 Geomagnetic pulsations 6
1:4-1 Definition 6
1:4-2 Short historical notes 8
1:4-3 Classification of geomagnetic pulsations 9

## CHAPTER 2 THEORETICAL BACKGROUND

2:1 Solar wind and Magnetosphere 13
2:1-1 Introduction 13
2:1-2 The solar wind 13
2:1-3 Interplanetary magnetic field (IMF) 14
2:1-4 The magnetosphere and its boundaries 15
2:1-5 The dynamics of the magnetosphere 21
2:2 Origin and transmission of micro-pulsations 23
2:2-1 Introduction 23
2:2-2 Hydromagnetic waves 26
2:2-3 Simplified solutions of the hydromagnetic equations 32
2:2-4 Generation mechanisms for micro-pulsations 34
2:2-5 Field line resonance 36
<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>Low-Frequency Waves in the Interplanetary Medium</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5:1</td>
<td>Introduction</td>
<td>171</td>
</tr>
<tr>
<td>5:2</td>
<td>Interplanetary magnetic field data selection and processing</td>
<td>178</td>
</tr>
<tr>
<td>5:2-1</td>
<td>Introduction</td>
<td>178</td>
</tr>
<tr>
<td>5:2-2</td>
<td>Selection procedure</td>
<td>179</td>
</tr>
<tr>
<td>5:3</td>
<td>Results</td>
<td>184</td>
</tr>
<tr>
<td>5:3-1</td>
<td>Classification of waves in the IMF</td>
<td>184</td>
</tr>
<tr>
<td>5:3-2</td>
<td>Period and amplitude of waves in the IMF</td>
<td>188</td>
</tr>
<tr>
<td>5:3-3</td>
<td>Effects of IMF orientation</td>
<td>192</td>
</tr>
<tr>
<td>5:3-4</td>
<td>Spectral character of IMF waves</td>
<td>203</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>Correlation of Ground and Satellite Pulsations</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6:1</td>
<td>Introduction</td>
<td>225</td>
</tr>
<tr>
<td>6:2</td>
<td>Direct comparison</td>
<td>232</td>
</tr>
<tr>
<td>6:2-1</td>
<td>High latitude station</td>
<td>232</td>
</tr>
<tr>
<td>6:2-2</td>
<td>Mid-latitude station</td>
<td>249</td>
</tr>
<tr>
<td>6:3</td>
<td>Statistical comparison</td>
<td>266</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>Summary, Discussions, Interpretations and Conclusions</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7:1</td>
<td>Scatter in the E - Vsw relation</td>
<td>271</td>
</tr>
<tr>
<td>7:2</td>
<td>Limitation of the use of the cone angle, ( \theta )</td>
<td>274</td>
</tr>
<tr>
<td>7:3</td>
<td>Low-frequency waves in the solar wind: summary and discussions</td>
<td>277</td>
</tr>
<tr>
<td>7:4</td>
<td>Derived relations, F - B in space and on the ground</td>
<td>292</td>
</tr>
<tr>
<td>7:5</td>
<td>Interplanetary origin of Pc 3, 4 pulsations</td>
<td>294</td>
</tr>
<tr>
<td>7:6</td>
<td>What model?</td>
<td>301</td>
</tr>
<tr>
<td></td>
<td>Summary and conclusions</td>
<td>Page</td>
</tr>
<tr>
<td>----</td>
<td>-------------------------</td>
<td>------</td>
</tr>
<tr>
<td>7:7</td>
<td></td>
<td>307</td>
</tr>
<tr>
<td>7:8</td>
<td>Suggestions for further work</td>
<td>311</td>
</tr>
</tbody>
</table>

APPENDIX A1

ACKNOWLEDGEMENTS

REFERENCES
<table>
<thead>
<tr>
<th>Tables</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:1</td>
<td>7</td>
</tr>
<tr>
<td>1:2</td>
<td>12</td>
</tr>
<tr>
<td>3:1</td>
<td>79</td>
</tr>
<tr>
<td>4:1</td>
<td>86</td>
</tr>
<tr>
<td>4:2</td>
<td>92</td>
</tr>
<tr>
<td>4:3</td>
<td>104</td>
</tr>
<tr>
<td>4:4</td>
<td>105</td>
</tr>
<tr>
<td>4:5</td>
<td>123</td>
</tr>
<tr>
<td>4:6</td>
<td>150</td>
</tr>
<tr>
<td>4:7</td>
<td>159</td>
</tr>
<tr>
<td>4:8</td>
<td>161</td>
</tr>
<tr>
<td>4:9</td>
<td>164</td>
</tr>
<tr>
<td>5:1</td>
<td>197</td>
</tr>
</tbody>
</table>

Tables 1:1 Periods of geomagnetic variations.  
1:2 Period ranges of pulsations.  
3:1 Locations of observations used in the studies of pulsations and solar wind, and quantities that were correlated.  
4:1 Recording stations locations.  
4:2 Orbital parameters of ISEE-2 satellite for different epoch.  
4:3 Summary: Integration of the solar wind parameters.  
4:4 Correlation coefficients of the solar wind parameters.  
4:5 Summary of the $E-V_{sw}$ relation.  
4:6 Summary of the cone angle effect on the pulsation energy.  
4:7 Summary of the $F - B$ relation of the $Pc3$, pulsations on the ground.  
4:8 $Pc3$ regression results.  
4:9 Regression results of simultaneous events.  
5:1 Statistics of Sunward/Antisunward IMF in relation to the presence of pulsations in the interplanetary medium.
<table>
<thead>
<tr>
<th>Tables</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5:2</td>
<td>218</td>
</tr>
<tr>
<td>5:3</td>
<td>222</td>
</tr>
<tr>
<td>5:4</td>
<td>223</td>
</tr>
<tr>
<td>7:1</td>
<td>308</td>
</tr>
<tr>
<td>7:2</td>
<td>309</td>
</tr>
</tbody>
</table>

5:2 Summary of result of regression analysis.

5:3 Significance test of the slopes and intercepts of the regression lines for the F - B relation.

5:4 Significance test: Regression lines forced through origin.

7:1 Number of data points.

7:2 Observational relations between solar wind parameters and Pc 3, 4 pulsations.
## FIGURE CAPTIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Caption</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:1</td>
<td>The lines of force of the quiet-day interplanetary magnetic field resulting from extension of the general solar field by an idealized uniform 300 km/sec quiet day solar wind directions (adapted from Parker, 1963).</td>
<td>16</td>
</tr>
<tr>
<td>2:2</td>
<td>Schematic view of the magnetosphere in the noon-midnight magnetic meridian plane (Ness, 1967).</td>
<td>18</td>
</tr>
<tr>
<td>2:3</td>
<td>Model of the magnetosphere according to Heikkila (1973).</td>
<td>19</td>
</tr>
<tr>
<td>2:4</td>
<td>The symmetry relations at magnetically conjugate points for oscillation of the lines of magnetic force. H, horizontal component; D, east declination (Sugiura and Wilson, 1964).</td>
<td>33</td>
</tr>
<tr>
<td>2:5</td>
<td>Schematic diagram of variation of amplitude and polarization as a function of L for unstable surface wave on the magnetopause coupled to a resonant field line.</td>
<td>39</td>
</tr>
<tr>
<td>2:6</td>
<td>Variation of low frequency micropulsation polarization as a function of local time and latitude (Samson et al., 1971). Amplitude is maximum at the lower latitude point (line AB) where polarization changes.</td>
<td>39</td>
</tr>
<tr>
<td>3:1</td>
<td>Average interplanetary magnetic field magnitude versus period of magnetic pulsations seen at a mid-latitude observatory (Troitskaya et al., 1972).</td>
<td>49</td>
</tr>
<tr>
<td>Figure</td>
<td>Caption</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>---------</td>
<td></td>
</tr>
<tr>
<td>3:2</td>
<td>Two versions of the observational results relating the IMF magnitude ( (B) ) to the period ( (T) ) of daytime pulsations. The curves are drawn from ( T = 160/B ).</td>
<td>50</td>
</tr>
<tr>
<td>3:3</td>
<td>Histograms of the occurrence of interplanetary field strengths for each level of the Borok-B-index (Russell and Fleming, 1976).</td>
<td>52</td>
</tr>
<tr>
<td>3:4</td>
<td>Dependence of median log power on solar wind velocity (Takahashi et al., 1981).</td>
<td>61</td>
</tr>
<tr>
<td>3:5</td>
<td>Patterns of shock pulsations for different orientations of interplanetary field in the ecliptic plane, (Greenstadt, 1972).</td>
<td>68</td>
</tr>
<tr>
<td>4:1</td>
<td>Map showing the locations of the IGS magnetometers in the Northern hemisphere with superimposed L-shells for epoch 1977.5, calculated for 120 km altitude from Barraclough et al. (1975).</td>
<td>85</td>
</tr>
<tr>
<td>4:2</td>
<td>An example of power spectral peak of Pc 3 pulsation event on the ground, for H and D components.</td>
<td>89</td>
</tr>
<tr>
<td>4:3</td>
<td>An example of power spectral peak of Pc 4 pulsation event on the ground, for H and D components.</td>
<td>89</td>
</tr>
<tr>
<td>4:4</td>
<td>The annual variation of apogee of ISEE-2 shown in relation to the magnetopause and bow-shock in the ecliptic plane. The apogee moves completely round the data circle once each year.</td>
<td>93</td>
</tr>
</tbody>
</table>
Figure 4:5  The geocentric solar ecliptic (GSE) coordinate system.  

Figure 4:6  A comparison between ISEE-2 and IMP-8 solar wind velocity records on days 313 and 318, 1977.  

Figure 4:7  Correlation between ½-hour average solar wind parameters. (a) Dependence of magnetic field magnitude on solar wind velocity. (b) Dependence of cone angle on solar wind velocity. (c) Dependence of magnetic field magnitude on cone angle.  

Figure 4:8  General distribution of three major solar wind parameters. (a) Occurrence frequency of solar wind velocity, V_sw. (b) Occurrence frequency of IMF magnitude, B. (c) Occurrence frequency of cone angle, ϑ_xB.  

Figure 4:9  Histograms showing the number of pulsation events against local time (LT). (a) Global events. (b) Local events.  

Figure 4:10  Histograms from 5 ground stations showing the number of pulsation events against solar wind velocity, V_sw.  

Figure 4:11  Effect of solar wind velocity on the diurnal occurrence pattern of Pc 3, 4 pulsations from 5 ground stations. The small triangles indicate the median local time for the occurrence of the pulsations.
<table>
<thead>
<tr>
<th>Figure</th>
<th>Caption</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4:12</td>
<td>Scatter plots of ground magnetic energy and solar wind velocity for (a) Pc 3 and (b) Pc 4 pulsations at Faroe.</td>
<td>118</td>
</tr>
<tr>
<td>4:13</td>
<td>Scatter plots of ground magnetic energy and solar wind velocity for (a) Pc 3 and (b) Pc 4 pulsations at St Anthony.</td>
<td>119</td>
</tr>
<tr>
<td>4:14</td>
<td>Scatter plots of ground magnetic energy and solar wind velocity for (a) Pc 3 and (b) Pc 4 pulsations at Oulu.</td>
<td>120</td>
</tr>
<tr>
<td>4:15</td>
<td>Scatter plots of ground magnetic energy and solar wind velocity for (a) Pc 3 and (b) Pc 4 at Eskdalemuir.</td>
<td>121</td>
</tr>
<tr>
<td>4:16</td>
<td>Scatter plots of ground magnetic energy and solar wind velocity for (a) Pc 3 and (b) Pc 4 at Cambridge.</td>
<td>122</td>
</tr>
<tr>
<td>4:17</td>
<td>Histograms from 5 ground stations showing the number of Pc 3, 4 pulsation events against cone angle, $\Theta_{xB}$. The general distribution of cone angle is inserted in the bottom right hand side of the diagrams.</td>
<td>125</td>
</tr>
<tr>
<td>4:18</td>
<td>Percentage cumulative frequencies of occurrence of cone angle from 5 ground stations for Pc 3, 4 pulsations.</td>
<td>127</td>
</tr>
<tr>
<td>4:19</td>
<td>Percentage cumulative frequencies of occurrence of cone angle from 5 ground stations for Pc 3 pulsation.</td>
<td>128</td>
</tr>
<tr>
<td>Figure</td>
<td>Caption</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>4:20</td>
<td>Percentage cumulative frequencies of occurrence of cone angle from 5 ground stations for Pc 4 pulsation.</td>
<td>129</td>
</tr>
<tr>
<td>4:21</td>
<td>Scatter plots of ground magnetic energy and cone angle for (a) Pc 3 and (b) Pc 4 pulsations at Faroe.</td>
<td>133</td>
</tr>
<tr>
<td>4:22</td>
<td>Scatter plots of ground magnetic energy and cone angle for (a) Pc 3 and (b) Pc 4 pulsations at St Anthony.</td>
<td>134</td>
</tr>
<tr>
<td>4:23</td>
<td>Scatter plots of ground magnetic energy and cone angle for (a) Pc 3 and (b) Pc 4 pulsations at Oulu.</td>
<td>135</td>
</tr>
<tr>
<td>4:24</td>
<td>Scatter plots of ground magnetic energy and cone angle for (a) Pc 3 and (b) Pc 4 pulsations at Eskdalemuir.</td>
<td>136</td>
</tr>
<tr>
<td>4:25</td>
<td>Scatter plots of ground magnetic energy and cone angle for (a) Pc 3 and (b) Pc 4 pulsations at Cambridge.</td>
<td>137</td>
</tr>
<tr>
<td>4:26</td>
<td>An example of variation in the amplitude of Pc 3 pulsations from 5 ground stations with a change in the cone angle; a 'switch off' event on day 325, 1977.</td>
<td>139</td>
</tr>
<tr>
<td>4:27</td>
<td>An example of variation in the amplitude of Pc 3 pulsations from 4 ground stations with changes in the cone angle on day 302, 1977.</td>
<td>140</td>
</tr>
<tr>
<td>Figure</td>
<td>Caption</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>4:28</td>
<td>Dynamic spectrum of the Pc 3 pulsation event shown in Figure 4:26 together with the cone angle, at Oulu.</td>
<td>142</td>
</tr>
<tr>
<td>4:29</td>
<td>Dynamic spectrum of the Pc 3 pulsation event shown in Figure 4:27 together with the cone angle, at Cambridge.</td>
<td>143</td>
</tr>
<tr>
<td>4:30</td>
<td>Cross-sections at 12 periods of the dynamic spectrum shown in Figure 4:28 together with the cone angle.</td>
<td>114</td>
</tr>
<tr>
<td>4:31</td>
<td>Records of large amplitude Pc 4 pulsations observed at five ground stations on day 337 at the time interval of 05 - 09 UT together with the IMF cone angle.</td>
<td>146</td>
</tr>
<tr>
<td>4:32</td>
<td>Extension of the records shown in Figure 4:31.</td>
<td>147</td>
</tr>
<tr>
<td>4:33</td>
<td>Dynamic spectrum of strong Pc 4 pulsation recorded at Faroe together with the cone angle at the time interval of 07 - 11 UT on day 337.</td>
<td>148</td>
</tr>
<tr>
<td>4:34</td>
<td>Scatter plots of frequency of ground pulsations and IMF magnitude, (a) Pc 3 and (b) Pc 4 at Faroe.</td>
<td>152</td>
</tr>
<tr>
<td>4:35</td>
<td>Scatter plots of frequency of ground pulsations and IMF magnitude, (a) Pc 3 and (b) Pc 4 at St Anthony.</td>
<td>153</td>
</tr>
</tbody>
</table>
Figure Caption Page
4:36 Scatter plots of frequency of ground pulsations and IMF magnitude, (a) Pc 3 and (b) Pc 4 at Oulu. 154
4:37 Scatter plots of frequency of ground pulsations and IMF magnitude, (a) Pc 3 and (b) Pc 4 at Eskdalemuir. 155
4:38 Scatter plots of frequency of ground pulsations and IMF magnitude, (a) Pc 3 and (b) Pc 4 at Cambridge. 156
4:39 Two groups of regression lines of the form $F = C_0 + C_1 B$ representing the $F - B$ relation from 5 ground stations, (a) 'inclined' regression lines for the Pc 3 pulsations and (b) near 'horizontal' regression lines for the Pc 4 pulsations. 158
4:40 Regression lines of the form $F = CB$ (forced through origin) from 5 ground stations together with the line representing $F = 6.25B$ ($T = 160/B$). 158
4:41 Scatter plots of measured frequency ($F$) against the IMF magnitude ($B$) when the pulsation periods at St Anthony and Oulu were the same within 10% ($T_{SA} = T_{OL}$); (a) Pc 3 and (b) Pc 4 pulsations. 165
4:42 Scatter plots of measured frequency ($F$) against the IMF magnitude ($B$) when the pulsation periods at St Anthony and Faroe were the same within 10% ($T_{SA} = T_{FA}$), (a) Pc 3 and (b) Pc 3, 4 pulsations. 166
<table>
<thead>
<tr>
<th>Figure</th>
<th>Caption</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4:43</td>
<td>Scatter plots of measured frequency (F) against the IMF magnitude (B) when the pulsation periods at Faroe and Oulu were the same within 10% ($T_{FA} = T_{OL}$), (a) Pc 3 and (b) Pc 3, 4 pulsations.</td>
<td>167</td>
</tr>
<tr>
<td>4:44</td>
<td>Scatter plots of measured frequency (F) against the IMF magnitude (B) when the pulsation periods at Cambridge and Faroe were the same within 10% ($T_{CA} = T_{FA}$), (a) Pc 3 and (b) Pc 3, 4 pulsations.</td>
<td>168</td>
</tr>
<tr>
<td>5:1</td>
<td>A schematic diagram of the foreshock region when the IMF direction is near Parker's spiral angle (45°): The disturbance velocity ($V_p$) plus the solar wind velocity ($V_{sw}$) determines the location of the boundary indicated by Q.</td>
<td>174</td>
</tr>
<tr>
<td>5:2</td>
<td>An example of interplanetary magnetic field (IMF) record, 64 sec data recorded on board ISEE-2 satellite on day 313.</td>
<td>180</td>
</tr>
<tr>
<td>5:3</td>
<td>Magnetic field signature of encounter of the Earth's bow-shock and magnetopause.</td>
<td>181</td>
</tr>
<tr>
<td>5:4</td>
<td>The geocentric solar magnetospheric (GSM) coordinate system together with the geocentric solar ecliptic (GSE) coordinate system.</td>
<td>182</td>
</tr>
<tr>
<td>5:5</td>
<td>Examples of Pc-type pulsations in the interplanetary medium, (a) 12.00 - 13.00 UT on day 325, and (b) 08.00 - 09.00 UT on day 337.</td>
<td>185</td>
</tr>
</tbody>
</table>
An example of quasi-periodic oscillations in the interplanetary medium, 15.00 - 16.00 UT on day 304.

Examples of discrete wave 'bundles' in the interplanetary medium, (a) 02.00 - 03.00 UT on day 328, and (b) 09.00 - 10.00 UT on day 306.

Locations of the ISEE-2 satellite in the morning sector during the one hour event on days 325, 337, (Figure 5:5) 304, (Figure 5:6) 328, and 306 (Figure 5:7).

Locations of the ISEE-2 satellite in the morning sector when the low frequency waves in the solar wind were observed (a) 286 cases of continuous wave events, (b) 814 cases of discrete wave 'bundles'.

Distributions of amplitude (a) and period (b) of continuous waves in the solar wind.

Distributions of amplitude (a) and period (b) of discrete wave 'bundles' in the solar wind.

An example of three components (Bx, By, Bz) IMF fluctuations for the high resolution (4-sec) data on board ISEE-2 spacecraft.
<table>
<thead>
<tr>
<th>Figure</th>
<th>Caption</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5:13</td>
<td>Distribution of the IMF cone angle for the 286 cases when continuous low frequency waves were present in the solar wind; the overall distribution of cone angle for all hours (1053 cases) when ISEE-2 was in the solar wind is inserted at the top left hand corner of the figure.</td>
<td>199</td>
</tr>
<tr>
<td>5:14</td>
<td>An example of variation in amplitude of waves in the solar wind with a change in the cone angle; 'a switch off' event on day 325.</td>
<td>201</td>
</tr>
<tr>
<td>5:15</td>
<td>An example of variation in amplitude of waves in the solar wind with changes in the cone angle; a 'switch off' and 'switch on' event on day 308.</td>
<td>202</td>
</tr>
<tr>
<td>5:16</td>
<td>An example of variation in amplitude of waves in the solar wind with a change in the cone angle; a 'switch on' event on day 359.</td>
<td>204</td>
</tr>
<tr>
<td>5:17</td>
<td>An example of variation in amplitude of waves in the solar wind with a change in the cone angle; a 'switch on' event on day 335.</td>
<td>205</td>
</tr>
<tr>
<td>5:18</td>
<td>Occurrence of continuous wave activity in the solar wind distributed over 13 period bands as a function of IMF magnitudes.</td>
<td>207</td>
</tr>
<tr>
<td>5:19</td>
<td>Measured periods of continuous waves in the solar wind as a function of IMF magnitude together with the curve representing the empirical relation $T = 160/B$.</td>
<td>208</td>
</tr>
<tr>
<td>Figure</td>
<td>Caption</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>5:20</td>
<td>Comparison between distribution of measured periods of waves in the solar wind and distribution of their predicted periods derived from the empirical relation, ( T = 160/B ).</td>
<td>209</td>
</tr>
<tr>
<td>5:21</td>
<td>Scatter plot of measured periods of selected wave events in the solar wind ((T_{\text{sat}})) against their predicted period ((T_{\text{pr}})).</td>
<td>212</td>
</tr>
<tr>
<td>5:22</td>
<td>Scatter plot of frequency ((F)) of Pc-like waves in the solar wind versus IMF magnitude ((B)) ((\text{group, A})).</td>
<td>214</td>
</tr>
<tr>
<td>5:23</td>
<td>Scatter diagram for (F - B) relation, group ((B)).</td>
<td>215</td>
</tr>
<tr>
<td>5:24</td>
<td>Scatter diagram for (F - B) relation, group ((C)).</td>
<td>216</td>
</tr>
<tr>
<td>5:25</td>
<td>Occurrence distribution of frequencies of pulsations in the solar wind from four data sets.</td>
<td>220</td>
</tr>
<tr>
<td>6:1</td>
<td>Dynamic spectrum of waves in the solar wind ((\text{top panel})) and the simultaneous Pc 3, 4 pulsations on the ground ((\text{bottom panel})) for 04.00 - 14.00 UT on day 337, Oulu.</td>
<td>234</td>
</tr>
<tr>
<td>6:2</td>
<td>Dynamic spectrum of waves in the solar wind ((\text{top panel})) and the simultaneous Pc 3, 4 pulsations on the ground ((\text{bottom panel})) for 14.00 - 24.00 UT on day 337, Oulu.</td>
<td>237</td>
</tr>
<tr>
<td>Figure</td>
<td>Caption</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>---------</td>
<td>------</td>
</tr>
<tr>
<td>6:3</td>
<td>Dynamic spectrum of waves in the solar wind (top panel) and the simultaneous Pc 3, 4 pulsations on the ground (bottom panel) for 04.00 - 11.00 UT on day 325, Oulu.</td>
<td>238</td>
</tr>
<tr>
<td>6:4</td>
<td>Dynamic spectrum of waves in the solar wind (top panel) and the simultaneous Pc 3, 4 pulsations on the ground (bottom panel) for 12.00 - 19.00 UT on day 325, Oulu.</td>
<td>240</td>
</tr>
<tr>
<td>6:5</td>
<td>Dynamic spectrum of waves in the solar wind (top panel) and the simultaneous Pc 3, 4 pulsations for 10.00 - 19.00 UT on day 304, Oulu.</td>
<td>241</td>
</tr>
<tr>
<td>6:6</td>
<td>Two-hour recordings of magnetic variations in space (ISEE-2) and on the ground (Oulu) for 10.00 - 12.00 UT on day 308.</td>
<td>243</td>
</tr>
<tr>
<td>6:7</td>
<td>Two-hour recordings of magnetic variations in space (ISEE-2) and on the ground (Oulu) for 07.00 - 09.00 UT on day 337.</td>
<td>245</td>
</tr>
<tr>
<td>6:8</td>
<td>Two-hour recordings of magnetic variations in space (ISEE-2) and on the ground (Oulu) for 17.00 - 19.00 UT on day 304.</td>
<td>247</td>
</tr>
<tr>
<td>6:9</td>
<td>Two-hour recordings of magnetic fluctuations in space (ISEE-2) and on the ground (Oulu) together with the IMF cone angle for 12.00 - 14.00 UT on day 325.</td>
<td>248</td>
</tr>
<tr>
<td>Figure</td>
<td>Caption</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>6:10</td>
<td>Dynamic spectrum of waves in the solar wind (top panel) and the simultaneous Pc 3, 4 pulsations on the ground (bottom panel) for 04.00 - 14.00 UT on day 337 at Cambridge.</td>
<td>251</td>
</tr>
<tr>
<td>6:11</td>
<td>Dynamic spectrum of waves in the solar wind (top panel) and the simultaneous Pc 3, 4 pulsations on the ground (bottom panel) for 14.00 - 24.00 UT on day 337 at Cambridge.</td>
<td>252</td>
</tr>
<tr>
<td>6:12</td>
<td>Dynamic spectrum of waves in the solar wind (top panel) and the simultaneous Pc 3, 4 pulsations on the ground (bottom panel) for 04.00 - 11.00 on day 325 at Cambridge.</td>
<td>254</td>
</tr>
<tr>
<td>6:13</td>
<td>Dynamic spectrum of waves in the solar wind (top panel) and the simultaneous Pc 3, 4 pulsations on the ground (bottom panel) for 12.00 - 14.00 UT on day 325 at Cambridge.</td>
<td>256</td>
</tr>
<tr>
<td>6:14</td>
<td>Dynamic spectrum of waves in the solar wind (top panel) and the simultaneous Pc 3, 4 pulsations on the ground (bottom panel) for 10.00 - 14.00 UT on day 304 at Cambridge.</td>
<td>257</td>
</tr>
<tr>
<td>6:15</td>
<td>Dynamic spectrum of waves in the solar wind (top panel) and the simultaneous Pc 3, 4 pulsations on the ground (bottom panel) for 15.00 - 19.00 UT on day 304 at Cambridge.</td>
<td>257</td>
</tr>
<tr>
<td>Figure</td>
<td>Caption</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>6:16</td>
<td>Two-hour recordings of magnetic variations in space (ISEE-2) and on the ground (Cambridge) for 10.00 - 12.00 UT on day 308.</td>
<td>260</td>
</tr>
<tr>
<td>6:17</td>
<td>Two-hour recordings of magnetic variations in space (ISEE-2) and on the ground (Cambridge) for 07.00 - 09.00 UT on day 337.</td>
<td>261</td>
</tr>
<tr>
<td>6:18</td>
<td>Two-hour recordings of magnetic variations in space (ISEE-2) and on the ground (Cambridge) for 17.00 - 19.00 UT on day 304.</td>
<td>263</td>
</tr>
<tr>
<td>6:19</td>
<td>Two-hour recordings of magnetic variations in space (ISEE-2) and on the ground (Cambridge) for 12.00 - 14.00 UT on day 325.</td>
<td>264</td>
</tr>
<tr>
<td>6:20</td>
<td>Scatter diagram of measured periods (T_{sat}) of waves in the solar wind on board ISEE-2 satellite and measured periods (T_{gr}) on the ground at Nagycenk (L = 1.8).</td>
<td>268</td>
</tr>
<tr>
<td>7:1</td>
<td>Transverse characteristics of upstream wave event recorded on board ISEE-2 satellite on day 337 (05 - 11, UT): Dynamic spectrum of Y and Z components.</td>
<td>278</td>
</tr>
<tr>
<td>7:2</td>
<td>Plot of $\theta_{Endc}$ versus, cone angle $\theta_{xB}$ (a) for some 'switch on/off' events upstream, (b) for Pc-like waves in the solar wind.</td>
<td>284</td>
</tr>
</tbody>
</table>
Figure 7:3  Measured wave frequency in the solar wind plotted against IMF magnitude and a family of regression lines together with the line representing $F = 6.25B$ ($T = 160/B$).

Page 286

Figure 7:4  Results of the calculations of upstream wave frequencies as a function of IMF magnitude, $B$, assuming the waves to be Doppler shifted magnetosonic waves. The solid line represents the approximation for high $V_{sw}/n$. The shaded area is the most likely range of variation for the solar wind (Green et al., 1982).

Page 291

Figure 7:5  Scatter plots of measured period ($T$) against predicted period ($T_{pr}$) at Borok and Hartland using $160/B$ as a generation model. The top two panels show Borok and Hartland respectively when the pulsation periods did not coincide at the two stations. The bottom panel shows those cases when the pulsation periods at the two stations were the same within 10%. (Stuart et al.).

Page 295
CHAPTER 1
GENERAL INTRODUCTORY NOTES

1:1 Introduction

The Earth's magnetic field is now known to exhibit variations on a time scale ranging from periods of a fraction of a second to millions of years. This work is concerned with those variations known as geomagnetic pulsations, the relatively rapid, small amplitude changes that typically have periods ranging from a fraction of a second to a few minutes and amplitudes of a fraction of a nanotesla (nT) to about a hundred of nanotesla. These variations are measured on the ground and on board satellites with sensitive magnetometers and are now recognized as originating from the interaction of the Earth's main field with ionised plasma in the exosphere. The actual process of their generation is not well understood, but some theory and observations have hinted that the pulsations are caused by emissions from the active regions of the Sun, which affect the magnetosphere and cause the Earth's magnetic lines of force to vibrate. The asymmetrical configuration of the geomagnetic field on the day and night side of the Earth results in two wave forms which have characteristic differences. These are continuous pulsations (Pc) seen during the day and irregular impulsive wave trains of Pi type observed at night.

The Pc is a series of regular and sinusoidal magnetic oscillations lasting for up to several hours with periods in the range from a few seconds to several hundred seconds and amplitudes from about 1/10 nanotesla to a hundred nanotesla. The continuous pulsations are most clearly recorded on the day-side magnetosphere particularly in the morning sector. The irregular pulsations (Pi) are usually seen as a damped train of wave packets on a magnetogram, each packet is sinusoidal lasting from 5 minutes to 20 minutes with periods from tens of seconds
to a few minutes. Their amplitudes are generally greater than those of the continuous pulsations. They are commonly observed before midnight.

Recently more interest has been directed to the study of a certain class of the Pc pulsations with period range of 10-150 sec., the so called Pc $3,4$ because of some observed associations with parameters of interplanetary space. The fact that waves with periods in the range of the Pc $3,4$ band have actually been seen in interplanetary medium has added further interest to the study of Pc $3,4$ pulsations.

1:2 Importance of geomagnetic pulsations

The primary goal of the studies of geomagnetic pulsations is to understand the process of their generation, the location of their source and their transmission in the magnetosphere. The knowledge of their generation would be used for indirect diagnostics of the magnetosphere and the state of the solar wind. Observations of geomagnetic pulsations on the surface of the Earth offer the possibility of diagnosing the locations of some boundaries of the magnetosphere. Because morphological characteristics of pulsations have been correlated with a wide variety of the solar wind parameters there is a possibility that they may also indicate aspects of solar wind parameters and the magnitude and orientation of the interplanetary magnetic field (IMF). Successful use of pulsations as indirect diagnostics of magnetospheric and solar wind conditions is of capital importance for two reasons. First accurate empirical understanding of surface observations and exospheric and solar wind parameters would open the path to a quantitative theoretical description of a transfer function for waves in the magnetosphere. Second surface diagnostics would be considerably cheaper than the continuous development of satellites for direct measurements. The costs of installing and maintaining a ground magnetometer site are small in comparison to the cost of
obtaining in situ magnetospheric and/or interplanetary data.

The study of geomagnetic pulsations is also important for some secondary reasons. For instance, geomagnetic pulsations provide background noise which is a nuisance to geophysical exploration for minerals and oil deposits using sensitive instruments for geophysical prospecting. The background noise problem is particularly serious in the auroral zones where such methods of geophysical prospecting are now very active. Another example of the secondary use of geomagnetic pulsations is connected with induction studies of the Earth's crust and upper mantle. For this the geomagnetic pulsations are used as a natural, external, primary source for inducing current in the conducting earth. For this application the scale size of the inducing field should be known in order to perform the required mathematical inversion on the recorded data rigorously.

Interest in pulsations studies has developed since 1950s when a new age was opened in the research of the upper atmosphere by use of spacecraft. An outstanding international interest in pulsations was shown for example by IAGA Assembly in Kyoto, Japan in September 1973 when approximately one-tenth of the papers dealt with various aspects of geomagnetic pulsations. This interest continues. However, the diagnostic capability which seems important has not been fully developed for any practical purposes. There are two basic methods for the determination of useful diagnostics. One involves the combination of observed data with a theoretical model of the solar-terrestrial system which can be tested, but a reasonable mathematical model for such a complex and variable environment as the magnetosphere, has not been found. Other methods which use an empirical approach have not yet produced conclusive results because of the many parameters involved. The range of parameters in the solar wind and in the magnetosphere and their possible
interdependence renders the predictive capability of pulsations uncertain, while still offering hope of future profitable applications.

This Work

It has been pointed out that the importance of studying the geomagnetic micropulsations is the possibility to use the pulsations as diagnostics of the magnetosphere and interplanetary medium. Information about magnetospheric conditions which are dependent on the state of interplanetary medium, in particular the solar wind plasma and the IMF, is important in understanding the solar-terrestrial relation. To improve the diagnostic capability of the geomagnetic pulsations, their primary source must be identified. Recent development in the studies of geomagnetic pulsations have hinted that some pulsations with periods in the range of \( \text{Pc} 3,4 \) originate in the interplanetary medium. The way the waves of the \( \text{Pc} 3,4 \) band in the interplanetary medium reach the surface of the Earth through the complex boundaries of the magnetosphere and are eventually identified as geomagnetic pulsations has not been clarified. Transfer of low frequency waves generated locally in the interplanetary medium to the Earth has been suggested, but left unspecified.

This work examines some of the relations which exist between the interplanetary medium and the ground pulsations, thereby investigating how waves in the solar wind could reach the ground. The first aim is to correlate the ground pulsations with the solar wind parameters. The second aim is to determine whether a direct link exists between the waves observed in the interplanetary medium and the \( \text{Pc} 3,4 \) pulsations activity observed at mid-latitude ground stations.

The approach which was adopted was to attempt to answer the following questions:
(a) Do the solar wind parameters control the generation of Pc 3, 4 pulsations in the mid-latitudes?
(b) Is there a direct link between low frequency waves (in the Pc 3, 4 range) observed in the interplanetary medium and the Pc 3, 4 pulsations activity in mid-latitudes on the ground?

The first question involves correlating the Pc 3, 4 pulsations activity with the solar wind parameters, the solar wind velocity ($V_{SW}$), the IMF magnitude (B), and the cone angle ($\Theta_{xB}$). The cone angle is the angle between the IMF direction and the Earth-Sun line (ecliptic x-axis). Previously data used in the correlation studies have involved averaging over one or more hourly intervals. The variability of the parameters which are involved within any given hour severely limits the use of value of hourly averages. In particular the cone angle and IMF effects on pulsations activity would be weakened. In this study correlation studies with short intervals are carried out; 30 min values of the solar wind parameters are used. The half hour interval was chosen because pulsations can be described better in the short interval than in the long interval (~ 1 hr). All the parameters considered were obtained mainly from ONE spacecraft (ISEE-2) carrying the most recently developed equipment for field and solar wind plasma experiments.

The second question involves statistical study of low frequency waves in the solar wind and correlating them with the simultaneous ground Pc 3, 4 activity. The high sensitivity and time resolution of plasma and field instrumentation aboard the ISEE-2 spacecraft has made such a study feasible. Identical equipment, for the magnetic field measurements, consisting of sensitive rubidium magnetometers recording digitally in the IGS array has added interest to the work by permitting sophisticated time series analysis.

The framework for this thesis has been divided into seven chapters. Chapter 1 is an introductory
note, Chapter 2 outlines some important theories, and
Chapter 3 gives a brief observational background, of
geomagnetic pulsations. In Chapter 4 results of statistical
analysis of the solar wind parameters \( V_{sw}, \theta x B, \) and \( B \) and
\( \text{Pc} 3,4 \) pulsations activity are presented. In Chapter 5
morphological study of the low-frequency waves locally
generated in the solar wind is given. A link between the
waves in the solar wind and the simultaneous \( \text{Pc} 3,4 \)
pulsations recorded on the ground is investigated in
Chapter 6. Finally the summary and discussions of the
results are given in Chapter 7.

1:4 Geomagnetic pulsations

1:4-1 Definition

Both the field intensity and the direction of the Earth's
magnetic field may vary with time scales ranging from
millions of years to a fraction of a second. The long period
changes (commonly known as the secular variations) are
internal (with respect to the Earth). The Earth's main
field originate within the Earth itself probably as a result
of dynamo action in the liquid core; the field strength at
the surface is about 35,000 nT on the average. Fluctuations
with periods less than a few days are of external origin.
Table(1:1) adopted from Jacobs (1970) shows the range of
temporal spectrum of fluctuations in the Earth's magnetic
field.

Rapid variations with periods ranging from a few
minutes to several seconds are commonly referred to as
geomagnetic pulsations. The spectrum of geomagnetic
pulsations is wide covering the period range from
approximately 10 minutes to about a 0.1 second. The power
level over the frequency range varies approximately as
inverse square law \( (P \sim 1/f^2) \). The amplitude of the
pulsations, as measured at the surface of the Earth can
range from several hundred of nanotesla (nT) for long
period pulsations in auroral latitudes to less than 0.1 nT
Table (1:1) Periods of geomagnetic variations

<table>
<thead>
<tr>
<th>Period(s)</th>
<th>Origin</th>
<th>Observed Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-1}$</td>
<td>External</td>
<td>Sub-acoustic</td>
</tr>
<tr>
<td>$10^0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^1$</td>
<td>External</td>
<td>Magnetic pulsations</td>
</tr>
<tr>
<td>$10^2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^3$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^4$</td>
<td>External</td>
<td>Magnetic substorm</td>
</tr>
<tr>
<td>$10^5$</td>
<td>External</td>
<td>Diurnal variations</td>
</tr>
<tr>
<td>$10^6$</td>
<td>External</td>
<td>Magnetic-storms</td>
</tr>
<tr>
<td>$10^7$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^8$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^9$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^{10}$</td>
<td>Internal-non-dipolar</td>
<td>Secular-variations</td>
</tr>
<tr>
<td>$10^{11}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^{12}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^{13}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^{14}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^{15}$</td>
<td>Dipolar-Internal</td>
<td>Dipole Reversals</td>
</tr>
<tr>
<td>$10^{16}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$10^{17}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
for those at the short period end of spectrum. For about a century geomagnetic pulsations have been studied under different names, for example geomagnetic oscillations, fluctuations, micropulsations, pulsations, hydromagnetic (HM) emissions, magnetohydrodynamic (MHD) waves and ULF waves. Throughout this work these rapid variations in the Earth's magnetic field will be usually referred to as 'geomagnetic pulsations' or simply 'pulsations'. Occasionally references would be made to other relevant names whenever necessary.

1:4-2 **Short historical notes**

The existance of variations of a few minutes period in the Earth's magnetic field has been known for over a hundred years. The first evidence for the existance of geomagnetic pulsations was given by Stewart in 1861 who reported on a great magnetic disturbance that was recorded at Kew Observatory, England in 1859. On examining the records, Stewart noticed that during this large magnetic storm there were very large and rapid changes in the Earth's field's magnitude and direction. This magnetic storm was associated with a large solar disruption. Its signature that was reported in 1860 by Loomis and Prescott was observed in the form of aurora over Europe, North America and Pacific islands.

Although the existance of the geomagnetic pulsations has been known for over a century the systematic and intensive approach to their study began during the International Geophysical Year (IGY) in 1957-1958. During this period a large global coverage was made for the investigations of the Earth's geophysical environment, and many more magnetometer stations were established to study the global occurrence of important geophysical phenomena such as the magnetic storms and geomagnetic pulsations. During this time and the succeeding years the first global morphology of the magnetic disturbances was established.
Several good reviews of these early observations have been made notably by Troitskaya (1967), Saito (1969) and Jacobs (1970) who outlined distinctive characteristics of the various types of the geomagnetic pulsations that had been identified. In this context the authors focussed their discussions on different but related important points of the previous achievements in geomagnetic pulsations studies. Troitskaya (1967) emphasized the changes that occur in the generation pattern of the geomagnetic pulsations with respect to the state of the magnetosphere. Early experimental and theoretical investigations indicated how geomagnetic pulsations might be useful in giving important information about the phenomena caused by the interaction of the solar wind with the magnetosphere and gave a hint to the formulation of the theory of generation of the pulsations under the influence of the solar wind on the Earth's environment. The success of the theory depends on there being improved understanding of several morphological properties of the geomagnetic pulsations especially the dependence of their amplitude, period and polarization on latitude and magnetic activity. Saito (1969) noted the great interest shown by early workers in studying the general morphology of pulsations particularly after 1940, when the induction magnetometers came into practical use; when the theory of magnetohydrodynamics was advocated; when the IGY cooperative observation was established and when systems of data recording and analysis improved. As a result of these early studies of the basic properties of geomagnetic pulsations a unified system of classification of the pulsation was thought necessary.

Classification of geomagnetic pulsations

An important problem in the study of geomagnetic pulsations is the classification of the observed types of oscillations. Such classifications should be simple but sufficient to express the great variety of oscillations in
a limited number of clearly identifiable types of pulsations.

Pulsations had been classified by researchers into various types under a variety of new names because of the three essentially independent principles of classification which had been adopted, namely classification on morphological properties, i.e. period, amplitude and time of occurrence; correlative classification (based on relation with other types of geophysical phenomena like magnetic storms, aurora and VLF emissions); and genetical classification based on mechanism of generation.

Since the true origin and the actual location of the source of the geomagnetic pulsations is not yet well understood the genetical classification, which would be the best one cannot serve as a general base for classification. The correlative principle, unfortunately, also cannot be used as a base because a clearly expressed correlation for all types of observed pulsations does not exist. This is why, in recent years the morphological principle of classification was popularly as accepted.

The first generally adopted classification based on the morphology of pulsation was introduced in 1957 by the International Association of Geomagnetism and Aeronomy (IAGA). The pulsations were divided broadly into three classes, namely continuous pulsation (Pc), pulsations trains (Pt) and giant pulsations (Pg). But during the IGY and the following years it became evident that the previous mode of classification had to be developed further. Other types of micropulsations, for example, the pearl types had been identified (Troitskaya, 1961).

The question of the new classification of pulsations was considered in detail at the 13th General Assembly of the International Union of Geodesy and Geophysics (IUGG) in Barkley, California in August, 1963. The subsequent
recommendations of the meetings were summarized by Jacobs et al. (1964). Although it was realized that it is difficult to decide where the boundaries of various types of pulsations should be drawn, it was agreed that the pulsations can be divided into two main classes, namely those of regular and mainly continuous character (Pc) and those with irregular wave pattern (Pi). The Pc pulsations activity is a daytime geomagnetic phenomenon consisting of a series of regular and fairly sinusoidal oscillations lasting several hours. The Pi is night time activity consisting of trains of impulsive irregular wave packets; oscillations in each packet may be sinusoidal lasting 5-10 minutes. Each class in turn was divided into subgroups according to their morphological properties.

The first class (Pc) covers the whole range of pulsations with period from 0.2 sec to 600 sec (5 Hz - 1.66 mHz). The second class covers a range of pulsations with period from 1 sec to 150 sec (1 Hz - 6.66 mHz). Table (1:2) shows the period range of the various subgroups of the pulsations from the two main classes; the notation of each subgroup is also shown.

The experience obtained during the years following the adoption of the new classification showed the necessity of even further subdivisions of the geomagnetic pulsations. The subgroups in parentheses are those introduced in 1973. The term Pi 3 was adopted for irregular pulsations having periods longer than 150 sec at the second IAGA General Scientific Assembly, Kyoto, Japan, 1973. At the same meeting the term Pc 6 was given to the class of continuous pulsations with periods above 600 sec. However, the classification which has been adopted is not perfect.
Table (1:2) Period ranges of pulsations

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Period Range (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pc 1</td>
<td></td>
<td>02 - 5</td>
</tr>
<tr>
<td>Pc 2</td>
<td>Continuous</td>
<td>5 - 10</td>
</tr>
<tr>
<td>Pc 3</td>
<td>Pulsations</td>
<td>10 - 45</td>
</tr>
<tr>
<td>Pc 4</td>
<td></td>
<td>45 - 150</td>
</tr>
<tr>
<td>Pc 5</td>
<td></td>
<td>150 - 600</td>
</tr>
<tr>
<td>(Pc 6)</td>
<td></td>
<td>over 600</td>
</tr>
<tr>
<td>Pi 1</td>
<td></td>
<td>1 - 40</td>
</tr>
<tr>
<td>Pi 2</td>
<td>Irregular</td>
<td>40 - 150</td>
</tr>
<tr>
<td>(Pi 3)</td>
<td>Pulsations</td>
<td>over 150</td>
</tr>
</tbody>
</table>

The different types of the pulsations do not differ always in all parameters. Even the period of the pulsations cannot be defined in many cases as the spectrum can have several peaks or be flat. However at present time, it would be impossible to give a much better classification than the one already adopted, though individual investigators may use entirely different subdivision techniques suitable for the purpose of their own studies. [For example Hollo et al. (1972) have characterized pulsations activity into 12 period bands]. Further investigations of pulsations are still in progress, and as the methods of research in this direction are becoming increasingly sophisticated a more detailed classification will be produced in future.

For the purpose of this work, reference is made especially to the continuous pulsations, particularly the Pc 3 and Pc 4 which will be jointly described as the Pc 3, 4 pulsations.
CHAPTER 2
THEORETICAL BACKGROUND

2:1 Solar Wind and Magnetosphere

2:1-1 Introduction

Direct measurements by satellites have confirmed the continuous emissions of plasma by the Sun known as the solar wind, and have provided detailed information of its interaction with the geomagnetic field, confining it to a finite volume - the magnetosphere. The background theory leading to the major boundaries of the magnetosphere are outlined, no detail is included here.

2:1-2 The Solar Wind

Theoretical work notably by Parker (1963) suggested a continual flux of substantial plasma from the Sun because of the very high temperature on its surface. The solar plasma, or the solar wind is blown radially, as ionized gas, outwards from the Sun. The theory predicted that velocities of 400 - 1000 km/sec would be observed at the Earth's orbit. Since then investigations of interplanetary space by artificial satellites and space probes have confirmed the model as developed by Parker. The interplanetary medium, in the vicinity of the Earth, is filled with a highly tenuous plasma which is continuously blown from the Sun at speeds averaging 300 - 500 km/sec. The wind is very 'gusty', however, showing temporal variation in energy, energy spread and density. The strength and irregularity of the wind is caused by hydrodynamic expansion of the solar corona, which is a direct consequence of the high temperatures ($10^6$K) of the corona. The solar wind is composed of coronal gas, fully ionized and electrically neutral. The ionized gas is mainly hydrogen with perhaps one in ten atoms of helium. The density is of the order of 10 ions/cm$^3$ on the average. The temperature corresponding to the wind fluctuates widely from $10^4$ K to $10^6$ K during the time of high solar activity.
The interplanetary magnetic fields are an extension of the solar magnetic fields by the outward flow of corona. The knowledge of large scale properties of the IMF began with Parker's work in 1958. Parker reasoned that the kinetic energy of the solar wind plasma as it left the Sun should decrease according to the inverse square law $1/r^2$, whereas the magnetic energy density would decrease more rapidly as $1/r^4$. It followed, therefore, that the general dipole field on the Sun would not significantly influence the motion of the outward flowing gas once the gas left the solar corona. Parker then considered a 'frozen in' magnetic field configuration of the interplanetary field. 'Frozen in' is generally used to mean that magnetic flux tubes are constrained to move with the plasma flow. Specifically this means that the field lines obey the equations.

$$\mathbf{E} = - \nabla \times \mathbf{B}$$

(2.1)

The field lines thus follow the stream lines of plasma. In general terms the solar wind is filled with magnetic lines of force of the general solar field which is of a few hundred thousand nanotesla at the solar photosphere. The outward expansion of the solar corona into the solar wind carries the lines of force through the interplanetary space. The solar wind and the extended solar field fill all of the interplanetary space out to a distance of, at least, 10 Astronomical Unit (AU), 1 AU = $1.5 \times 10^8$ km. At the Earth's orbit the IMF strength is about 5 nT during quiet solar activity, but can increase to approximately 40 nT during solar flares. The magnetic lines of force extending out through the interplanetary medium maintain a prolonged connection with the Sun as a consequence of the high electrical conductivity of the solar plasma flowing radially from the Sun.
The interplanetary magnetic lines of force would also be radial in space were it not for the 27 day rotation of the Sun. The result of the rotation is that the lines of force are twisted in the form of Archimedean spiral configuration defined by the following expression

\[ r = \frac{V\phi}{\Omega} \sin \theta \]  

(2:2)

where \( V \) is the solar wind velocity; \( \Omega \) is the angular velocity of the rotating Sun; \( r \) is the distance as measured from the Sun; \( \theta \) is the polar angle measured from the axis of rotation of the Sun; \( \phi \) is the azimuth measured around the Sun. Parker (1963) used the solar wind speed of 300 km/sec that corresponds to quiet solar period, to determine the spiral pattern of the field lines of force in the equatorial plane, see Figure (2:1) (after Parker 1963). This resulted in the near 45° average interplanetary magnetic field direction from the Sun-Earth line, at the orbit of the Earth. The 45° IMF orientation is commonly referred to as the Parker spiral angle or the Archimedean spiral. The quiet day IMF appears to be principally radial inside the orbit of the Earth though it approaches the Earth from a direction somewhat to the west of the direction to the Sun. Beyond the Earth's orbit the IMF is principally azimuthal.

The magnetosphere and its boundaries

When the solar wind arrives at the Earth being a good electrical conductor, it does not penetrate freely into the Earth's magnetic field. The Earth's field therefore acts like a blunt obstacle in the path of the solar wind. The pressure of the wind confines the geomagnetic field to a finite volume around the Earth. In 1931 Chapman and Ferraro had predicted the confinement of the Earth's magnetic field inside an elongated cavity during magnetic storm activity. The region inside the cavity is called the magnetosphere. The continual presence of the magnetosphere has been experimentally verified by many
satellite observations.

In addition the solar wind velocity is great enough to be highly supersonic and a detached shock wave is produced in the region ahead of the cavity boundary. The shock is produced by the action of the magnetic field and the characteristic dimension is the cyclotron radius of the solar wind particle (which is approximately 1000 km for a 1 keV proton in the interplanetary magnetic field of 5 nT). The shocked gas behind the bowshock constitutes a thick layer called the magnetosheath or transitional region. The boundary between the magnetosphere and the magnetosheath is known as the magnetopause. Beyond the magnetosheath, i.e., beyond the bowshock is the truly interplanetary medium undisturbed by the presence of the Earth and its magnetic field. The magnetosphere stretches out behind the Earth to form the geomagnetic tail - the magnetotail whose length is very large and extends beyond the orbit of the Moon to an as yet undetermined limit.

The first measurements of the outer region of the magnetosphere were made in 1958 on the Pioneer I space probe and reported by Sonett et al. (1960). Since then many investigations have been carried out in extra-terrestrial space using a variety of satellites and space probes. Ness (1967) gave a good summary of the early Soviet and American satellites and space probes that had provided information about the various magnetosphere boundaries. These early measurements and the more recent observations made by modern spacecraft have accumulated a growing library of information about the various features of the magnetosphere and its surrounding regions as illustrated in Figure (2:2) after Ness (1967) and in more detailed version Figure (2:3), after Heikkila (1973).

The magnetosheath is a region of interaction between the interplanetary magnetic field and the magnetospheric volume. The conditions in the magnetosheath are described
as generally turbulent. The region contains a generally disordered field which is carried by the solar wind plasma flowing past the magnetosphere. The field in this region is of interplanetary origin but has undergone considerable physical changes, i.e., compression in the shock front and further distortion by non-linear flow of plasma in the magnetosheath.

The dimension of the magnetosphere depends on the intensity of the solar wind although large changes in the solar wind intensity produce only relatively small changes in the physical volume of the magnetosphere. The distance from the centre of the Earth to the magnetopause along the Sun-Earth line is approximately 10 Earth radii (RE), although distances less than 8 RE and greater than 13 RE have been observed sometimes. The shock is located about 4 RE beyond the magnetopause. Towards the dawn and dusk meridian both the magnetopause and the bow-shock flare out to distance about 30-50 per cent greater than in the subsolar direction.

Results from several spacecraft investigations, notably the IMP data revealed the existence of a neutral sheet in the tail region. The sheet separates those regions beyond 10 RE near the midnight meridian, where the field is antisunward from those where the field is sunward. The intensity of the magnetic field sharply decreases inside the sheet to a small fraction of its value in the adjacent regions of the magnetotail. The sudden change of the magnetic field vector across the neutral sheet indicates the existence of a strong electric current flowing in the sheet perpendicular to the geomagnetic field lines.

**Plasmapause**

One of the distinctive features of the magnetosphere is the plasmapause.
The Earth is surrounded by a region of dense plasma - the plasmasphere where thermal electrons and protons of atmospheric origin predominate. This dense (~ 100 - 1000 el/cm$^3$) inner region is separated from a tenuous (~ 1 to 10 el/cm$^3$) outer one - the plasma-trough, by a narrow field aligned surface known as the plasmapause.

Early experimental investigations reviewed by Rycroft (1975) indicate that the plasmapause may be defined as the 'knee' in the equatorial plane (or nearly so) of electron density profile. At the plasmapause there is an abrupt change in the plasma density a factor of 10 - 100, ie, from 100/cm$^3$ to 1/cm$^3$ within a geocentric distance of less than 0.15 RE, particularly at the equator, though satellite VLF experiments suggest changes which may often be far more rapid than this. In the tenuous outer region (plasmatrough) the density decreases approximately as $1/R^4$ whereas in the plasmasphere the density distribution along the field line is much less rapid than this.

The mean equatorial radius of the plasmapause is typically 4 RE, but may vary from 7 RE during very quiet periods to 2 RE during great magnetic storm; the variations also depend on local time. In the equatorial plane the shape of the plasmapause is asymmetric in the dawn-dusk direction, with a bulge occurring in the dusk sector. This shape changes according to magnetic conditions, becoming more circular during very quiet period of magnetic activity. These main characteristics of the plasmapause were initially derived from whistler measurements by Carpenter (1966), where more details of the plasmapause may be found.

2:1-5

The dynamics of the magnetosphere

The dynamic nature of the magnetosphere is probably the most significant physical aspect of the Earth's environment. The boundaries sketched in Figures (2:2)
and (2:3) are in constant motion, hence any point in the diagrams only represents the average position in the magnetosphere. Gosling et al. (1967) showed the variations in positions of the magnetopause and bowshock and indicated that, by rough estimate, the bow shock may move at a speed of approximately 1000 km/sec. Fairfield (1971) observed the average and unusual locations of the Earth's magnetopause and bow shock. On some occasions, though very rare, the bow shock was observed at a distance of 22 RE beyond the average position which is approximately 11.5 RE in the subsolar direction. Fairfield's observations supported the general opinion that the magnetospheric boundaries are in constant dynamic state.

The search for the reasons for the variations in the boundaries position has been going on since 1960. For example, Gosling et al. (1967) tried to relate the average position of the magnetopause and bow shock to the solar wind through the planetary geomagnetic index (Kp). Since it is the solar wind that confines the geomagnetic field and the supersonic character of the wind that necessitates the formation of the bow shock it is logical to expect that variations in the flow speed (and consequently the dynamic pressure of the solar wind) to be factors in determining the position of the magnetopause and bow shock. In fact analysis of IMP 4 plasma data in conjunction with the boundary positions (Fairfield, 1971) showed that the solar wind flux appears to be the primary factor controlling the average position of the magnetopause and the bow shock observed at any given time. Knowledge of the solar wind density and velocity was found to be adequate to predict the average position of the bow shock to better than 1 RE 80% of the time and better than 0.5 RE 50% of the time.

Preliminary results from recent measurements on board ISEE spacecraft have confirmed early results that the boundaries of the magnetosphere are constantly moving.
The ISEE spacecraft have been designed particularly to make the first comprehensive study of the magnetospheric dynamics. Details of the ISEE satellites will be given in Chapter 4 of this work. Many multiple crossings of the bow shock have been observed as it passed back and forth over the relatively slow moving spacecraft. The speeds have been found to be highly variable, being approximately 40 km/sec on one occasion and about 100 km/sec on another occasion.

Information about detailed structure and the dynamic state of the magnetosphere is still coming from the ISEE spacecraft. In fact the IAGA Assembly in Edinburgh, August 1981, devoted considerable time to various discussions on the ISEE-1,2 results. Some of the interesting results included the evidence of constant motion (average of 30 km/sec) of the magnetopause boundary with the varying thickness of approximately 600 km. One detailed structure of the magnetopause was reported to be a low latitude boundary layer (LLBL). The LLBL is a layer of magnetosheath like plasma on the earthward side of the magnetosphere.

As the ISEE mission continues more information about the magnetosphere and its boundaries will be available. Meanwhile it is assumed throughout this work that the magnetopause, the bow shock and other distinctive boundaries of the magnetosphere are smooth and well defined boundaries.

2:2 Origin and transmission of micropulsations

2:2-1 Introduction

Continuous pulsations consists of long trains of nearly monochromatic oscillations observed mainly during the day time. Their regularity compared with other geomagnetic disturbances gave early workers reason to believe that they involved certain resonant processes.
It is unlikely that there can be any conceivable electrical process within the Earth's interior that generate waves with frequencies comparable to those of the micropulsations. This situation, together with the fact that some correlation has been found between the solar activity and the micropulsations led all investigators to look for the origin of the pulsations outside the Earth, particularly in the magnetosphere. In fact at present the only successful theory of micropulsations is based on the magnetohydrodynamic oscillations in the magnetosphere which transmit waves through ionosphere to the ground. Two fundamental problems are involved, namely the excitation mechanisms and the nature of the pulsations.

There are a number of likely sources of hydromagnetic waves, most of which have been associated with the interaction of solar wind with the dayside magnetosphere and particle acceleration processes in the nightside magnetosphere. Other mechanisms are associated with current systems inside the magnetosphere and in the tail. These mechanisms produce hydromagnetic waves within the magnetosphere, which can be classified broadly into travelling short wave bursts like the Pi 1 and Pc 1 and the standing waves on field lines like Pi 2 and Pc 2-5 pulsations. The period of the standing waves depends on the content of plasma in the flux tube that is oscillating like a stretched string.

There are obvious mathematical difficulties in the method of applying the vibrating string formalism since it is deduced from uniform magnetic field and broadly idealized condition of plasma. However many workers still believe the method gives a useful estimate, in the absence of a fully developed theory.

A physical parameter that is used frequently in associating the nature of oscillations of micropulsations with the magnetospheric dimension is L-shells, which
was introduced by McIlwain (1961). L-values are normalized to equatorial radius of the dipole field lines and are measured in Earth radii. Field lines (or flux tubes) in the magnetosphere are capable of oscillating into two main configurations, namely toroidal and poloidal oscillations. The toroidal oscillations arise on magnetic surfaces (or shells) formed by rotations of the field lines around the geomagnetic dipole axis. They are transverse oscillations produced by twisting of the magnetic surfaces around the dipole axis. [Each oscillating surface is represented by letter (L) which describes the vibrating magnetic shell]. It is important that different surfaces oscillate independently of each other. The poloidal oscillations are produced by compressions of a volume consisting of all the magnetic shells in the magnetosphere. The oscillations embrace all, or a significant part, of the vibrating volume. They are longitudinal (or compressional) oscillations in the meridional plane.

The theoretical work by Alfvén in 1942 and Alfvén and Falthammar (1963) are fundamental in understanding magnetohydrodynamics. Dungey's 1954 theory is important in describing geomagnetic pulsations in the context of magnetohydrodynamic waves. A notable review on the magnetohydrodynamic (or hydromagnetic) waves has been made by Orr (1973); see also Southwood (1974, 1978) and Lanzerotti and Southwood (1979). The latest and useful contribution to the understanding of the theory of hydromagnetic waves in the magnetosphere has been made by Southwood and Hughes (1982). In the following sections some points in the fundamental theory and observations which are thought to be important for understanding this work are recalled. First the principle of magnetohydrodynamic (MHD) or hydromagnetic theory is outlined. Second a few specific excitation models which have been associated with the generation of continuous micropulsations are discussed briefly together with relevant experimental observations.
Lastly the problems involving transmission of micropulsations through ionosphere are mentioned. In every case the mathematical treatment is avoided or kept as simple as possible while maintaining sufficient background to the theories of hydromagnetic waves in the magnetosphere.

**Hydromagnetic waves**

Dungey made the first attempt in 1954 to attribute hydromagnetic waves in the exosphere to the source of geomagnetic pulsations. Earlier in 1942 Alfven originated the basic theory of magnetohydrodynamics and the magnetohydrodynamic (MHD) waves.

Basically, electric currents are produced in a moving perfectly conducting medium permeated by magnetic field. These currents interact with the main field producing mechanical forces which may be strong enough to modify the state of original motion of the conducting medium quite appreciably. In this way the motion of the magnetized conducting fluid (hydrodynamic motion) and electromagnetic phenomena are coupled, which permits the application of magnetohydrodynamic theory. Alfven and Falthammar (1963) showed that in a steady magnetic field, waves of low enough frequency may propagate in a fluid of high electrical conductivity provided the interaction between the electromagnetic and hydromagnetic phenomena takes place on a large scale. Assuming a uniform magnetic field the authors gave a comprehensive physical picture of the way the MHD disturbance propagates through the conducting fluid in the direction of the ambient uniform magnetic field. Alfven and Falthammar (1963) formalism has been summarized well by Orr (1973).

**Uniform magnetic field**

In a perfectly conducting fluid penetrated by a uniform magnetic field the magnetic flux tube can be considered as frozen into the fluid motion. Combining this idea with the use of Maxwell's magnetic stress tensor to
describe the forces of the medium due to the magnetic field leads to a description by analogy of two magnetohydrodynamic wave modes. One wave mode in 'cold' plasma theory (when the fluid is assumed incompressible and its pressure effect is ignored) is associated with Maxwell's tension \( B^2 / \mu_0 \) along the magnetic field, so the field line behaves like a 'stretched string'. This mode is a transverse wave and only bends the field line. A disturbance is guided along the field line with velocity.

\[
V_A = B \left( \mu_0 \rho \right)^{-\frac{1}{2}}
\]  

(2:3)

known as Alfven velocity \( (V_A) \), where \( \rho \) is the mass density of the medium of propagation. The second hydromagnetic wave mode comprises the fast and slow magneto-acoustic waves, represented in a simplified form when a compressible conducting fluid is considered particularly for two special cases. The first case arises if turbulence is introduced into the fluid perpendicular to the direction of the ambient magnetic field. The field responds with a restoring force equivalent to that from a pressure distribution defined by Maxwell's magnetic pressure. As a consequence there exist compressional waves known as fast magneto sonic or magneto-acoustic waves that propagate longitudinally across the magnetic field with the speed of

\[
V = \left( U_S^2 + V_A^2 \right)^{\frac{1}{2}}
\]  

(2:4)

where \( U_S \) is the speed of sound. Another special case arises if the velocity of particle and the velocity of the wave in the fluid are both parallel to the magnetic field. In this case there is no magnetic force acting and the waves in the fluid will be acoustic waves which propagate with the speed of sound \( (U_S) \).

In a general case when the wave is propagating at an angle of \( \theta \) to the uniform magnetic field, the required dispersion relation is given by
In terms of phase velocity \((V = \omega/k)\) the dispersion relation reduces to

\[
\omega^4 - \omega^2 k^2 \left( V_A^2 + U_S^2 \right) + U_S V_A \omega^2 \cos \theta = 0
\]  

(2.5)

The roots of the equation (2.6) above give the phase speed \((V)\) of the magneto-acoustic or magnetosonic modes of propagation. Within the magnetosphere the velocity of sound \((U_S)\) and Alfven velocity \((V_A)\) are related by inequality \(V_A > U_S\). Hence there are always two real roots for \(V^2\) corresponding to the different modes of wave propagation, ie. for \(\theta = \pi/2\) there is only one mode, that is the fast mode in which the waves are propagated at right angles to the magnetic field with the speed

\[
V^2 = U_S^2 + V_A^2
\]

(2.7)

For \(\theta = 0\), the roots of equation (2.6) are \(\pm V_A\) and \(\pm U_S\) so that, the motion is a superposition of a pure Alfven wave and a pure acoustic wave field.

The above assumption on pressure variation will not, however be realized in the magnetosphere where major contribution to pressure comes from energetic protons whose speed is comparable to the maximum Alfven speed \((V_A\text{ max})\) in the magnetosphere, so transport of the disturbance by particle is important. Also the time interval between collisions of thermal protons is of the same order as the period of the waves. So the collisions will not have time to remove anisotropy of the velocity distribution due to anisotropic compression, hence a compressible fluid approach may not be valid. The situation becomes even more complicated for a non-uniform magnetic field like the Earth's dipole field in the magnetosphere.

Non Uniform magnetic field

Dungey (1954) made a detailed study of the electrodynamics of the exosphere which may be described in terms of Alfven waves, and showed that the interaction between
the geomagnetic field and its variations and the exospheric particles allowed the transmission of low frequency fluctuations. He found that the system possesses eigenfrequencies of oscillations, and he gave a hint on how the solar wind could excite these frequencies. No details of Dungey's formation are included here. Indication is only given of the basic mathematical approach.

In order to relate the phenomena of electrodynamics and hydrodynamics in a non-uniform magnetic field Maxwell's (electromagnetic) equations and the basic equations of hydrodynamics are used after making certain simplifying assumptions. The starting equations (written in SI units) are

1. the usual electromagnetic wave equations

\[
\text{curl } \vec{B} = \mu_0 \vec{j} \quad (2:8)
\]

\[
\text{div } \vec{B} = 0 \quad (2:9)
\]

\[
\text{div } \vec{j} = 0 \quad (2:10)
\]

\[
\text{curl } \vec{E} = \frac{\partial \vec{B}}{\partial t} \quad (2:11)
\]

2. Ohm's law for a perfect conductor moving with velocity \( \vec{V} \)

\[
\vec{E} = - \vec{V} \times \vec{B} \quad (2:12)
\]

3. the basic equation of hydrodynamics with the sum of all the non-magnetic forces set to zero.

\[
\rho \frac{d\vec{V}}{dt} = \vec{j} \times \vec{B} \quad (2:13)
\]

where \( \rho \) is the mass density of plasma.

Combining equation (2:8) with equation (2:13) gives

\[
\mu_0 \rho \frac{d\vec{V}}{dt} = - \vec{B} \times \text{curl } \vec{B} \quad (2:14)
\]

By considering the disturbance field \( \vec{b} \) defined by

\[
\vec{B} = \vec{B}_0 + \vec{b}, \quad \text{where the constant dipole field } \vec{B}_0 \text{ is such that } |\vec{B}_0| >> |\vec{b}|, \text{ it is possible to arrive at the equation}
\]
This is the general wave equation for the propagation of Alfvén waves along the line of force in a non-uniform field, the wave velocity \( V_A \) is known as Alfvén velocity being given by

\[
V_A = \frac{B}{\rho (\mu_0)^{\frac{1}{2}}} \tag{2.16}
\]

Dungey wrote the equation in the form of spherical polar coordinates \((R, \Theta, \phi)\) with \( \mathbf{B}_0 = (B_R, B_\Theta, 0) \) and obtained the coupled differential equations which hydromagnetic disturbances must obey. The equations relate the azimuthal component of electric field of wave \( E_\phi \) to azimuthal component plasma particle velocity \( V_\phi \) and show that two modes of oscillations may be excited, namely toroidal and poloidal oscillations.

The equations governing toroidal and poloidal oscillations (as written by Dungey in 1954) have not been solved, and are far too complicated to be of much use in studying the geomagnetic micropulsations. However, some first estimates of likely eigenperiods have been made by considering the simplest idealized solutions. The simplifying cases below have been considered when assuming a hydromagnetic wave varying as \( \exp (im\phi) \) where \( \phi \) is longitude.

(i) The axially symmetric case, ie

\[
\frac{\partial}{\partial \phi} = 0 \quad m = 0
\]

This condition leads to the decoupling of the toroidal and poloidal equations.

The toroidal equation then describes a transverse oscillation of Alfvén mode in which complete magnetic shells perform torsional oscillations. This is known as toroidal mode. The motion of plasma \( V_\phi \) and the associated bend of the magnetic shell would result in the appearance of pulsations, \( b_\phi \) in the east-west component (or D) of the magnetic field. In this mode the energy flux density known as the Poynting vector (\( \mathbf{E} \times \mathbf{B} \)) is directed along the geo-
magnetic field line $\vec{B}_0$ and the hydromagnetic waves have periods which vary with latitude in accordance with different L-values. For a plasma distribution where the Alfvén velocity is constant on a particular field line, the fundamental period associated with the oscillating field line is twice the travel time for a wave disturbance moving along the field line from hemisphere to hemisphere. For other plasma distribution the eigenperiod is modified in the way such as that described recently by Singer et al. (1979) who indicated that the period of the oscillations depends on L-value and the product of number density and mass of ions.

The decoupled poloidal equation describes a fast mode of longitudinal (or compressional) waves which spread in the whole of the magnetosphere. The motion of plasma and the magnetic field lines is in the meridian plane; the electric field ($\vec{E}$) is directed east-west. Generally the wave has $b_R$, and $b_\phi$ corresponds to north-south or horizontal H component observed on the magnetic records. The Poynting vector for the poloidal mode of oscillation points across the field line: the hydromagnetic energy spreads to fill the whole or a substantial part of the magnetosphere. Thus the L shells resonate with the period that may be identical at all points on the Earth's surface. Strong latitude dependence is not expected in this case, at least for ideal conditions. The fundamental period of the compressional wave is approximately four times the travel time for a hydromagnetic disturbance in the isotropic mode, between the boundaries (in equatorial plane) such as the magnetopause, the plasmapause or ionosphere.

In summary the decoupled form of toroidal and poloidal oscillations govern the following quantities, respectively

$$(E_R, E_\phi, 0); (0, 0, b_\phi); (0, 0, V_\phi)$$ and
$$(0, 0, E_\phi); (b_R, b_\phi, 0); (V_R, V_\phi, 0).$$
Both modes describe longitude independent (axisymmetric) condition which demands that the hydromagnetic oscillations and the disturbances occur in phase over the whole Earth.

(ii) The guided poloidal mode; This mode has the magnetic fluctuation $b_n$ in the direction of the principal normal to the geomagnetic field in the meridian plane. It is highly localized in longitudinal extent, implying that $m$ is large.

2:2-3 Simplified solutions of the hydromagnetic equations

The uncoupled toroidal and guided poloidal equations (case (i) and (ii)) may be solved by numerical integration giving eigenvalues of the differential equations. Orr and Matthews (1971) have calculated the eigenperiods of the symmetric toroidal and the asymmetric guided poloidal oscillations for dipole field line and found the eigenperiods for the toroidal and poloidal modes. These turn out to be significantly separated; the fundamental harmonic period for the guided poloidal mode being approximately 20% longer than for the symmetric toroidal oscillations. The higher harmonics were found to have similar periods for the two modes.

The simplifying conditions which were introduced to the magnetohydrodynamic equations are supported experimentally in parts, but not established in total.

On one hand is the encouraging experimental result that the latitude dependence of certain classes of pulsations (which now seem to be fairly well established). Also, observations at conjugate points by, for example, Jacobs and Wright (1965) and Fam Vanchi et al. (1968) and from satellite (Cummins et al. 1969) indicate a high degree of guidance of some hydromagnetic waves along the geomagnetic field lines, and suggest that standing waves are actually set up within the magnetosphere. The symmetric relations at magnetically conjugate points for standing waves set up along the lines of magnetic force are illustrated in Figure (2:4) (after Suguira and
FIGURE 2:4
Wilson, 1964). The conjugate points are the two points on the Earth's surface linked by a geomagnetic field line.

On the other hand it is unlikely that symmetric toroidal and poloidal modes are ever excited in the magnetosphere as they imply oscillations in phase over the whole world, and such coherent oscillations have not been identified. Typically, magnetograms show localized elliptically polarized waves, whereas the simplified symmetric toroidal and asymmetric guided poloidal wave equations solved by Orr and Mathews (1971) predict linear polarization of the standing waves. In view of these differences between experimental observations and the theoretical assumptions it is not clear which mode of the hydromagnetic waves is dominantly responsible for the geomagnetic pulsations within the magnetosphere. It seems reasonable to retain the coupling terms in the asymmetric case of the hydromagnetic equation if the actual observations of geomagnetic pulsations within the magnetosphere are to be explained. Recently Southwood (1974) and Chen and Hasegawa (1974) made notable contributions on the subject of coupled oscillations within the magnetosphere. Before this is discussed it is necessary to describe briefly how the geomagnetic oscillations in the magnetosphere could be excited, especially by Kelvin-Helmholtz instability.

Generation mechanisms for micropulsations

Kelvin-Helmholtz instability: The Kelvin-Helmholtz or 'wind over water' instability on the magnetopause has been a popular candidate for generating micropulsations for some time. Basically, growing surface waves can develop on an excited surface separating two fluids, if one fluid flows along the surface with sufficient velocity relative to the other.

The theory of Kelvin-Helmholtz instability in the magnetohydrodynamic models, of which the magnetosphere is a good example, has been studied by several authors, eg Chandrasekhar (1961), but always with
restrictive simplifying assumptions until a general treatment was given by Southwood (1968), which related parameters more nearly to experimentally observed ones. Southwood, in a rigorous theoretical treatment of an infinite plane interface between compressible infinitely conducting fluids, (assumed to be moving relative to each other) calculated the critical plasma flow velocity \( U_c \) for the onset of the Kelvin-Helmholtz instability at the magnetopause.

\[
U_c = A_2 \frac{\sin(x_1 - x_2)}{\sin x_1} \quad (2:17)
\]

where \( x_1 \) and \( x_2 \) are angles between the magnetic field and the plasma flow direction in the magnetosphere and in the magnetosheath, respectively, and \( A_2 \) is the magnetosheath Alfvén velocity. Plasma flow velocities along the magnetopause greater than the critical velocity \( U_c \) should drive the above instability mechanism. Important feature brought out by Southwood's theoretical treatment is that if the Alfvén speed on one side of the boundary is significantly greater than that on the other side, the form and direction of the first growing wave modes is relatively independent of the direction of streaming velocity provided it is not too closely aligned to the field with the larger Alfvén speed. This, as applied to the magnetosphere boundary, gives a mechanism that produced circularly polarized hydromagnetic waves at the boundary with the disturbance vector closely aligned to the plane perpendicular to the Earth's field. The spectrum of micropulsations excited by the Kelvin-Helmholtz instability mechanism was not defined by Southwood, but he speculated that waves would be consistent with the observed \( \text{Po} \ 2-5 \) and \( \text{Pi} \ 2 \) pulsations.

Evidence for the generation of low frequency waves on the boundary (magnetopause in this case) by the Kelvin-Helmholtz was initially given by Dungey and Southwood (1970). The authors analysed the magnetic data recorded on Explorer 33 and showed that the waves have diurnal variation in
polarization as predicted by theory. They also indicated that the waves are found not only on the Earth-side of the magnetopause but also are a source of some hydromagnetic turbulence observed in the magnetosheath. Amplitudes in general were higher on the sheath side than the Earth-side of the boundary; the average polarization in the magnetosheath had opposite sense.

Further support for the Kelvin-Helmholtz instability as the generation mechanism for the micropulsations have been shown in one way or another. For instance Boillier and Stolov (1970) associated the semiannual variations of the geomagnetic activity with the similar changes that occur on the Kelvin-Helmholtz instability along the flanks of the magnetosphere. Computer simulations of the magnetosphere in both two and three dimensions have produced fluttering of the magnetopause that may be interpreted as caused by the Kelvin-Helmholtz process (Leboeuf et al. 1979, 1980), and phenomena characteristics of waves have been observed at or near the magnetopause (Kaufman et al., 1970, and Boillier and Stolov, 1973). The present successful theory of field line resonance (Southwood 1974 and Chen and Hasegawa, 1974) assumed that the Kelvin-Helmholtz instability is the driving force of the magnetopause. The field line resonance process is described below.

2:2-5 Field line resonance

Once surface waves are established by processes such as that of the Kelvin-Helmholtz instability, they would be transferred into and through the magnetosphere by the way suggested theoretically by Southwood (1974) and Chen and Hasegawa (1974). These theoretical treatments retain the coupling terms in the general hydromagnetic equations.

According to the theory, the signals generated at the magnetopause would travel into the magnetosphere and be amplified on those flux tubes where the signal frequency matched the local resonance frequency for a standing Alfven
mode on the field. The Alfven mode or transverse mode is guided by the magnetic field and so the signal energy can become trapped on a flux tube provided ionospheric reflection is effective enough at the foot of the flux tube. This process which gives rise to the localized magnetic shells where signal amplitudes are high is called the field line resonance.

Southwood's (1974) theoretical treatment considered a model with straight magnetic field lines $B_z$ and cold plasma distribution which varies in the $x$ direction. The model predicts that any surface wave generated at the magnetopause by, for example, the Kelvin-Hemlholtz instability will propagate across the magnetic field lines, the amplitude decaying until near to the field line resonance position where the amplitude grows sharply and then decays inside the resonant field line position as shown schematically in Figure (2:5). It was implied that, if within the magnetosphere, there is a magnetic field line whose natural frequency (in the transverse mode) is equal to the driving frequency at the magnetopause, then the energy will be coupled from the fast mode into the transverse mode and a field line resonance occurs; if the waves have a definite sense of propagation (say in the $y$ direction) the sense of polarization is a function only of the direction of increase of amplitude and the direction of propagation in the $y$ direction - (east-west when related to the Earth); in particular, the sense of polarization switches on each side of a maximum or minimum in amplitude. For the magnetosphere an eastwards propagating wave would have clockwise polarization south of the resonant field and anti-clockwise north of the resonance - the sense of polarization is described for one looking down along the field line in the northern hemisphere. The reverse applies to a westwards propagating wave. In the immediate vicinity of the resonance where the amplitude is largest the polarization is linear.
Chen and Hasegawa (1974a) developed the field line resonance theory using a dipole magnetic field of which the Earth's field is a good approximation. This allowed detailed prediction to be made concerning the orientation angle of the major axis of the polarization ellipse.

Generally the Southwood and Chen and Hasegawa papers independently came to similar conclusions in the role of resonant field lines in filtering a possible broad band source of waves at the magnetopause, and the results of the authors were remarkably in accord with the high latitude structure of micropulsations reported by Samson et al. (1971). Working with a chain of stations at geomagnetic latitudes between 59°N and 77°N (within 2° longitude 302°E) Samson et al. found not only a latitudinal dependence of peak amplitude with frequency but also a switch in polarization sense on each side of the latitude where peak amplitude was found. They also found a distinct switch in the polarization at about midday. Their polarization results for a fixed frequency (5 mHz) are summarized schematically in Figure (2:6).

The switch in propagation direction indicated by the noon switch in polarization is consistent with waves propagating eastwards in the afternoon and westwards in the morning. This in turn suggests generation by the solar wind through the Kelvin-Helmholtz instability process at the magnetopause: the Kelvin-Helmholtz instability model driven by the solar wind demands that waves at the magnetopause move in antisolar direction both in the morning and afternoon sectors; in this situation, one would expect eastward motion of the waves in the afternoon and westward motion occurring at around local noon. Given the indication that of further switch in polarization at very high latitude one is led to believe that the origin of the pulsations that Samson et al. observed are at the boundary (magnetopause) feeding energy into resonant field lines at some considerable distance away
FIGURE 2:5

FIGURE 2:6
from the boundary. In other words, the Kelvin-Helmholtz generation coupled to resonant field lines explains the dayside polarization changes observed.

Further examination of the field line resonance process by Lanzerotti et al. (1977) with a more restricted chain of stations at a lower latitude found further agreement with theory. Two coincident satellites observations by Hughes et al. (1977) found strong evidence that the pulsation activity was a result of a field resonance: in both cases of the two pulsation events studied the wave polarization characteristics indicated that a resonating field line was between the two satellites.

It is noted that the field line resonance model which now seems to be commonly supported by experimental observations invokes the Kelvin-Helmholtz instability at the magnetopause as a generating mechanism which makes specific predictions about the wave motion relative to the Earth at different local times. Another way of looking at the wave motion in the context of the Kelvin-Helmholtz instability is by East-West (E-W) phase structure of the signals, a type of measurement largely pioneered by the Imperial College of Science and Technology (ICST) group and collaborators (Green 1976; Hughes et al. 1978; Mier-Jedrzejowicz and Southwood, 1979). The measurement involves the diurnal variations in azimuthal wave numbers and polarizations in an E-W chain of magnetometers so that the propagation can be determined. The azimuthal wave number (usually denoted by m) is the rate of change of phase per degree longitude. If the Kelvin-Helmholtz instability is the ultimate source of pulsation energy eastward longitudinal phase motion in the afternoon and westward in the morning is predicted. A high latitude study by Olson and Rostoker (1978) of Pc 5 band pulsations found a diurnal variation in the propagation sense consistent with a Kelvin-Helmholtz source whilst the study using three synchronous spacecraft by
Hughes et al. (1978) found a similar tendency which was most clearly evident in the longest period band of pulsations (80-200 sec) examined.

In the midlatitudes, however, the situation has been rather different. Several studies made on the phase motion of $P_c$ 3-4 pulsation signals from an E-W chain of magnetometers found no evidence for the Kelvin-Helmholtz source. In particular papers by Green (1976), Mier Jedrzejowicz and Southwood (1979, 1981) all reported a similar result, that is the diurnal variation in the phase motion predicted by theory does not appear in the data, although the role of the field line resonance process remained significant. Mier Jedrzejowicz and Southwood (1981) concluded that it seems unlikely that the Kelvin-Helmholtz instability is the major source of midlatitude pulsations.

2:2-6 Solar wind irregularities

The incident solar wind develops significant irregularities particularly the proton density and velocity. Such fluctuations in the solar wind produce variable pressure on the magnetopause. For example, Scarf et al. (1970) estimated that the solar wind energy density associated with the changes in density of the solar wind particles is approximately $3.6 \times 10^{-9}$ erg/cm$^3$. Whenever a pressure of this magnitude is coherent over a large scale in the magnetosphere major geophysical perturbations must be expected as the magnetosphere responds to the periodic compressions. Such variations would generate mainly poloidal waves over the central section of the sunlit magnetosphere. The waves have been associated with transient Pc 2 and Pc 3 pulsations accompanying SSC's (storm sudden commencements) and SI's (sudden impulses) as had been illustrated, for example earlier by Saito and Matsushita (1967) and more recently by Tatrallyay and Vero (1973) and Vero (1975). The last two papers show good examples of the pulsations in the Pc 3 band associated with the sudden impulses (SI's).
Wave-particle interactions; plasma instabilities

Wave-particle interactions is one of the most important consequences of plasma instabilities, in the magnetosphere. A notable review on plasma instabilities in the magnetosphere has been given for example, by Hasegawa (1971) who hinted that most the theories of instability-generated pulsations are based on excitation of a proton-cyclotron wave by beam. The idea of wave generation by a beam has recently become so popular that there has been a tendency to attribute any wave to some kind of beam with a sufficient energy. Two cases of wave-particle interactions involving streaming charged particles (beam) and hydromagnetic waves are mentioned below for general descriptions.

(a) Cyclotron resonance: The dominant resonant interaction between streaming charged particles and any hydromagnetic waves already present in the plasma may be cyclotron resonant. The resonance occurs when the electric and magnetic vectors of the wave rotate in the same sense as the protons with angular frequency equal to the gyrofrequency of the proton. Operation of the resonance mechanism requires the hydromagnetic wave and resonant protons to be travelling in opposite directions. The proton velocity parallel to the geomagnetic field line must be sufficient to Doppler shift the wave frequency up to the local proton gyrofrequency.

Generally a strong wave particle interaction is likely to occur in plasma in a uniform magnetic field when

\[ kU_{\parallel} = N\Omega_{i} \]  (2:18)

where \( k \) is the wave number; \( U_{\parallel} \) and \( \Omega_{i} \) are parallel velocity (to the magnetic field) and angular gyrofrequency of particle; \( N \) is an interger. When the above condition is fulfilled the resonance can build up; for \( N = \pm 1 \) gyroresonance prevails, that is the wave vector rotates at the same angular frequency as the gyrating charged particle. In the wave frame of reference we have
\[ kU_{11} = \pm \Omega i \]  
(2.19)

in the Earth's rest frame, the condition for gyroresonance becomes

\[ kU_{11} + \omega = N\Omega i \]  
(2.20)

where \( \omega \) is the angular frequency of the wave.

Resonant particles exchange energy with the wave; if the wave gains energy from the particle it is amplified and if it loses energy to the particle it is attenuated; this latter effect is called collisionless or 'Landau' damping. The total particle population trapped within a given flux tube, i.e. particle distribution function decides whether or not the waves will be amplified. It seems that the resultant amplification of waves takes place when the pitch angle of the particles decreases (zero pitch angle corresponds to the particles travelling parallel to the field lines).

The stable state of the Pc 1 oscillations may be attributed to cyclotron resonance process. The Pc 1 wave-packets can be amplified by cyclotron or gyroresonance interaction involving protons in the magnetosphere.

(b) Bounce resonance interactions: When charged particles are trapped, they have periodic bounce between 'mirror' points and drift around the Earth in longitude. The reflection phenomena that takes place in a region of converging magnetic field is known as the magnetic mirror. In the region between two magnetic mirrors a particle whose velocity vector makes sufficient angle with the field will be reflected at both ends of the region and become trapped. The magnetic trapping of this kind occurs in dipole field like the Earth's field.

The additional periodicities which the bouncing particles attain make possible a resonant interaction, other than gyroresonance, with hydromagnetic waves. A suitable instability involving bounce resonance has been formulated by Southwood et al. (1969) and later summarized by Dungey and
Southwood (1970) and Orr (1973). Southwood et al. considered energetic protons bouncing between northern and southern hemispheres and drifting westwards in azimuth thereby interacting with waves travelling westwards. For this choice of charged particles and waves the authors showed that it is possible for the protons to lose energy to the wave and therefore amplify it. This mechanism could provide a plausible explanation of the regular and almost monochromatic Pc 4,5 oscillations seen on the geostationary satellite ATS-1 by Cummings et al. (1969).

2:2-8 Others

Some theories of excitation of continuous micropulsations are not equally popular as those described above; but have been considered as contributing to a reasonable proportion of geomagnetic fluctuations in the magnetosphere. One of the theories worth mentioning here involves transient magnetospheric current sheets. The radial diffusion of trapped particles in equatorial plane could stimulate Pc 3 and Pc 4 pulsations activity on the dayside magnetosphere while Pi 2 oscillations could be triggered in the nightside magnetosphere by transient current sheet produced during the inward movements (in the equatorial plane) of the neutral sheet imbedded in the westward current system. A transient current sheet moving transverse to the magnetic field would generate broad band geomagnetic fluctuations which would be channelled along the magnetic field line to account for continuous micropulsation observed on the surface of the Earth.

2:2-9 Ionospheric and atmospheric transmission

The hydromagnetic waves outlined in section 2:2-2 must propagate through ionosphere and atmosphere to be recorded on the surface of the Earth as geomagnetic pulsations. The ionosphere and atmosphere, which form a non-uniform layer of approximately 2000 km thick, render the propagation of hydromagnetic waves there complicated. The interaction of
hydromagnetic waves with both conducting and dielectric slabs of medium, 2000 km thick above the ground can be interpreted as the interaction of wave with a medium of non-uniform refractive index that varies from place to place on the surface of the Earth. In this medium it has been known that waves do not only change their amplitudes but also their polarization characteristics. Three main conclusions have been reached from the recent theoretical treatments originated by Inoue (1973), Hughes (1974) and subsequently developed by Hughes and Southwood (1976a, b). First the horizontal signal polarization at the ground is at right angles to the transverse magnetospheric signal, i.e., the signal's polarization ellipse is rotated through 90° by the ionosphere. Second, signals with horizontal scale length shorter than ~ 120 km (the height of the conducting E region) are attenuated between the ionosphere and the ground. The reduction in ground amplitude relative to the magnetospheric amplitude increases as the horizontal scale length is decreased, the ground amplitude is often one order of the magnitude smaller than the magnetospheric signal for a given horizontal scale. The effect means that a limitation may be placed on the detectability on the ground of small scale structure in the magnetosphere. In other words the localized structure in the magnetosphere may be smoothed out or even totally shielded from the ground meaning that some signals may only be seen in space. Finally, the magnetospheric signals reflect well off a typical dayside ionosphere but absorption can be very high on midlatitude nightside ionosphere where conductivities are low. This could possibly explain the prevalence of damped Pi pulsations observed at night and Pc pulsations observed in the day, as less than perfect reflection of hydromagnetic waves means that the field line resonance standing wave structures have characteristic time scale on which they damp. However day and night sources may differ and could be a deciding factor in determining continuous or damped wave occurrence.
These three conclusions have not found entire experimental support. For example, the field line resonance theory outlined in section 2:2-5 also predicts that the resonance region thickness is inversely proportional to the damping time except for waves generated at steep gradients (for which the plasmapause serves as a good example). A measure of resonance region thickness in space by Hughes et al. (1978) suggested that dayside ionospheric damping is not sufficient to account for that observed and that other sources of damping such as the ones suggested by Newton et al. (1978) were important. Collisionless damping process was the alternative. On the other hand it appears that observational evidence is building in strong favour of the polarization ellipse rotation between magnetosphere and ground as predicted by theory. A statistical study of Pc 3 magnetic pulsations at synchronous orbit, ATS-6 by Arthur et al. (1977) combined with the statistical results from ground observation at Lac Rebours of conjugate waves (Lac-Rebours/Siple) by Lanzerotti et al. (1972) indicates that the waves ellipse orientation in the magnetosphere is rotated from that observed on the ground. The study by Walker et al. (1979) using the Stare (Scandinavian twin auroral radar experiment) auroral radar system to measure ionospheric electric fields associated with Pc 5 indicated that the magnetic polarization ellipse is indeed rotated through 90° by the ionosphere. Also in favour of the rotation effect is a general feature often found in ground measurements, that is far more latitudinal structures are observed in the North-South component of the signals on the ground while resonance theory predicts such structure to occur in azimuthal component in space.
CHAPTER 3

OBSERVATION BACKGROUND

3:1 Solar wind controlled pulsations

3:1-1 Introduction

In the preceding section some of the commonly suggested excitation mechanisms that are responsible for micropulsations observed on the surface of the Earth and in the magnetosphere have been mentioned. It is to be remembered that one class of pulsations may be associated with one or several models of excitation and it is not established which excitation process dominates. There are two classes of pulsations which have been correlated with parameters of the interplanetary medium, notably solar wind velocity ($V_{SW}$), and interplanetary magnetic field (IMF) magnitude and orientation. These classes are the $Pc_3$ and $Pc_4$ pulsations activity and referred to simply as $Pc_3$, $Pc_4$ pulsations.

The earliest work linking the $Pc_3$, $Pc_4$ pulsations to the interplanetary parameters has been reviewed by Gul'elmi (1974). Good reviews of more recent studies have been given by Greenstadt (1979), Saito et al. (1979) and Greenstadt et al. (1980). Only the highlights of the early and more recent studies are given here, emphasising the most convincing evidence relating solar wind parameters to pulsations recorded on the ground.

In the following sections the experimental studies relating the solar wind parameters to the control of the $Pc_3$, $Pc_4$ pulsations activity are summarised. Then two principal models which have been proposed to connect the solar wind parameters with midperiod ($Pc_3$, $Pc_4$) daytime geomagnetic pulsations are described. Selected references are given.

3:1-2 Period of $Pc_3$, $Pc_4$ pulsations

The early correlation studies of the period of
pulsations on the ground and the solar wind parameters were made by Gringauz et al. (1971) who reported a 'U' shaped dependence of period on the solar wind flux density (\(nV\)), that is the dependence is different for two period (\(T\)) ranges (\(T \leq 40\) sec. and \(T \geq 40\) sec.); for the first range the period decreases with the rise of flux density; for the second range the period increases. The authors illustrated that only the proton density (\(n\)) of the solar wind particles (but not the bulk velocity (\(V\)) of the solar wind) was responsible for the dependence. They interpreted their result as the simultaneous generation of two types of pulsations, but noted the difficulty of explaining the increase of period with the rise of the solar wind flux density for the pulsations with \(T > 40\) sec., which corresponds to the Pc 4 type of pulsations.

The most convincing correlation yet found between a property of the solar wind and the Pc 3,4 pulsations on the ground has been that of the IMF magnitude (\(B\)) and the period (\(T\)). Troitskaya et al. (1971) found the relation between frequency in millihertz (mHz) of ground Pc 3,4 pulsations and the IMF magnitude in nanotesla (nT) to be \(F = 6.15 B\). Similar relationship was reported by Troitskaya et al. (1972). Figure (3:1) shows the average IMF magnitude versus period of magnetic pulsations (after Troitskaya et al. 1972). Later authors notably Gul'elmi on different occasions derived similar relationships with different quantitative results, in particular \(F = 6.25 B\) or \(T = 160/B\) (Gul'elmi et al. 1973) where \(T\) is measured in seconds (sec.) and \(B\) in nanotesla (nT); \(F = 5.5 B\) (Gul'elmi 1974); and \(F = 11.8 + 5.1 B\) (Gul'elmi and Bolshakova, 1973). Figure (3:2) shows two versions of the correlation; one developed by Gul'elmi et al. (1973) and the other by Vero and Hollo (1978). The curves through the data points in both cases represent the relation \(T = 160/B\). The apparently close agreement between the data points and the relationship represented by the curves has been qualified.
FIGURE 3:1
FIGURE 3:2

Gulémi et al. (1973)

Veró and Holló (1978)
by Vero (1979), who cautioned that the correlation is a 'very rough' one with T really representing the peak of a band of excited frequencies; in other words, the period $T = 160/B$ is by no means a distinct line in the spectrum; it is much more the centre of a band where amplification occurs. Varga's (1980) numerical computations indicate that the bandwidth of the periods where amplification may occur is some tens of seconds. Other qualifications have also emerged, generally in the form of modification of the empirical expression $T = 160/B$ by changing the constants of proportionality in the way given by Gul'elmi and Bolshakova (1973) and by adding a linear term in Kp to account for the general increase of pulsations activity with geomagnetic disturbance. One such composite representation formed the basis for the 'Borok-B-Index', an hourly number designed to provide an indirect measure of the IMF magnitude from pulsation data. The formula used was

$$B = 0.7 + 0.16Kp + 150/T \quad (3:1)$$

The validity of the Borok Index was later tested independently by Russell and Fleming (1976) who showed that there was a spread of field magnitude corresponding to each B-Index Figure (3:3) and that the test had only 27% success. However the authors observed that the index could be improved by a suitable recalibration. They devised such a recalibration which gave

$$B = 3.96 + 0.18Kp + 173/T \quad (3:2)$$

and noted that when so adjusted the Borok index was an appreciably better predictor of the IMF than random numbers but still fell short of providing one-to-one substitute for direct measurement. Another evidence of weakness of the Borok index was reported by Greenstadt and Olson (1976), who used the expression for the Borok index revised according to Russell and Fleming correction, to select those hours for which the IMF and the Kp index predicted no pulsations...
FIGURE 3:3

Number of Occurrence

Percent Occurrence

IMF MAGNITUDE ; B nT.
in the Pc 3 range. They analysed the selected data and found that the Pc 3 signals were present after all.

Despite the reservations evidence is still mounting that the frequency of Pc 3,4 pulsations is related with the IMF magnitude. Preliminary result of the work by Stuart and Plyasova-Bakounina, involving one-year data (now in progress) indicates that there is a good relationship between the frequency of Pc 3,4 pulsations observed on the ground stations, Hartland and Borok, and that the relationship improves when the same frequencies are seen simultaneously at the two stations.

The evidence of good relationship between the Pc 3,4 pulsations activity and the IMF magnitude is just beginning to appear from measurements of the pulsations in the interplanetary medium too. Recently Russell and Hoppe (1981) derived the relation $F = 5.81 B$ on the basis of 63 events observed aboard ISEE-2 spacecraft. Later Hoppe and Russell (1982) showed that the above derived relation is approximately true (although left unspecified) at all the planets.

3:1-3 Occurrence and/or amplitude of pulsations

(1) **Effect of IMF orientation.** The daytime Pc 3,4 geomagnetic pulsations have been known to appear and disappear in accordance with direction of the interplanetary magnetic field. The evidence of the effects of the IMF orientation on the stable generation of the Pc 3,4 was initially given by Bolshakova and Troitskaya (1968). They showed that the variation in the predominant interplanetary magnetic field direction in the plane of the ecliptic appeared to correspond well to a certain change of groups of the stable oscillations, namely the most common Pc 3 type of stable oscillations corresponds to the main field direction coincident with that of Parker Spiral, while oscillations of Pc 4 are correlative with nearly radial direction of the IMF. They noted that the oscillations are absent when the
field direction is perpendicular to the Earth-Sun line. The implication of these results is that the excitation of stable oscillations of the different Pc groups is related to a definite orientation in the interplanetary magnetic field; the modulation of the Pc amplitude is governed by the variations in the field direction, and the amplitude will decrease to zero if the field is oriented at right angles to the Earth-Sun line.

Webb and Orr (1976) showed that when the interplanetary field is confined to the ecliptic plane in the radial direction for a long period of time, magnetic activity in the Pc 3,4 band is turned on or off abruptly with a 180° shift in the field direction. In an extension to this work, Webb et al. (1977) demonstrated that during the above special cases the magnetic activity is enhanced over an azimuthal extent of approximately 5 hours in local time. Statistical study by Vero and Hollo (1978) made on the basis of about 5000 hours ground-based pulsation data has shown that the amplitudes are maximum for the Pc type if the IMF vector has an angle of 30° with the ecliptic x-axis, and that the minimum amplitudes of Pc 3,4 are found if the IMF vector is perpendicular to ecliptic x-axis.

The effect of the IMF orientation on the generation condition of the Pc 3,4 pulsations has been examined further by using a more convenient angular parameter, that is the cone angle. The cone angle (θ_{XB}), which is only mentioned here and will be described later in Chapter 4, is the angle between the IMF direction and the Earth-Sun line or ecliptic x-axis. The cone angle is defined by polar angle θ (ecliptic latitude) and the azimuthal angle φ (ecliptic longitude) as follows

\[ θ_{XB} = \arccos (\cos φ \cos θ) \] (3:3)

The use of the cone angle as a measure of IMF orientation simplifies the analysis.
The cone angle, \( \theta_{XB} \) was used initially by Greenstadt and Olson (1976), who examined the Pc 3,4 micropulsation wave forms recorded at Calgary. They showed that the signal enhancement tended to occur when the interplanetary magnetic field made a small cone angle with the Earth-Sun line, although their illustrations fell short of providing clear proof for a one-for-one correlation of low \( \theta_{XB} \) with high Pc 3 or Pc 4 incidence on an event-by-event-basis. However, the scatter plots derived from hourly minimum \( \theta_{XB} \) and hourly maximum amplitude of Pc 3,4 showed a definite trend towards large signals when \( \theta_{XB} < 50^\circ-60^\circ \) and a corresponding disappearance of significant amplitude when \( \theta_{XB} > 60^\circ \), but there was appreciable variability in individual cases. This study was extended by Greenstadt and Olson (1977) who examined larger sample of hourly values recorded at the same station as before. The results confirmed and/or amplified their earlier findings, that is there was an IMF related contribution to Pc 3 and Pc 4 signal amplitudes that disregards the conventional separation between the bands at \( T = 45 \) sec., in that both period ranges showed the same trend of rising signal amplitude with decreasing angle \( (\theta_{XB}) \) between B and the solar ecliptic x-axis. The trend was most apparent under geomagnetically quiet conditions \( (Kp < 2) \) in both period ranges. The existence of such a ULF contribution in the Pc 3 ranges was contrary to the then published Soviet results for Pc 3 and the relationship was improved visually by substituting \( \cos \theta_{XB} \) for \( \theta_{XB} \) alone, suggesting a propagation property of waves with respect to B.

Analysis involving the cone angle has been made also in the magnetosphere on board the geostationary satellite, ATS-6 by Arthur and McPherron (1977). The results of the study were in agreement with the results published in the Soviet Union that Pc 3 are commonly observed when the IMF direction is near Parker's spiral. Also there was a clear, although weak, relationship between the cone angle, \( \theta_{XB} \) and
the amplitudes of the pulsations. Similar observations made by Saito et al. (1979) revealed that maximum power of hydro-magnetic waves in the Pc 3 range in the magnetosheath increases with the decreasing cone angle.

(2) The solar wind speed: Recent measurements by Singer et al. (1977) confirmed early observations by Saito (1964) that the solar wind velocity has a positive correlation with ground pulsations activity. The authors examined the same data set used by Greenstadt and Olson (1976, 1977) and demonstrated that large amplitudes were associated with larger velocities. They showed that for the Pc 3 band the amplitude of pulsations for velocities in the 500-600 km/sec range was nearly twice the amplitude for the 300-400 km/sec range, and that 67% of the high amplitude (≥ 2 nT) had velocities ≥ 500 km/sec., for the Pc 4 band nearly 78% of the high amplitude events (≥ 4 nT) were associated with velocities ≥ 500 km/sec. They however, noted clear exceptions to the general trend of dependence of pulsation amplitude on the solar wind velocity as had been found on the cone angle. At times of large solar wind velocity the expected large amplitude pulsation was not observed at all. Conversely, other exceptions occurred during times of small solar wind velocities when large amplitude pulsations activity was observed. These exceptional cases were used to explain the large scatter that was found by Greenstadt and Olson, and gave a hint to the possible combined effect of the solar wind speed and IMF orientation. It was therefore necessary for Greenstadt et al. (1979) to examine the joint action of the solar wind velocity and the cone angle on the generation of Pc 3,4 activity.

(3) Joint action: Greenstadt et al. (1979) reported a joint correlation of velocity and field direction with parameters representing hourly distribution rather than minima of IMF orientation angle which Greenstadt and Olson used in their previous papers. The use of the minimum value
of $\theta_{XB}$ during a one hour interval may be misleading, for $\theta_{XB}$ may attain its minimum value only briefly during the one hour interval. One would not necessarily expect to see large amplitude activity for hours during which $\theta_{XB}$ minimum ($\theta_{XB} \text{ min}$) was small for only short intervals. The joint correlation reduced the overall scatter and showed that the solar wind speeds above 200 - 300 km/sec and angles $\theta_{XB}$ between the IMF and the Earth-Sun line of less than $50^\circ - 60^\circ$ were associated with enlarged magnetic pulsations amplitude. It was not clear from this study which parameter predominates. Nevertheless there was a clear indication that the most self-evident correlations were in amplitude versus velocity, but the correlations were strongest for the most favourable distribution of angle. $\theta_{XB}$, and appeared to require some favourable angles to emerge at all. The correlations of amplitude versus angle were more apparent at high velocity than at low, and amplitudes in general were elevated at the highest velocities over those at the lowest velocities. There was indication that between $50^\circ$ and $60^\circ$ there was a threshold above which $\theta_{XB}$ did cut off any amplitude correlation with velocity while it was clear that velocities below approximately 300 km/sec would be correlated only with insignificant amplitude regardless of angle.

One attempt to separate the influence of solar wind variables on ground-level pulsations activity has been made by Wolfe et al. (1980). Integrated hourly power spectra were used to obtain hourly magnetic energy. The results of correlation of the hourly magnetic energy and the solar wind variables ($V_{sw}$ and $\theta_{XB}$) were similar to those cited in the proceeding paragraphs for $P_c$ 3, 4. The authors found, however, that correlation of pulsations activity with the cone angle depends on frequency, i.e., the correlation was good with the pulsations activity in the period range of 31 - 60 sec, but the correlation became weak or nonexistent for the longest periods (120 - 240 sec), although the correlation with solar wind velocity remained strong throughout the entire period range.
Wolfe (1980) has lately replaced visually defined correlations with more rigorous multivariate analysis, or multiple linear regression (MLR) analysis. MLR is a technique for determining which of the many so-called independent variables (interplanetary parameters in this case) are highly correlated with a dependent variable (ground dayside hourly hydromagnetic energy in this case). Eight interplanetary parameters, solar wind velocity, IMF directions, IMF value and its geocentric solar magnetospheric (GSM) X, Y, Z components, solar wind proton density, and temperature were taken as independent variables to represent the state of the solar wind. Estimates of power spectral density were used to obtain quantitative measure of hourly pulsation signals in the period range of 31 - 60 sec, 60 - 120 sec and 120 - 240 sec. The best linear polynomial, in the least squares sense, was fitted to the log of ground power. Four levels of grades were used to denote the 'T' ratios of the variables and thus indicate the relative importance of each parameter to the overall fit. The T ratios are defined by the coefficients (slopes) of each independent variable divided by the errors in their respective coefficients and indicative of the importance of each parameter. Larger T ratios imply greater stabilities for the slopes of each parameter, thereby increasing that parameter's importance to the fit.

In 120 - 240 sec range, the solar wind velocity had the highest T ratio among the eight parameters, showing that it was the key variable in affecting changes in the ground hourly magnetic energy. In the 60 - 120 sec range both \( V_{sw} \) and \( \Theta_{XB} \) were found to play equal key roles, whereas in the 31 - 60 sec the cone angle \( \Theta_{XB} \) was the most important parameter followed by the solar wind velocity.

Hourly average values of the leading solar wind parameters (eg, temperature, density, speed, cone angle) were also examined to determine which might be sufficiently uncorrelated to serve as truly independent measures of solar wind state; solar wind speed and IMF cone angle were the best candidates.
Wolfe and Meloni (1981) has extended the previous papers by Wolfe et al. (1980) and Wolfe (1980) in three ways. First additional interplanetary quantities were examined with emphasis placed on two energy input quantities, the kinetic energy flux density \( f_k \) and the interplanetary quantity \( \epsilon \) defined respectively by

\[
f_k = \frac{1}{2} N_p m_p v_{sw}^3
\]

\[
\epsilon = v_{sw} B^2 \left( \sin^2 \frac{\theta}{2} \right) l_o^2
\]

where \( N_p \) and \( m_p \) are proton number density and mass respectively, \( l_o = 7RE \); and \( \theta \) is the polar angle. Second, relationships were examined during nighttime in addition to local daytime. Finally, details of the dayside local time dependence of the results were shown. Dayside and nightside ground hourly magnetic energy were found generally to correlate best with the solar wind kinetic flux density of which the solar wind velocity is the most important parameter. The highest linear correlation coefficients found between power versus \( f_k \) and power versus \( v_{sw} \) were obtained during local afternoon hours, with a sharp reduction in correlation occurring at local noon (this is consistent with a Kelvin-Helmholtz instability source). The highest correlations found for the dayside power with the upstream solar wind quantities were found to be reduced for the nightside power within each period range. It was suggested that additional sources were contributing to the observed nightside power; \( \epsilon \) was considered as a possibility in this respect, particularly for the longest period band, although the effect of \( \epsilon \) is partially attributed to the high correlation of the nightside power with \( Ae \), which in turn has high correlation with \( \epsilon \) (Wolfe and Meloni 1981). An important consequence of this suggestion was that more significant relationships are expected for the nightside power with geomagnetic tail parameters rather than with upstream parameters.

(4) **Solar wind speed and IMF cone angle at synchronous orbits:**

As the phenomena in question are magnetospheric hydromagnetic waves, of which the geomagnetic micropulsations at the Earth's
surface are only one manifestation, an additional approach to tying the magnetospheric oscillations to the solar wind is through satellite measurements within the magnetosphere. Those made in geostationary satellites constitute readily available data from which some new results have been compiled by Takahashi et al. (1981). The data base was one year of two-hour intervals at ATS-6 magnetometer records between June 1974 and May 1975. First the authors made intercomparison of solar wind parameters to find out whether the correlations of pulsations activity with $V_{SW}$ and $\theta_{XB}$ already found at the ground for hourly averages are independent, or whether $V_{SW}$ and $\theta_{XB}$ are themselves so tightly connected over two hour intervals that correlation of activity with one is already equivalent to correlation of activity with the other. The result of this exercise indicated that $\theta_{XB}$ had little correlation with $V_{SW}$, and that the field magnitude ($B$) was not correlated with either $V_{SW}$ or $\theta_{XB}$. However it turned out that the effect of $B$ was smaller than that of $V_{SW}$ or $\theta_{XB}$ (when occurrence and/or amplitude of pulsation activity was considered). Therefore the authors focussed only on the effect $V_{SW}$ and $\theta_{XB}$ as outlined below.

The dependence of the occurrence probability of Pc 3 pulsations (frequency 0.022 - 0.10 Hz) at synchronous orbit on factors such as local time and the solar wind parameters were studied. Power spectra calculated in two-hour segments from the magnetometer records were used to identify Pc 3 pulsation occurrence. The average diurnal occurrence pattern was found to be a maximum at 09.00 LT; the maximum shifting towards the morning sector for higher solar wind velocity. The signal power in the range of Pc 3 band was shown to increase with rise of solar wind velocity as illustrated in Figure (3:4) just as the hourly maximal amplitude does on the ground.

A correlation with velocity gives a hint that pulsation occurrence should be connected in some way with the
Takahashi et al. (1981)

Pc 3, ATS-6

\[ \log P = -11 + 0.003 V_{sw} \]

FIGURE 3:4
stream structure of the solar wind. This seems to be the case as illustrated by Takahashi et al., whereby the solar wind velocity for two solar rotations (Bartel's solar rotations 1926 - 1927) was compared with the corresponding Pc 3 occurrence probability.

The occurrence probability of Pc 3 at 6.00 - 16.00 LT was taken as a function of $V_{\text{SW}}$ and $\theta_{\text{XB}}$ combined and shown as a contour map in the $V_{\text{SW}} - \theta_{\text{XB}}$ plane. $V_{\text{SW}}$ and $\theta_{\text{XB}}$ had ranges of 300 - 800 km/sec and 0 - 90°, respectively. In these ranges, $V_{\text{SW}}$ and $\theta_{\text{XB}}$ contributed to the Pc pulsations with almost equal significance. The joint effects of $V_{\text{SW}}$ and $\theta_{\text{XB}}$ decreased the probability to about 10% for $V_{\text{SW}} \leq 400$ km/sec and $\theta_{\text{XB}} \geq 60^\circ$, and increased it to about 80° for $V_{\text{SW}} \geq 600$ km/sec, and $\theta_{\text{XB}} \leq 20^\circ$.

It is noted in summary that one result of the ATS-6 study has been significant in verification of the joint dependence of pulsation activity on the solar wind velocity and the cone angle. The same pattern of pulsation activity rising with the solar wind speed and cosine of the cone angle appears at synchronous orbit as on the ground, despite different methods of analysis. This fact has been brought out more clearly by Greenstadt et al. (1980) who compared two diagrams of joint distribution of pulsations with $V_{\text{SW}}$, $\theta_{\text{XB}}$ for ATS-6 data and on the ground. The dependence of Pc 3, 4 amplitude on $V_{\text{SW}}$ is much steeper, and its occurrence much higher at low angle than high; the dependence of Pc 3, 4 amplitude is more pronounced, and the occurrence much higher at high velocity than at low. There is a hint in the ATS-6 data that Pc 3 occurrence peaks at $V_{\text{SW}} = 600 - 700$ km/sec but confirmation of this requires more data containing the unusual solar wind speed above 700 km/sec.

Table (3:1) adopted from Greenstadt et al. (1980) gives a broad overview of the locations on the ground and in/beyond the magnetosphere where pulsations have been correlated with the solar wind parameters, the parameters which have been used and the principal reporters of those
correlations. The contribution by this work (our study) is shown in parenthesis. It is noticeable that the majority of studies have examined pulsations between $L \sim 1.8$ and $L \sim 3.5$ on the ground. The early studies concentrated on observations between $L = 1.8$ and $L = 2.8$; the later ones concentrated on observations around $L = 3.5$ plus the geosynchronous orbits of $L = 6.6$. Very few observations have been made beyond the magnetosphere in the interplanetary medium. It can hardly be said that the magnetic latitudes have been sufficiently covered, but the extremes of positions are spread satisfactorily to allow confidence in the interpretation of the connection between solar wind parameters and waves throughout the dayside magnetosphere. The interpretation may be summarized in terms of models of generation of pulsation activity under the influence of the state of the solar wind. These models are outlined in the following section.

3:1-4 Models for solar wind control of Pc 3,4 pulsations

Models of the Pc 3,4 pulsations can be divided into two broad classes: internal and external, depending on whether the cause for generation is inside or outside the magnetosphere. Internal models account for pulsations in terms of processes within the magnetosphere, where opportunities exist, for example at the plasmapause boundary, for generating oscillations through local instabilities. External models attribute pulsations to forces outside the magnetosphere because circumstantial evidence links their occurrence to the solar wind parameters. Each model in turn can rest on either stimulation or control in making its case. The wave may be generated in one location (for example, at the magnetopause) but the driving force necessary for the generation, or transfer it to the Earth's surface, may be controlled by other regime.

At present there is no comprehensive theory of internal generation that include external control compatible with experimental observations. D'Angelo (1975)
advocated an endogenic (internal) mechanism that could generate pulsations with a spectrum of the form $T \sim 1/B$, but his model did not provide for other experimentally measured dependence on IMF orientation and solar wind velocity. It seems that the model of external excitation is mostly favoured but there has been no direct proof of where the wave source actually lies. Hence, we deliberately assign the solar wind to 'control' rather than 'generation', although the two principal models of solar wind control are models of external generation too.

The explanation for the external origin of pulsation divides into two categories. Origin at the magnetopause and origin beyond the magnetopause. Presently only one model is strongly advocated in each category, but others are not excluded. Origin at the magnetopause is attributed to generation and amplification of surface waves via Kelvin-Helmholtz instability; origin beyond the magnetopause is attributed to large amplitude waves arising in the quasi-parallel bow shock (see below) swept back into the magnetosheath and penetrating the magnetopause (Greenstadt, 1972). The former model will be referred to here as surface wave model, and the latter as signal model. Neither model necessarily excludes the other, so their joint action is possible; both depend upon parameters of the solar wind. The key parameter for the surface wave model is solar wind speed; the key parameter for signal model is IMF cone angle. The two models are described briefly in the following paragraphs.

1. **Surface wave model.** The surface wave model is focussed on the operation of the Kelvin-Helmholtz instability. The description of the Kelvin-Helmholtz instability is already given in section 2:2-4. To see Kelvin-Helmholtz in its basic form one considers the interface between two uniform plasmas in relative motion. In this situation surface waves are likely to be excited. If this formulation is applied to
the magnetopause the surface waves arise because the solar wind in the innermost magnetosheath flows along a relatively stationary magnetopause, like 'wind over water'. The waves are sustained along the flanks of the boundary separating the magnetosheath from the magnetosphere. The waves are amplified when the relative velocity (effectively the magnetosheath velocity in this case) exceeds a critical value. Once surface waves are established they are likely to be transferred into and through the magnetosphere to the surface of the Earth through field line resonance. At resonance a particular period or a band of periods, is selected and large amplitude monochromatic oscillations delivered through the flux tube to appear on the Earth's surface as traditional geomagnetic pulsations.

According to the Kelvin-Helmholtz instability the surface waves are more likely to be driven by large solar wind velocity. The driven waves would move in antisolar direction both in the morning and afternoon sectors of the magnetosphere. In the Earth's frame, the waves would move eastwards in the afternoon and westwards in the morning.

**Signal Model:** The signal model is based on the idea that waves of tens of seconds period already present in the magnetosheath should, by interacting with the magnetopause, or penetrating it, reach the magnetosphere and appear finally on the surface of the Earth (as traditional midday geomagnetic pulsations) as a consequence of processes such as the field line resonance. The notion arose from observations that alignment of IMF (B<sub>SW</sub>) with the solar wind flow, (hence essentially with the ecliptic x-axis and therefore parallel to the nominal shock normal at the subsolar point), would furnish the most favourable circumstance for the bowshock and magnetosheath to contain, or consist of large amplitude magnetic pulsations (now called quasi-parallel structure) that can reach the magnetopause (Greenstadt 1972). Daytime Pc 3, 4 micropulsations would
thereby be excited on the magnetospheric field line and would appear as large amplitude oscillations on the ground where the field lines are rooted. The model also suggests the converse; namely, that orthogonality of $B_{sw}$ and x-axis ( ecliptic) should remove all areas of quasi-parallel structure to the flanks of the bow shock, a situation producing the least favourable conditions for transfer of oscillations to the subsolar magnetopause and therefore leaving $Pc_3, 4$ unstimulated, at least by this postulated mechanism.

Let us explain the term 'quasi-parallel structure' which is mentioned above and will be met often elsewhere, and in this work, in connection with the signal model.

It is noted that the signal model is focussed on bow shock induced turbulence in the solar wind. The structure of the shock is dependent on the orientation of the interplanetary field to the nominal shock contour. A thin jump shock occurs when the field is locally tangent to the shock contour, while a thick pulsation shock occurs when the field is locally normal to the contour. Tangency and normalcy are defined with respect to a two dimensional contour formed by intersection of the nominal shock with a plane formed by vectors $B_{sw}$ and solar wind velocity $V_{sw}$ (Greenstadt et al., 1980). This is termed the B-V, or simply the B-X plane since $V_{sw}$ and X are approximately parallel in the geocentric solar ecliptic (GSE) coordinates.

It has been observed, for example, by Greenstadt (1972) that the bow shock is most turbulent at locations where the magnetic field is parallel or antiparallel to the shock normal. In the usual situation of a 45° spiral field the condition is met in the mid morning local time. Some turbulence exists for all angles $\theta_{Bn}$ between B and n (where n is a unit vector along the local shock normal) up to 50° but is greatest when $\theta_{Bn} < 20°$. Thus, in the most common situation turbulence referred to by Greenstadt as pulsations
of the shock, prevails on the morning side to about the subsolar point of the bow shock. These pulsations which are associated with the local oblique orientation of the interplanetary field to the nominal shock surface have been described initially by E W Greenstadt as quasi-parallel shock structure. The structure however, is transitional around the subsolar point where $\theta_{Bn} = 45^\circ$ and becomes less oscillatory as $\theta_{Bn}$ increases. Typical quasi-perpendicular structure prevails when the IMF is transverse to the solar wind.

Profiles of the bow shock boundary are illustrated in Figure (3:5) (after Greenstadt, 1972) for three different interplanetary field orientations, in the ecliptic plane. In Figure (3:5a) the average Parker's spiral, or Archimedian stream angle gives a non-uniform pulsation boundary with east-west, or dawn-dusk asymmetry; in Figure (3:5b) a field parallel (or antiparallel) to the solar wind flow gives a pulsation boundary everywhere; in Figure (3:5c) a field transverse to the solar wind flow give symmetrically-located pulsations downstream along the flanks of the shock.

The conditions that control the pulsations now called quasi-parallel structure also produce upstream waves in the solar wind. The upstream waves are described in detail in Chapter 5 of this work. Gul'elmi 1974 suggested that the upstream waves contribute to a significant part of the Pc 3, 4 activity observed on the surface of the Earth. It has been advocated by Kovner et al. (1976) that the upstream waves may simply propagate to the Earth, regime by regime, in some way, left undefined, but including amplification at the bow shock.

It is noted that the two external models are not mutually exclusive. The Kelvin-Helmholtz mechanism would presumably operate on initial perturbation at the magnetopause; and the signal transfer model needs to get its perturbations across the magnetopause preferably with amplification. In this situation the joint action of wave excitation and wave
FIGURE 3:5
transfer is possible (Greenstadt et al. 1980) whereby the Kelvin-Helmholtz instability amplifies, as surface waves, oscillations delivered to the magnetopause from quasi-parallel structure in the subsolar section of the bow shock. The cone angle $\theta_{xB}$ is important in determining whether, and to what extent the flux tubes directed at the magnetopause contain the large amplitude waves. The solar wind speed is important in determining the degree of amplification at the magnetopause.

Observations: The two external models have been supported experimentally, in parts, but not established in total. The current state of attempts to verify the models has been described by Greenstadt (1979). The critical views of the models has been presented by Greenstadt et al. (1980). A few but significant observations made on the role of the solar wind speed and the IMF orientations are recalled here.

If it is noted that small angle $\theta_{xB}$ between the IMF and increasing velocity of the solar wind ($V_{sw}$) moves the pattern of maximum turbulence towards local noon, and that the only solar wind plasma actually making contact with the magnetopause is in the flow tube through the subsolar shock, it is expected that larger waves would illuminate the magnetopause when the cone angle is small, enhancing the pulsations transfer. Conversely it would be expected that the IMF transverse to the solar wind flow ($\theta_{xB} = 90^0$) would remove turbulence entirely from the subsolar shock suppressing pulsations transfer. The picture described is illustrated in Figure (3:5a,b,c).

The experimental observations cited at the beginning of this section are unanimous fundamentally on one point, that is the occurrence habits and amplitude of the Pc 3, 4 pulsations are significantly influenced by the solar wind speed and the IMF orientation. Large solar wind velocity $V_{sw} > 400$ km/sec and small cone angle, $\theta_{xB} < 50^0$ are responsible for the enhancement of the Pc 3, 4 activity on the
ground and in the magnetosphere. Detailed results indicate
(a) there is a joint effect of $V_{sw}$ and $\theta_x B$ on the amplitude
and/or occurrence of Pc 3,4 pulsation activity (Greenstadt
et al., 1980 and Takahashi et al., 1981) (b) the frequency
dependence of the effect of cone angle (Wolfe et al., 1980)
and (c) the diurnal variations of the linear correlations
coefficients between the solar wind velocity and occurrence
of pulsations (Wolfe and Meloni 1981). These results have
been interpreted as signal and surface wave models operating
either independently (Greenstadt and Olson, 1976, 1977;
Webb and Orr, 1976; Webb et al., 1977; Singer et al., 1977;
Arthur and McPherron, 1977; Saito et al., 1979; Wolfe et
al., 1980; Wolfe, 1980; Wolfe and Meloni 1981) or jointly
(Greenstadt et al., 1979 and Takahashi et al. 1981).

The empirically established relation, $T = 160/B$ is an
outstanding manifestation of the signal model. We recognise
this inverse proportionality as the same one defining the
proton gyroperiod. An obvious inference from this relation
is that some Pc 3,4 were waves that originally had been
generated in the solar wind by a cyclotron resonant
interaction and transmitted to the magnetosphere. The
consequence of this inference is that the period of waves
in the solar wind should correspond to the relation, $T = 160/B$.
Alternatively, the period of waves in the solar wind should
be similar to the period of Pc 3,4 on the Earth's surface.
Gul'elmi (1974) and Kovner et al. (1976) have shown
theoretically how the period of waves in the solar wind should
correspond well to the $T = 160/B$ relation. In situ measurements
by Russell and Hoppe (1981) showed that the relation $T = 160/B$
approximately holds in the foreshock region. Plyasova-
Bakounina et al. (1978) compared the periods of pulsations
activity, recorded by the HEOS-1 satellite in the solar
wind upstream from the Earth's bow shock with the records of
Pc 3,4 activity at Soviet Borok Observatory. They found
eight events with closely similar periods at the satellite
and on the ground, particularly when the IMF was directed away from the Sun; the periods were inversely proportional to the IMF magnitude. There was, however, one event which showed similar onset time but had rather different dominant periodicity at the two locations.

In summary, the observational results have demonstrated that an important part of the Pc 3, 14 activity consists of magnetospheric signals whose amplitude, period and occurrence are controlled by the state of the solar wind. The two models postulated to account for the signals as waves in the magnetosphere actually generated at and beyond the magnetopause have been experimentally supported partly, but not yet completely verified. An attempt at interpretation of experimental results has been made difficult by large scatter in some of the referenced correlations.

Observations of Pc 3, 4 in the UK

In this section attention will be concentrated on some selected experimental studies which have been made recently in the UK using the range of Pc activity covering (but not necessarily limited to) the Pc 3, 4 pulsations. The selection is based on what is thought to be good examples in terms of general analysis and specific studies that have developed our understanding of properties of the pulsations in the midlatitude region, particularly with reference to state of the solar wind. Under this condition those studies which have used any of the observatories in the UK, plus one or more stations outside the UK, but are now occupied by the IGS magnetometer array will be outlined here.

An early contribution to the general studies in the UK was made by Stuart and Usher (1966), who examined rubidium magnetometer data recorded simultaneously at three UK observatories (Lerwick, Eskdalemuir and Hartland). The results of the general analysis indicated: (a) that the times of Pc occurrence were notably different at the three stations, the maximum being 08.00 at Lerwick and 12.00 at Hartland.
(b) latitudinal dependence of period: the Pc spectra at the three stations showed peaks of micropulsation occurrence 30 sec. at Lerwick, 60 sec. at Eskdalemuir and 40 sec. at Hartland, a secondary peak at 25 sec. was apparent at Eskdalemuir; (c) energy difference between stations, which the authors associated with local induction effect. These results were obtained at early stage when the state of the solar wind and its interaction with the magnetosphere was very little known. So it is not surprising that Stuart and Usher did not tie any of their results specifically to the solar wind, although they suggested (but left unspecified) that the solar wind stream might be responsible for the difference in occurrence of the Pc activity at the different latitudes. An extensive statistical study of geomagnetic pulsations with periods between 10 and 70 sec. by Orr and Webb (1975) examined 12 observatory-years worth of data recorded from five observatories covering a range of L-values 3.1-6.6 which included two observatories in the UK (Lerwick, L = 4.0, and Eskdalemuir, L = 3.1). The other stations were St. Anthony (L = 4.9), Sodankyla (L = 5.3) and Tromso (L = 6.6).

The results of the studies indicated that the high latitude stations (L = 4-6.6) recorded pulsations with periods centred on 30 sec. as the dominant daytime Pc 3,4 pulsations activity. The pulsations were observed most frequently in the morning at around 08.45 local time. The detection of Pc 3 events was found to be dependant upon latitude of the observatory and the average night-time Kp index; the maximum occurrence frequency was defined by the relationship L = 8.1-1.2 Kp. Combining this relationship with the average positions of plasmapause (the plasmapause has been described in section 2:1-4) estimated from OGO-5 data the authors deduced that the Pc 3 events were enhanced at a ground position which depends on the night-time Kp index, that is, as the Kp-index increases the region of Pc 3 enhancement moves to lower latitudes. It was
concluded that the Pc 3 events observed were usually connected with hydromagnetic standing wave associated with flux tubes in the plasma-trough region of the magnetosphere. This conclusion enabled the authors to explain the two peaks of Pc pulsations activity, at Eskdalemuir, which had earlier been reported by Stuart and Usher: it was implied that Eskdalemuir detected Pc 3 events when the plasmapause was driven inwards towards the station at times of high magnetic activity; at quieter time Pc 4 activity centred on 60 sec. was frequently measured there; this was interpreted as a field line resonance within the plasmasphere. The Orr and Webb results raised a question as to whether geomagnetic pulsation measurements could give useful information about the plasmapause position. Orr (1975) using the same set of data used in the previous paper examined each type of geomagnetic pulsations with particular emphasis on their relationship to the plasmapause. He showed how the position of the plasmapause could be deduced from the amplitude variation of Pc 3 and Pc 4 pulsations with latitudes assuming field line resonance excitation in the plasmatrough and plasmasphere, that is when constant period Pc 3 are measured over the complete array with two maxima in amplitude one at high latitude the other at a lower latitude (within plasmasphere), the minimum amplitude defines the plasmapause; also when constant period Pc 4 are measured over the complete array there is the possibility of two maxima in amplitude profile, the lower one being on the low latitude side of the plasmapause.

The only observation directly tying the solar wind parameters with generation of Pc 3,4 pulsations at the mid-latitude stations in the UK so far has been reported by Webb and Orr (1976). The author examined recordings of telluric (Earth) current measurements from a network of three British stations (Eskdalemuir, L = 3.1; South Uist, L = 3.6; and East Anglia, L = 2.6) and compared the data
with the IMF measurements made aboard the HEOS-2 satellite. The results of the comparison showed how the radial component of the IMF modulated the amplitude of pulsations in the period range 20-60 sec.; there was an enhancement of the pulsations amplitude when the IMF was confined to the ecliptic plane in the radial direction; the amplitude turned on or off abruptly with a $180^\circ$ shift in the field direction. Of the three events examined, two corresponded to the sunward orientation of the IMF, one event was related to the anti-sunward orientation. The authors estimated the delay time between switching of events in the IMF and enhancement in the geomagnetic pulsations activity to be in the region of about 10-20 min, with an indication of a dependence on local time, such that the shortest delays were observed in the local dawn-to-noon sector; 15 min. time lag between the interplanetary change and the onset of pulsation at the Earth's surface was typical. These results were associated with the bow shock induced turbulence (signal model) outlined in section (3:1-4). Webb et al. (1977) extended the work of Webb and Orr in order to study the global effects of the IMF parameters. Data from the most northerly station in the UK network (South Uist) were compared with data obtained from one of the fluxgate magnetometer stations in the Bell Laboratories network near the same geomagnetic latitude (Pittsburg, $L = 3.5$). The two stations are separated by approximately 5 hours in local time. The result indicated that for the three events initially reported by Webb and Orr (1976) the pulsations activity was simultaneously enhanced over the azimuthal extent of about 5 hour local time.

Recently the studies of micropulsations in the UK have focussed specifically on the polarization and propagation characteristics in the mid latitudes. These studies have been encouraged by the extensive use of latitudinal and longitudinal array of IGS magnetometers and stimulated by the joint projects for International Magnetospheric Studies
(IMS) involving IGS, Imperial College, York University and the British Antarctic Survey. Green (1981) has given a good review of some recent important results obtained from the IGS array of magnetometer studies that may be linked either indirectly or directly to the generation mechanisms for the pulsations by the solar wind velocity and the interplanetary magnetic field.

The influence of the solar wind on the generation of continuous pulsations in the mid latitudes has been studied indirectly by the use of the E-W phase structure of the signal, a type of measurement largely pioneered by the Imperial College group and collaborators (Green, 1976; Hughes et al., 1978, Mier Jedrzejowicz and Southwood, 1979). As one intuitively expects, the Kelvin-Helmholtz mechanism as driven by the solar wind, predicts that waves produced at the magnetopause move away from the Sun, both in the morning and afternoon sector. Thus, if the Kelvin-Helmholtz instability is the ultimate source of pulsation energy at a particular latitude, one expects the diurnal variation in the longitudinal phase structure, eastward longitudinal phase motion in the afternoon and westwards in the morning.

Green (1976) examined the longitudinal phase variation of mid latitude Pc 3, 4 micropulsations and found results which were inconsistent with the solar wind driven Kelvin-Helmholtz instability. Using data from three British stations, Green revealed that the most westerly station (Velentia, Eire) led Stonyhurst and York (both in England) in phase in most events and no diurnal variation in the E-W propagation was detected; phase differences were small, generally less than 10° per degree of longitude and often no significant phase difference could be noticed over the 50 km separating the English stations.

Mier Jedrzejowicz and Southwood (1979) made a similar study to that of Green (1976) using four stations very close to a geomagnetic latitude 56.5°N and extending over
about 2 hours in local time between Scotland and Finland. The data used were largely Pc 4 pulsation (40 - 125 sec) signals. The results obtained in many respects paralleled Greens (1976) results, although Green examined mainly the Pc 3 pulsations activity: phase differences between the four E-W stations were relatively small, differences rarely exceeded 60 per degree of longitude when signals were coherent enough for a reliable determination of the azimuthal wave number (m), a measure of the change of phase per degree longitude; field line resonance was found to play some parts in the signal; no agreement with the Kelvin-Helmholtz instability prediction was found; if anything, dayside pulsations were found to be propagating away from the nightside. In conclusion it was suggested that a significant source of the mid-latitude pulsations was on the nightside and associated with processes similar to those responsible for the excitation of nightside Pi 2 pulsations activity. The work was extended by Mier-Jedrzejowicz and Southwood, (1981) with the emphasis on the comparison between the Pc 3 and Pc 4 pulsations with regard to the E-W phase structure. The same stations, but different data set randomly picked from five other days in 1976 and 1977, were used. The results of their analysis indicated that Pc 3 signals showed some remarkably similarities to Pc 4: near local midnight when the Pc 3 signals were a component of Pi 2 pulsations, they shared the characteristics of high coherence across chain of stations; at other times the Pc 3 and Pc 4 signals, both had small longitudinal (azimuthal) wave number, and no clear diurnal propagation pattern was systematically observed, but at times there was evidence of preferential sunward phase motion in all daylight hours; by night westward propagation dominated. It was thought that the similarity of the E-W phase structure of the signals in the Pc 3 and Pc 4 frequency band was a point that implied a common source for the Pc 3 and Pc 4 pulsations in the mid-latitudes. Whatever that source might have been it was unlikely to be the Kelvin-Helmholtz instability.
A high resolution study of continuous pulsations in the European sector including the UK has been made recently by Hanson et al. (1979) using a newly re-introduced 'complex demodulation' technique. Complex demodulation has been described in detail and applied to Pi 2 pulsations by Beamish et al. (1979). The technique allows the amplitude and phase of spectral component of a time series to be re-expressed in the time domain. Hanson et al. used the complex demodulation to demonstrate spatio-temporal variations in the fundamental characteristics (amplitude, ellipticity and ellipse orientation) of Pc 3 and Pc 4 pulsations along a meridional profile extending from Cambridge in the UK to Eidar in Iceland (L = 2.48 - 6.68). Using the empirical model of Orr and Webb (1975) to estimate the position of plasmapause Hanson et al. deduced the double resonance regions for the Pc 3 and Pc 4 pulsations, one region in the plasmasphere and another in the plasmatrough. The resonance regions (one such resonance occurred close to the inferred position of the plasmapause) for the Pc 3 pulsations occurred at lower latitudes than the Pc 4 resonance in accord with theory on toroidal field resonances. The plasmaspheric resonances of both Pc 3 and Pc 4 wave-forms were found to be predominantly in the H-component, a behaviour consistent with 90 degrees rotation of a magnetospheric toroidal field line resonance introduced by the ionosphere; no polarization reversal was detected about the amplitude maximum in case of the plasmaspheric resonances, a result which is consistent with ionospheric screening reported by Green (1978). In the plasmatrough the Pc 3, unlike the Pc 4 pulsations, exhibited characteristics of toroidal field line resonance, there was a reversal in the sense of polarization about the amplitude maximum.

It is to be noted that the plasmapause position based on the empirical results were used by Hanson et al. in the absence of in situ measurements of plasma density, without which
the above results were only tentative.

Orr and Hanson (1981) used in situ plasma density measurements aboard GEOS-1 and geomagnetic pulsations measurements spanning the range of geomagnetic latitude from 50.6° to 66.6° to illustrate their simplified theoretical model of forced oscillations in the dayside magnetosphere. According to the model a geomagnetic pulsation driven by a source at the magnetopause large phase shifts associated with resonances in the plasmatrough, at the plasmapause and within the plasmasphere should be observed. Applying the complex demodulation technique the authors showed that polarization reversal indeed often occurred at resonances in the plasmatrough and at the plasmapause with the probable smoothing of the polarization variation in the plasmasphere; it was indicated that, in the plasmasphere, the variation of H-component phase with latitude was likely to be a better predictor of the resonance position than the ellipticity variation.

From the studies outlined above it appears that field line structures and the E-W propagation characteristics have been fairly covered in the mid-latitudes. One outstanding result of these studies is that of the latitudinal variation of the geomagnetic pulsations in accord with the field line resonance process; another is that the E-W propagation pattern is incompatible with the solar wind driven Kelvin-Helmholtz instability at the magnetopause. It is noted that the solar wind effect can only be expected intuitively from these results and that little attention has been focussed on measurements directly relating the Pc 3, 4 activity with the solar wind parameters. The more direct attempt tying the solar wind parameters with the geomagnetic pulsations was made initially by Webb and Orr (1976) using three selected events. In Green's (1981) review also a report has been made of the preliminary results of the statistical studies in progress at the IGS, directly correlating the solar wind parameters with continuous geomagnetic pulsations in the period range of Pc 3 and Pc 4. The work is now completed and the results are presented in the chapters which follow.
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<td>Bolshakova and Troitskaya</td>
<td>G</td>
<td>IMF·Long</td>
</tr>
<tr>
<td>1969</td>
<td>Troitskaya et al.</td>
<td>GG G</td>
<td>B, Vsw</td>
</tr>
<tr>
<td>1973</td>
<td>Troitskaya et al.</td>
<td>G G</td>
<td>Vsw</td>
</tr>
<tr>
<td>1973</td>
<td>Gul'el'mi et al.</td>
<td>GG G</td>
<td>IMF Long</td>
</tr>
<tr>
<td>1973</td>
<td>Gul'el'mi and Bol'shakova</td>
<td>G G</td>
<td>Vsw</td>
</tr>
<tr>
<td>1974</td>
<td>Vinogradov and Parkhomov</td>
<td>G</td>
<td>B, Kp Ae</td>
</tr>
<tr>
<td>1976</td>
<td>Greenstadt and Olson</td>
<td>G</td>
<td>Vsw</td>
</tr>
<tr>
<td>1976</td>
<td>Kovner et al.</td>
<td>GG G</td>
<td></td>
</tr>
<tr>
<td>YEAR</td>
<td>INVESTIGATORS</td>
<td>LOCATION OF OBSERVATIONS</td>
<td>CORRELATED QUANTITIES</td>
</tr>
<tr>
<td>------</td>
<td>-----------------------</td>
<td>--------------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>1976</td>
<td>Nourry</td>
<td>G</td>
<td>ATS-1</td>
</tr>
<tr>
<td></td>
<td>Russell and Fleming</td>
<td>G</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Webb and Orr</td>
<td>G G G</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Greenstadt and</td>
<td>G</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Olson</td>
<td>G</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Singer et al.</td>
<td>G</td>
<td></td>
</tr>
<tr>
<td>1978</td>
<td>Plyasova-Bakounina et al.</td>
<td>G</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vero and Hollo</td>
<td>G</td>
<td></td>
</tr>
<tr>
<td>1979</td>
<td>Greenstadt et al.</td>
<td>G</td>
<td></td>
</tr>
</tbody>
</table>
Table 3:1.

Locations of observations used in the studies of pulsations and solar wind, and quantities that were correlated.
Key to Table 3:1

(a) **Observation Points**

- G  - Ground stations
- ATS - Geosynchronous satellite
- ISEE - International Sun-Earth Explorer
- IM - Interplanetary medium

(b) **Quantities Correlated**

- Ae - Auroral electrojet activity index
- B - Interplanetary magnetic field (IMF) magnitude
- IMF rad. - Radial IMF
- IMF long - Azimuthal IMF
- Kp - Planetary index
- N - Number density
- Tsw (IM) - Period of waves in the solar wind (or interplanetary medium)
- Vsw - Solar wind velocity
CHAPTER 4

CONTROL OF THE SOLAR WIND PARAMETERS ON THE GROUND PC 3,4 PULSATIONS

4:1 Introduction

The energy which drives many magnetospheric processes is provided by the solar wind. How this energy enters the magnetosphere and appears as hydromagnetic waves responsible for the appearance of the Pc 3,4 pulsations activity on the surface of the Earth is not yet well understood.

Several approaches noted in Chapter 3 section (3:1) have recently been used to attempt to establish experimentaly what relationships exist between the dayside ground magnetic activities and the interplanetary medium. The relationships suggest that some Pc 3,4 pulsations are of external origin. Such relationships, if they exist, would be important for monitoring the state of the interplanetary space. Theoretical consideration have guided these studies to choose the solar wind speed ($V_{SW}$) and the interplanetary magnetic field (IMF) as the two key interplanetary parameters controlling dayside Pc 3-4 activity on the ground. The generation of the magnetopause surface waves by the Kelvin-Helmholtz instability (Southwood, 1968) and the convection and propagation of upstream waves to the magnetosphere (Greenstadt, 1972 and Kovner et al., 1976) have been shown theoretically to be controlled by solar wind speed and IMF direction. Waves produced at the magnetopause by either increase of the solar wind or magnetic fluctuations arising from the upstream waves can excite field line resonances in the magnetosphere (Radoski, 1966; Chen and Hasegawa, 1974; and Southwood, 1974) thereby increasing the Pc 3-4 magnetic activity on the Earth's surface. The enhancement of the ground activity has been reported by Troitskaya (1967) and Webb et al. (1977) to be of global character.

Numerous interplanetary, magnetosheath and magnetospheric processes are involved in the various wave excitation and
coupling mechanisms responsible for the \( \text{Pc} 3-4 \) activity on the ground. A detailed study examining all parameters related to these mechanisms is not feasible in this work, because of lack of data. On the basis of contemporary ideas reflected in the previous works such as those by Greenstadt et al. (1979); Wolfe et al. (1980), Vero (1980) and Takahashi et al. (1981) three parameters representing the interplanetary environment were selected for statistical study. These were solar wind speed \( (V_{SW}) \), cone angle \( (\Theta_xB) \) and IMF magnitude \( (B) \).

This chapter studies the effect of the three interplanetary parameters on the generation conditions of \( \text{Pc} 3-4 \) pulsations at five ground stations. The sources of data that are examined, the process to which they have been subjected and the methods of experimental analysis are described. Then the results of the various investigations performed are shown.

4:2 Data

4:2-1 Ground data

The ground data used in this work were obtained from five stations in the network of magnetometers in Europe operated during the International Magnetospheric Study (IMS) by the Geomagnetism Unit of the Institute of Geological Sciences (IGS), Figure (4:1) shows a map of North Western Europe and North Atlantic with most of the stations occupied by IGS magnetometers during the IMS. On the map are drawn L-values computed at 120 km altitude for epoch 1977.5 from the main field model of Barraclough et al. (1975). The geographic and geomagnetic coordinates and L-values along with the stations identifier of the five stations are listed in Table (4:1). The stations are listed in order of decreasing geomagnetic latitude.

The instrument at each station was a three axis rubidium vapour magnetometer. The rubidium magnetometer is an atomic oscillator providing a frequency proportional to the
Table (4:1) Recording Station Location

<table>
<thead>
<tr>
<th>STATIONS</th>
<th>CODE</th>
<th>LATITUDE</th>
<th>LONGITUDE</th>
<th>LATITUDE</th>
<th>LONGITUDE</th>
<th>L-VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faroe</td>
<td>FA</td>
<td>62.03</td>
<td>-6.78</td>
<td>65.03</td>
<td>86.02</td>
<td>4.30</td>
</tr>
<tr>
<td>St Anthony</td>
<td>SA</td>
<td>51.35</td>
<td>-55.60</td>
<td>62.13</td>
<td>20.34</td>
<td>4.07</td>
</tr>
<tr>
<td>Oulu</td>
<td>OL</td>
<td>65.11</td>
<td>25.49</td>
<td>61.72</td>
<td>117.96</td>
<td>4.34</td>
</tr>
<tr>
<td>Eskdalemuir</td>
<td>ES</td>
<td>55.32</td>
<td>-3.20</td>
<td>58.11</td>
<td>84.29</td>
<td>2.81</td>
</tr>
<tr>
<td>Cambridge</td>
<td>CA</td>
<td>52.23</td>
<td>+0.05</td>
<td>54.56</td>
<td>85.71</td>
<td>2.37</td>
</tr>
</tbody>
</table>

The coordinates are given in degrees, where (-) means West in Longitude and South in Latitude; unqualified numbers signify East in Longitude and North in Latitude.

*L-values computed at 120 km altitude for epoch 1977.5 from the main field model of Barraclough et al. (1975).
magnitude of the ambient magnetic field. The magnetometer had essentially flat frequency response and a noise level typically < 0.05 nT. It recorded magnetic variations in three orthogonal directions - magnetic NE, NW and Z (Stuart, 1971). H and D components can easily be recovered from NE and NW components. The sensitivity of the magnetometer was usually in the range of 0.04 - 0.16 nT. The magnetic variations were sampled at 2.5 sec. intervals, timing accuracy being controlled by a crystal clock, and recorded digitally on cassette tape, as described by Riddick et al. (1975), who gave details of the sensing and recording engineering. The recorded data were subsequently transcribed into computer compatible format (Mills et al., 1977) for storage on master data bank tapes at the IGS. Analogue records were usually produced directly from the cassette tapes before transcription, but could also be obtained from the data bank tapes. The analogue records and the data bank tapes provided data used here. The data were prepared using the standard methods of data handling developed at IGS (Stuart and Green, 1981).

Selection procedure:

(a) Initial Selection: The choice of suitable criteria for selection of Pc pulsation events is made difficult by the complex nature of the pulsations. Many changes occur in their parameters within the duration of the activity. So the estimate of parameters such as amplitude and period in a given interval may not be characteristic for the whole interval. The longer the interval considered the worse the effects of changing parameters, but the use of shorter intervals amounts to large volumes of data sets which may be laborious to analyse.

The initial selection of the Pc 3-4 events was made on the basis of 30 minute intervals. In each interval selected the amplitude of the Pc 3 or Pc 4 event must have been above the average background noise level most of the time; the
period must have not changed by more than 10% of the apparent dominant period; the oscillations should be regular and fairly continuous for more than half the interval.

Analogue records were visually inspected and 30 minute intervals beginning at the hour or half hour were selected during which there appeared to be good Pc 3 or Pc 4 pulsations. Good quality Pc activity usually occurs at times when the background field is relatively quiet and the Pc's can be selected quickly and easily for analysis.

(b) Final selection: Ground data for this study were selected using the technique of power spectral analysis. Power spectra were performed on the 30 minute segments of data. A low pass digital filter was first applied before the spectra were calculated by using Fast Fourier Transform (FFT) algorithm. 32 spectral estimates were obtained between 1.66 mHz and 98.54 mHz. The resultant frequency resolution was 3.12 mHz and the number of degrees of freedom per estimate was 10.1 with a normalized standard error of 0.44. During the spectral analysis data were converted from the recorded NE and NW to H and D-components which are physically more meaningful. Figures (4:2) and (4:3) show typical power spectra for H and D-components for events with energy mainly in the Pc 3 and Pc 4 frequency bands respectively. The power peak is shown by an arrow.

The procedure for selecting the pulsation events was as follows. Computer output for the spectral estimates was examined (1514, 30-minute spectra were treated in this way). It was determined whether a spectral peak appeared in the appropriate frequency band. If there was clearly identifiable power peak it was counted as an event and its power and corresponding period were noted. Whenever there was some ambiguity in identifying the peaks the event was rejected. Two components, H and D were considered in this exercise. If in one segment there were two outstanding peaks showing in both components at the same period band,
FIGURE 4:2

FIGURE 4:3
as shown in Figure (4:2), only the component with the higher peak was chosen. If the peaks appeared in both components at different period bands in the same segment then the peaks were treated as two separate events. Although two components (H and D) were considered it turned out that H-component contained much more power than D-components. For this reason analysis was basically of H-components. 1514 events were treated in this way and resulted in finally selected sections of record.

### Satellite Data

Data from the interplanetary medium were obtained mainly from the ISEE-2 satellite, one of the three spacecraft forming the International Sun-Earth Explorer (ISEE) mission.

ISEE is a joint European space Agency (ESA) and National Aeronautics and Space Administration (NASA) mission of three spacecraft designed to make the first comprehensive study of magnetospheric dynamics. The mission was timed to make a large contribution to the International Magnetospheric Study (IMS). The main objectives of the ISEE mission and details of orbital parameters of the spacecraft was outlined by Durney (1977).

The nucleus of the ISEE mission is a pair of spacecraft—namely ISEE-1 and ISEE-2 (sometimes referred to as ISEE-A and ISEE-B or 'Mother' and 'Daughter', respectively) which circulate the magnetospheric boundaries on the same orbit at a known and controllable distance apart. Since most of the events that occur inside the magnetosphere may be due to the varying conditions in the interplanetary medium a third spacecraft, ISEE-3 (or ISEE-C) is stationed 235 RE at the libration point between the Sun and the Earth where it circulates in a 'halo' orbit monitoring the interplanetary medium.

The pair of spacecraft were launched as a stacked pair by a single Thor Delta 2914 from the Eastern Test Range on 22nd October, 1977. The twin spacecraft travel in the same orbit which had initial apogee and perigee of 22.6 RE and
280 km respectively. Table (4:2) shows some of the major orbital parameters of the spacecraft for different epoch. It was deliberately planned that the initial line of apsides should be such that the early apogee would be in the interplanetary space to ensure some measurements of the magnetopause, magnetosheath and the bow shock in case of early failures. The orbit remains fixed in space and as the Earth revolves around the Sun, the line of apsides rotates through the magnetosphere in a circular form as shown in Figure (4:4). In the diagram the date circle indicates the position of the Earth centre/apogee line at the time shown in calendar months. It should be noticed, for example, that apogees in October penetrated the interplanetary medium and will continue to do so in the Autumn throughout the life of the mission, whereas apogees in the magnetic tail occur during Spring.

The wide range of scientific experiments covered by the twin spacecraft, and which involved over a hundred investigators makes the ISEE a suitable source of the interplanetary data useful in this work. Generally the instruments carried aboard the spacecraft use the latest techniques and are more sensitive than the previous version. In particular a large effort went into reducing electric and magnetic interference from the spacecraft itself, so the instruments have extraordinary low thresholds with high time resolution. UCLA-fluxgate magnetometers and solar wind plasma instrumentation aboard the ISEE-2 spacecraft provided the interplanetary medium data used in this study. There were two types of the interplanetary data, that is the interplanetary magnetic field (IMF) data and solar wind plasma data. Both types of data are described below.

(a) IMF Data   The IMF data were provided from the University College of Los Angeles (UCLA) fluxgate magnetometers experiment aboard the ISEE-2 spacecraft. The instrumentation is described in detail by Russell (1978). A few points are recalled. The triaxial magnetometers have a wide dynamic range of ± 8092 nT with a commandable range change to
Table 4:2 Orbital parameters of ISEE-2 satellite for different epoch

<table>
<thead>
<tr>
<th>Launch date</th>
<th>22nd Oct., 1977</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit Type</td>
<td>Geocentric</td>
</tr>
<tr>
<td>Epoch (Month-Day-Year)</td>
<td>10-22-77</td>
</tr>
<tr>
<td>Period (min)</td>
<td>3453.1</td>
</tr>
<tr>
<td>Inclination</td>
<td>28.7°</td>
</tr>
<tr>
<td>Perigee (km)</td>
<td>280</td>
</tr>
<tr>
<td>Apogee (km)</td>
<td>138,217</td>
</tr>
</tbody>
</table>

\( \pm 256 \) nT. The ranges had \( 2.5 \times 10^{-1} \) nT and \( 7.8 \times 10^{-3} \) nT resolution respectively. Digital aliasing filters which were the same for all three sensors were used to prevent contamination of recorded data by power at frequencies higher than the sampling rate. Because the ISEE-2 spacecraft had to spin linearity of the instrument was desirable. Spinning the spacecraft is an advantage because the sensitivity to the spacecraft itself (or sensor offsets in the spin plane of the spacecraft) is very small. The linearity is measured by calibrating with a computer controlled field. The temperature dependence of the magnetometer's zero level is less than \( 10^{-2} \) nT/c° in its most sensitive mode; the overall gain dependence is \( 10^{-5} \) to \( 10^{-4} \) /c°. The basic noise level of the instrument is about \( 10^{-5} \) nT/Hz at 1 Hz and the trend is inversely proportional to the frequency. The output rate of the magnetometer is either 4 or 16 vectors per second depending on the bit rate of the spacecraft telemetry system. Data for all the time periods used in this study were taken at low bit rate corresponding to 4 vectors per second or the sampling interval of 0.25 sec.
FIGURE 4:4
Data from the instruments for the period from 22 October to 31 December, 1977 were used in this study. This period covers the first 30 orbits of the ISEE-2 spacecraft. Data were in two forms (a) 4-seconds samples generated by a 12 second running mean shifting along the raw data and (b) 64-seconds average values. Each sample consisted of more than two months data recorded mostly in the interplanetary space and least in the magnetosphere. The data tapes included three orthogonal components of the IMF records in geocentric solar ecliptic (GSE) coordinate system together with satellite position and time (UT). There were also back-up analogue records for the 64-seconds data.

The GSE system to which the original data refers is suitable for this study. The GSE coordinate system has its X-axis pointing from the Earth towards the Sun; Z-axis is positively northwards normal to the ecliptic plane and the Y-axis is chosen so that the rectangular Cartesian coordinate system is right handed. The values of X, Y, Z are often given in terms of Earth radii (RE) units. In the GSE system a magnetic vector $B(X,Y,Z)$ can be specified by magnitude $(B)$ and two angles, i.e. $\theta$ (ecliptic latitude) and $\varphi$ (ecliptic longitude). These parameters are related as follows:

$$B = \left( B_x^2 + B_y^2 + B_z^2 \right)^{\frac{1}{2}} \quad (4:1)$$

$$\theta = \arctan \frac{B_z}{\left( B_x^2 + B_y^2 \right)^{\frac{1}{2}}} \quad (4:2)$$

$$\varphi = \arctan \frac{B_y}{B_x} \quad (4:3)$$

Figure (4:5) shows the GSE coordinate system and the associated IMF parameters used in this work.

It should be remembered that different coordinate systems exist for experimental and theoretical work on solar terrestrial relationship. The need for a variety of coordinate systems is essential because various physical processes are better understood, experimental data are more ordered or calculations are more easily performed in one
FIGURE 4.5
or another of the various systems (Russell, 1971). When dealing with the Earth-Interplanetary-Space relation the GSE system is preferable.

For the analysis described in this work it was not possible to use the data straight as it was received from data pool tapes, for two reasons. First there were many spikes of artificial origin, which had to be removed; second there were unwanted records when the spacecraft was crossing the bow shock and magnetopause and when it was inside the magnetosheath and magnetosphere. Several editing programmes were designed to remove the spikes, to throw away unwanted records and to ensure that the observation point of the spacecraft was inside the interplanetary medium. Satellite position was verified by visual inspection of the analogue records of the 64-second data from which it was possible to identify magnetopause and bow shock crossings. Specific examples of the boundary crossing are given in Chapter 5, Figure (5:3).

(b) Solar wind data

The solar wind data were obtained from the positive ion electrostatic deflector on board the ISEE-2 satellite.

A detailed description of the instrumentation system has been given elsewhere by Bonifazi et al. (1978). Here only a few basic features of the experiment relevant to this study are recalled.

The instrument is based on two identical hemispherical electrostatic energy selectors to which variable voltages are applied in order to perform simultaneous measurements of positive ions in two different energy windows. The instrument measures the flux of ions in 64 energy channels (the relative energy response ΔE/E is about 4%) from ~ 50 eV/Z to ~ 11 KeV/Z. The two energy windows - a factor of 1.5 apart are sampled simultaneously each revolution (~ 3s) of the spacecraft.

The experiment operates in two different modes referred to as 'wide energy spectrum' (WES) and 'high time resolution'
(HTR) modes which alternate automatically. In the WES mode the experiment supplies a full ion energy spectrum every \( \sim 96 \) seconds. In the HTR mode the experiment tracks the maximum of the ion energy spectrum obtaining significant observations of proton energy spectrum every two spacecraft revolutions (\( \sim 6s \)).

The values of the solar wind velocity used in this work were derived operation in the WES mode. The data were received from the Consiglio Nazionale Delle Ricerch (CNR) Frascati, Rome. They were in the form of continuous 24 hr plots of the solar wind speed. As the positive ions measured by the experiment were in the range from 50 eV/Z to 11 keV/Z velocities well beyond 450 km/sec could be recorded. In order to obtain a good display of the data (G. Moreno, 1981 personal communication) scales for the plots were restricted to the range of 200–450 km/sec during the interval in which the velocities did not exceed this limit (which was common). The scale was compressed to include higher velocities than the 450 km/sec margin (these were relatively few).

The records of the solar wind velocity were digitized by a trace follower digitizer using continuous mode of digitization. The points were first digitized at 1 mm (1 mm = 6 min) interval, interpolated at 30 minutes interval and finally scaled down every half-hour to obtain 30-min values of the solar wind speed. Approximately 1402, 30-min data points were prepared in this way.

**Supplementary solar wind velocity data**

There were insufficient records of solar wind velocity data to cover all the ground and IMF records. Many data gaps (of various lengths) occurred in the solar wind velocity records at times when both ground and IMF data were good and continuous. There were several reasons for the gaps. The solar wind plasma experiment on board
the spacecraft was switched on on day 304 (9 days later than the time for the start of the ISEE mission on 22nd October 1977), and, the apogee of the ISEE-2 orbits penetrated the magnetosheath most of the time during the last part of December 1977. Therefore, there were few patches of reliable solar wind velocity records in the interplanetary medium at this time. Therewere also occasional gaps of relatively short duration because of instrument malfunction. Hence there were no records of the solar wind velocity on the satellite for the days 295-304 and days 360-365. The available records were supplemented by records from the Interplanetary Medium Data Book (King 1979). The supplementary data were about 15% of the basic data available from the ISEE-2 plasma experiment.

The solar wind velocity records in the Interplanetary Medium Data Book are obtained mainly from the IMP-7 and IMP-8 spacecraft. The values in the book are given in one-hour blocks. The records from the ISEE-2 spacecraft were computed in half hour blocks as described in the previous section. Because of the differences in time resolution of the data and the difference of instruments on board the two different spacecraft (IMP and ISEE) it was necessary to make certain simple adjustments to the records from the IMP spacecraft to minimize any discrepancy, in final analysis, which may be caused by the differences. First the one-hour values of the solar wind velocity listed in the Interplanetary Medium Data Book were each assigned equally to the corresponding two half hour blocks. This procedure is acceptable particularly for the solar wind velocity which does not change very much within one hour. Second a spot check was carried out to compare the data from the two spacecraft. Two extreme cases were considered, a very quiet day (313) and a very disturbed day (318). The choice of the two extreme conditions was based on the state of the interplanetary medium as measured by the $\Sigma Kp$ value for the day. On the
quiet day 313 the Kp was 6; on the disturbed day 318 the Kp was 38; in fact, the day 318 was by far the most disturbed day of the period covered by this study. Only sections with continuous records on both spacecraft were used. Figure (4:6) shows the plots of the solar wind velocity for IMP-7,8 and ISEE 2 spacecraft. The points are plotted at half-hour interval. The upper panel is for the quiet day 313; the lower panel is for the disturbed day 318; the scales of the two plots are different. It is clear in both panels that the IMP data are consistently higher than the ISEE-2 data. However, the difference between the two data sets for the quiet day is small and almost negligible ($\Delta V < 4 \text{ km/sec}$); for the disturbed day the difference is comparatively large and varied but not larger than 45 km/sec.

It is not sufficient to use the results above to make the necessary adjustment to the two data sets since the two days may not represent a true picture of the records for the rest of the days included in this study. It would be necessary to make a detailed statistical comparison using large enough data to cover the whole period of study. Fortunately Bonifazi et al. (1980) have made such a comparison. Bonifazi et al. (1980) performed an extended statistical analysis to check the consistency of the solar wind velocity derived from the ISEE 2 and IMP.8 plasma experiments for the period covered by this study. The analysis was based on 895 cases of the solar wind observations performed simultaneously by the two spacecraft during the period from 3 November, 1977 to 6th December, 1977 and when the two spacecraft were in the interplanetary medium. The authors found that the solar wind velocity measured by the two satellites differed systematically by 8-10 km/sec on the average (values from IMP-8 being consistently larger than the values from the ISEE-2 satellite). The consistency of the two sets of data was ensured by the fact that the straight line best fitting the points had a slope of
FIGURE 4:6

ISEE-2 & IMP-8 SOLAR WIND VELOCITY

V_{SW}

600
500
400
300
200
100

6 8 10 12 14 16 UT

DAYS 313 1977

ISEE-2

IMP-8
approximately 45° and by the small value of the standard error of estimate (SD = 4.3 km/sec). Data from IMP-7 and IMP-8 are also quite consistent (King 1979). On the basis of Bonifazi's results, the IMP-7, 8 data used in this study were reduced by 10 km/sec.

4:3

Analysis and Results

4:3-1 Inter-relation of \( V_{sw} \), \( \Theta_{xB} \) and \( B \)

Before a correlation study was made the characteristics of the solar wind parameters themselves were studied. The inter-relation of \( B \), \( V_{sw} \) and \( \Theta_{xB} \) was examined by performing linear regression and correlation analysis using 713 30 min data samples.

It should be noted that the cone angle (\( \Theta_{xB} \)) is used here instead of the ordinary polar angle \( \Theta \) (ecliptic latitude) and \( \varphi \) (ecliptic longitude) for two main reasons. First the use of one angular parameter simplifies the analysis. Second it had been earlier noted by authors, notably Greenstadt and Olson (1976); Arthus and McPherron (1977); Wolfe et al. (1980) and Takahashi et al. (1981), that the cone angle appreciably affects the Pc 3-4 amplitude and occurrence.

The definition of 30-minute values for the cone angle adopted here is the average of 450 points taken from the 4 second IMF data, representing 30-minutes data length. By this definition the cone angle was given by the following expression

\[
\langle \Theta_{xB} \rangle = \frac{1}{N} \sum_{i=1}^{N} \Theta_{xBi} \quad (4:4)
\]

where \( N \) is the number of data points for summation. The cone angle was calculated from the IMF data according to Wolfe et al. (1980)

\[
\Theta_{xB} = \arccos \left( \frac{|B_x|}{B} \right) \quad (4:5)
\]

Hence the expression (4:4) can be written as

\[
\langle \Theta_{xB} \rangle = \frac{1}{N} \sum_{i=1}^{N} \arccos \left( \frac{|B_{xi}|}{B_{i}} \right) \quad (4:6)
\]
The 30-minute values for the IMF magnitude were computed using the following impression

\[ < B > = \frac{1}{N} \sum_{i=1}^{N} (B_{x}^2 + B_{y}^2 + B_{z}^2)^{1/2} \]  \hspace{1cm} (4:7)

Scatter plots using hourly average values of the solar wind parameters are shown in Figures (4.7a - 4.7c). From these, the least square best fit lines for the scatter plots and the coefficient of linear correlation were computed.

Generally there is a large scatter implying that any inter-relation of B, V_{sw} and \( \theta_{xB} \) is weak. More particularly, there is a very small positive correlation coefficient of 0.02 between the IMF magnitude (B) and the solar wind velocity (V_{sw}); the correlation coefficient establishes the best fit line to be not significant at the 95% confidence level for the number of data points (713) used. The dependence of B on the cone angle (\( \theta_{xB} \)) is also weak with a linear correlation coefficient of 0.18. This is, however significant at the 95% confidence level. Similarly the dependence of \( \theta_{xB} \) on the solar wind velocity (V_{sw}) is poor with a linear correlation coefficient of 0.19. It must be, however, remembered that no autocorrelation is assumed in the data. Examination of the scatter diagram would suggest that the correlation is in fact insignificant and that auto-correlation is present in the data set and the final number of degrees of freedom is much less than 711.

The results of the linear regression analysis are summarized in Table (4:3). In particular Table (4:4) shows the linear correlation coefficient of the pairs of the solar wind parameters. It is evident from the poor correlations shown in the table that B and \( \theta_{xB} \) are not sufficiently related and that neither \( \theta_{xB} \) nor B is correlated well to the solar wind velocity, V_{sw}. The evidence of poor correlations among the three parameters is brought out more clearly by the two regression lines drawn...
FIGURE 4:7

(a) B (NANOTESLA) vs. SOLAR WIND VELOCITY (KM/SEC) with $N = 713$ and $R = 0.02$

(b) B (NANOTESLA) vs. CONE ANGLE (DEG) with $N = 713$ and $R = 0.19$

(c) B (NANOTESLA) vs. CONE ANGLE (DEG) with $N = 713$ and $R = 0.18$
<table>
<thead>
<tr>
<th>N</th>
<th>MEAN VALUES</th>
<th>FUNCTIONAL RELATION</th>
<th>SLOPE ( (c_1) )</th>
<th>INTERCEPT ( (c_0) )</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>713</td>
<td>( \bar{B} = 6.22 \pm 0.1 )</td>
<td>( \bar{B} = c_1 \bar{V}_{sw} + c_0 )</td>
<td>( 0.001 \pm 0.002 )</td>
<td>( 5.86 \pm 0.59 )</td>
<td>0.02</td>
</tr>
<tr>
<td>713</td>
<td>( \bar{V}_{sw} = 393.02 \pm 2.57 )</td>
<td>( \bar{V}_{sw} = c_1 \bar{B} + c_0 )</td>
<td>( 0.57 \pm 0.94 )</td>
<td>( 389.46 \pm 6.39 )</td>
<td>0.18</td>
</tr>
<tr>
<td>713</td>
<td>( \bar{\theta}_{XB} = 49.24 \pm 0.69 )</td>
<td>( \bar{\theta}_{XB} = c_1 \bar{B} + c_0 )</td>
<td>( 0.03 \pm 0.006 )</td>
<td>( 4.90 \pm 0.29 )</td>
<td>0.19</td>
</tr>
<tr>
<td>713</td>
<td>( \bar{B} = c_1 \bar{V}_{sw} + c_0 )</td>
<td>( \bar{\theta}<em>{XB} = c_1 \bar{V}</em>{sw} + c_0 )</td>
<td>( 0.051 \pm 0.01 )</td>
<td>( 29.12 \pm 3.92 )</td>
<td>0.19</td>
</tr>
<tr>
<td>713</td>
<td>( \bar{V}<em>{sw} = c_1 \bar{\theta}</em>{XB} + c_0 )</td>
<td>( \bar{V}<em>{sw} = c_1 \bar{\theta}</em>{XB} + c_0 )</td>
<td>( 0.72 \pm 0.14 )</td>
<td>( 357.7 \pm 7.24 )</td>
<td>0.19</td>
</tr>
</tbody>
</table>
**TABLE (4:1) Correlation coefficient of the solar wind parameters**

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>$V_{sw}$</th>
<th>$\theta_{xB}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>0.02</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>$V_{sw}$</td>
<td></td>
<td></td>
<td>0.19</td>
</tr>
<tr>
<td>$\theta_{xB}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
on each scatter diagram. The two regression lines, in each case intersect each other at an acute angle more than $65^\circ$ (non correlation means that the angle of intersection is a right angle). In fact for the $B$ and $V_{SW}$ relation the angle of intersection ($88^\circ$) is very nearly a right angle. Because of these results $B$, $V_{SW}$ and $G_{XB}$ were regarded as independent parameters. For the correlation analysis to follow, $\frac{1}{2}$ hourly values of the three solar wind parameters will be used, unless specified to the contrary.

A network of five ground stations listed in Table (4:1) was used in the correlation study presented in the following sections. The five stations were chosen from the IGS chain of magnetometers primarily to get sufficient ground coverage. Green (1981) has described the profile of the IGS magnetometer array during the period of this study. The basic configuration in Europe is of two lines approximately along the geomagnetic meridian about 2 hours apart. The eastern meridional line runs through Scandinavia and covers L-values of $\sim 3.3-6.3$, and the western line runs through the UK to Iceland, $L = 2.4-6.5$. In addition there is a station at St Anthony in Newfoundland about 4 hours to the west of the UK line and 6 hours to the Scandinavia line. Oulu lies in the eastern meridional line; Faroe, Eskdalemuir and Cambridge lie in the UK line. In this configuration Cambridge and Faroe have the largest latitudinal separation of $\Delta \theta = 10.0^\circ$ whereas St Anthony and Oulu have the largest longitudinal separation of $\Delta \varphi = 81.09^\circ$ giving 6 hours (to the nearest whole hour) local time difference between the two stations. These stations had relatively continuous good records for the geomagnetic field data during the most part of the period covered by this study. In addition the stations recorded good Pc 3-4 activity in terms of amplitude and continuity

4:3-2 General distribution of $V_{SW}, B, \theta_{XB}$

The general distribution of each of the solar wind parameters during the whole period of this study is shown by
the histograms in Figure (4:8 a,b,c). The histograms were made from the same number of data points used in the scatter plots (Figure 4:7 a,b,c) plus a few other points which could not be included in the scatter plot because they lacked correspondence in the records; in other words, in a given half hour time interval one parameter was present while there was data gap for another parameter. The total number of $\frac{1}{2}$ hour data points used in each diagram is shown in brackets. Each histogram represents the natural distribution of the parameter regardless of whether there was any pulsations activity observed or not.

Examination of the figures indicates that the distribution of the solar wind velocity has an outstanding maximum at 350-400 km/sec, Figure (4:8a). There are few records for unusually high solar wind velocity, $V_{SW} \geq 600$ km/sec and for unusually low velocity, $V_{SW} \leq 250$ km/sec. Figure (4:8b) shows an outstanding peak at 4-5 nT. There is a gradual decrease in the IMF distribution pattern for $B > 6$ nT, the distribution approaches zero at $B = 17-18$ nT, i.e. there are few records of IMF in this range. There are few records also for $B < 1-2$ nT. The cone angle distribution, Figure (4:8c) peaks at $45^\circ-60^\circ$ with minima at $\Theta_{xB} = 75^\circ$ and $\Theta_{xB} \leq 15^\circ$.

The peaks of the three distribution diagrams are considered to be at the usual or normal values of the corresponding solar wind parameter during the period of this study, that is for $V_{SW}$ the usual range is 350-400 km/sec, for $B$ the usual range is 4-5 nT and for $\Theta_{xB}$ the usual range is $45^\circ-60^\circ$. It is to be noted that the usual values of the parameters may not necessarily be equal to their mean values.

4:3-3 Geomagnetic pulsations occurrence and variation with local time

All the Pc 3, 4 activity at the five stations listed in Table (4:1) for the whole period of study (22nd Oct. to
FIGURE 4.8

(a) $V_{SW}$ (km sec$^{-1}$)

(b) $B$ (nT)

(c) $\Theta_{XB}$
31st Dec., 1977) were generally classified according to the
time of day when they occurred simultaneously at more than
two stations and when they occurred locally at one or two of
the stations; eight 3 hr blocks were used. Figures (4:9 a,b)
are histograms from the five stations showing the number of
pulsation events versus local time (LT). The occurrence
distribution is shown in Figure (4:9 a) for the
simultaneous events and in Figure (4:9 b) for the local
events.

The two histograms are very different. The first
one corresponding to the simultaneous events has an almost
symmetrical or bell shaped type of frequency curve with a
distinct maximum occurring at 09:12 LT; the second histogram
(corresponding to the local events) has a rather flat-shaped
type of frequency curve with no obvious peak. Generally
there are fewer local events than the simultaneous events;
there are 136 local events and 347 simultaneous events;
these numbers are shown in brackets in the corresponding
diagram. Both diagrams indicate the Pc 3,4 pulsations
are daytime phenomena.

4:3-4

Effect of solar wind velocity

General occurrence pattern

The general occurrence pattern of the Pc 3,4 pulsation
events was presented in terms of the histograms shown in
Figure (4:10) for the five ground stations. Each event in
the distribution diagram represents the 30-min power spectral
peak as described in the section 4:2-1. Few events at the
end and beginning of each distribution diagram simply means
that there were few records of the solar wind velocity
$V_{SW}$ > 450 km/sec and $V_{SW}$ < 300 km/sec. and does not
reflect any intrinsic property of frequency distribution of
events against the velocity of solar wind, see Figure (4:8a).

In the range of velocity, $V_{SW}$ = 300-450 km/sec. there
are more Pc 3,4 pulsation events for $V_{SW}$ ≥ 400 than for
Pc 3,4
OCT.- DEC., 1977

FIGURE 4:9
FIGURE 4:10
the $V_{SW} \leq 400$ km/sec; in fact there is a clear maximum at $V_{SW} = 400$ km/sec for all the five stations. This result is shown below in a different way.

**Diurnal occurrence pattern**

The diurnal variation of the occurrence of Pc 3,4 activity at two ranges of solar wind velocity ($V_{SW} = 300-400$ km/sec and $400-500$ km/sec) for the five stations is shown in Figure (4:11). Each plot is a frequency polygon (a line graph) of occurrence frequency of Pc 3,4 events plotted against local time (LT).

The effect of the solar wind velocity on the diurnal occurrence pattern is positive. Before noon (LT) the occurrence of pulsations activity is generally higher for $400 \leq V_{SW} < 500$ km/sec than for $300 \leq V_{SW} \leq 400$ km/sec at all five stations, although Eskdalemuir does not show this trend very clearly. There is a pre-noon peak of the occurrence pattern common to all stations.

One important feature visible in the plots is that high solar wind velocity drives the Pc 3,4 pulsations activity earlier, in the local morning sector, than low solar wind velocity does: the small triangles in the diagrams have their apex showing the median of the occurrence distribution of the Pc 3,4 activity at different local times; the median of each distribution moves towards the morning local time as the solar wind velocity increases, suggesting that high solar wind velocity affects the Pc 3,4 pulsations at earlier local morning hours than the time when low solar wind velocity is effective; for $400-500$ km/sec the median is at around 08 LT, for $300-400$ km/sec the median is at ~ 10 LT.

The precise relation of energy level of Pc 3,4 activity to the solar wind velocity cannot be judged from the results above. In the following section, are presented the results of regression analysis performed to determine more precisely the relationship which exist between the
solar wind velocity and the magnetic energy.

**Effect of $V_{SW}$ on the Pc 3,4 pulsations energy**

The power spectra provide measures of magnetic energy density in $(nT)^2/Hz$. The total energy of magnetic fluctuations is obtained by integrating the power spectral density estimates over a given frequency range. Assuming that power is related to energy the magnetic energy density is referred to simply as magnetic energy.

Using the same number of events as was in Figure (4:10) scatter plots were produced to illustrate the general trend of the relationship between the Pc 3,4 energy and the solar wind velocity as shown in Figures (4:12-4:16). The upper panel (a) shows the Pc 3 data and the lower panel (b) shows the Pc 4 data. $N$ is the number of data points used in each scatter diagram. The magnetic energy was measured in terms of log peak power density (dB). Each point in the scatter diagrams corresponds to the power peak of the power spectrum calculated at 30 min segments and the corresponding 30-min value of the solar wind velocity.

Linear regression analysis was performed to determine quantitatively the relationship between the energy of the ground pulsations and the solar wind velocity. The least square best fitting lines for the scatter plots were derived; the standard error of estimates (SEE) was determined to indicate the degree of scatter about the regression line; and the coefficient of linear correlation (R) was calculated.

The dependence of the ground magnetic energy on the solar wind velocity in the two period bands, i.e. Pc 3 and Pc 4 at each of the five ground stations is described below.

**Faroe**

The magnetic energy in each period band was observed to increase with the rise in solar wind velocity, see Figure (4:12 a,b). The Pc 4 pulsations show this general trend very clearly. A positive correlation coefficient
R = 0.41 was found for the best fitting line in case of the Pc 4 pulsations. The standard error of estimate (SEE) was 7.3 dB. For the Pc 3 pulsations, the coefficient of linear correlation was low \( R = 0.24 \) with SEE of 3.28 dB. The high correlation coefficient is significant at the 99.9% confidence level but the low coefficient of correlation is significant at the 97.5% confidence level.

**St Anthony**

The energy in each period band was observed to increase with the increase of the solar wind velocity. The Pc 3 pulsations show this trend more clearly than the Pc 4 pulsations at this station, Figure (4:13). A very high positive correlation coefficient of 0.66 with a relatively small scatter (SEE = 2.87 dB) was found for the Pc 3 activity. The high correlation coefficient establishes the best fit line to be significant at the 99.9% confidence level. The Pc 4 pulsations show large scatter (SEE = 7.44 dB) The correlation coefficient, \( R = 0.32 \) establishes the best fit line to be significant at the 99.9% confidence level.

**Oulu**

The energy in both period bands was found to increase with the increase in the solar wind velocity as shown in Figure (4:14). Both Pc 3 and Pc 4 activities show similar trend of their energy dependence on the solar wind velocity, although the Pc 4 pulsations give a better picture of the relation at this station. The Pc 4 pulsations show relatively large scatter of (SEE = 5.96 dB) but indicate higher correlation coefficient than the Pc 3 pulsations. The Pc 3 pulsations show relatively small scatter (SEE 3.71 dB) but lower correlation coefficient of 0.39. The coefficient of correlation at both period bands are significant at the 99.9% confidence level.

The difference between the linear correlation coefficients for the Pc 3 and Pc 4 bands has been verified using Fishers
Z-transformation The transformation allows comparison between two linear correlation coefficients derived from different number of degrees of freedom. Alternative method involving the upper and lower 95% confidence limit was applied to confirm that the two correlation coefficients actually differ significantly. For Oulu the upper and the lower 95% confidence limit of the linear correlation coefficient for Pc 3 band is 0.45 and 0.31 respectively; for the Pc 4 band the upper and lower 95% confidence limit is 0.59 and 0.44; thus there is certainly no significant overlapping in the values of the linear correlation coefficients for the two bands (Pc 3 and Pc 4). This implies that the correlation coefficients differ significantly.

Eskdalemuir

The situation is quite different from what is described at the three ground stations above. Very few Pc 3 pulsation events were observed at this station. This was due to the instrument malfunction especially at the end of October, 1977 through to a few days at the beginning of November, 1977. However more Pc 4 pulsations were observed than Pc 3. The few Pc 3 events observed show the increase of energy with the increase in the solar wind velocity Figure (4:15). The degree of scatter is reasonable (SEE = 5.26 dB) considering the few number of data points in the scatter plot. The correlation coefficient of 0.43 establishes the best fit line to be significant at the 95% confidence level. The Pc 4 pulsations behave totally different. There is a very poor and negative correlation coefficient, R = -0.13 between the energy and the solar wind velocity, the degree of scatter (SEE = 4.3 dB) is comparatively small.

Cambridge

Here no dependence of the ground magnetic energy on the
solar wind velocity was detected, see Figure (4:16). There is a very poor and almost negative correlation coefficient \( R = -0.07 \) for the Pc 3 pulsations, establishing the best fit line to be not significant at the 95\% confidence level. The Pc 4 pulsations also show no good dependence at all on the solar wind velocity. The correlation coefficient is small though positive, \( R = 0.09 \) and not significant at the 95\% confidence level.

The same procedure of analysis was applied to the combined Pc 3 and Pc 4 often denoted as Pc 3,4 activity. The results obtained together with those ones described above for the Pc 3 and Pc 4 separately are summarized in Table (4:5). Taken in order of columns the table contains the following items: station (STN), number of events (N), average solar wind velocity \( (V_{sw}) \), average energy level \( (E) \), slope \( (C_1) \), intercept \( (C_0) \), coefficient of linear correlation \( (R) \) and type of pulsation. The table clearly indicates that there is no consistency in the influence of the solar wind velocity on the energy of pulsations among the five stations, at least in terms of the period of the magnetic activity; the variations in slope and coefficient of linear correlation do not follow any definite order with respect to the periods of the pulsations. However, broadly there is a general tendency of rise in the energy level of the pulsations with the increase of the solar wind velocity. The correlation coefficient, although consistently low and insignificant at Cambridge is positive and significant at four stations in the network of five stations. The average solar wind velocity for the pulsations activity at all stations and at the various period bands is approximately 400 km/sec.

Looking at the scatter plots more closely there is latitudinal effect on the dependence of magnetic energy \( (E) \) on the solar wind velocity \( (V_{sw}) \). [Later in this work the dependence will be referred to simply as the \( E-V_{sw} \) relation].
FAROE

**Pc3**

- $N = 76$
- $R = 0.23$

**Pc4**

- $N = 104$
- $R = 0.41$

**SOLAR WIND VELOCITY (KM/SEC)**

**LOG POWER (DB)**
ST ANTHONY

Log Power (dB) vs. Solar Wind Velocity (km/sec)

(a) $N=90$

$P_{c3}$

$R=0.66$

(b) $N=72$

$P_{c4}$

$R=0.32$
ESKDALEMUIR

a) $N=20$

$Pc_3$

$R=0.43$

b) $N=81$

$Pc_4$

$R=-0.13$

LOG POWER (DB)

SOLAR WIND VELOCITY (KM/SEC)
The diagram shows two scatter plots comparing solar wind velocity (km/sec) against log power (dB). The upper plot is labeled as a, with the number of data points, \( N = 66 \), and has a correlation coefficient, \( R = -0.07 \). The lower plot is labeled as b, with \( N = 55 \), and has a correlation coefficient, \( R = 0.09 \).
TABLE (4.5): Summary of the $E - V_{sw}$ relation

<table>
<thead>
<tr>
<th>STN</th>
<th>N</th>
<th>$V_{sw}$</th>
<th>$E$</th>
<th>$E = C_1 V_{sw} + C_0$</th>
<th>$C_1$</th>
<th>$C_0$</th>
<th>R</th>
<th>TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>FA</td>
<td>76</td>
<td>411.85±8.07</td>
<td>10.99±0.38</td>
<td>0.01±0.005</td>
<td>6.35±2.25</td>
<td>0.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SA</td>
<td>90</td>
<td>406.78±6.51</td>
<td>10.77±0.40</td>
<td>0.40±0.005</td>
<td>-5.76±2.03</td>
<td>0.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OL</td>
<td>107</td>
<td>382.64±5.86</td>
<td>9.94±0.39</td>
<td>0.03±0.006</td>
<td>0.19±2.30</td>
<td>0.39 Pc3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ES</td>
<td>20</td>
<td>413.15±11.29</td>
<td>6.61±1.27</td>
<td>0.05±0.02</td>
<td>-13.26±9.94</td>
<td>0.43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CA</td>
<td>66</td>
<td>424.76±6.37</td>
<td>9.36±0.55</td>
<td>-0.006±0.011</td>
<td>11.98±4.59</td>
<td>0.07</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| FA  | 104| 391.00±5.19| 17.02±0.77 | 0.06±0.01              | -6.98±5.29| 0.41    |
| SA  | 72 | 381.14±5.97| 14.24±0.92 | 0.05±0.02              | -4.39±6.71| 0.32    |
| OL  | 68 | 406.46±7.05| 20.52±0.84 | 0.06±0.01              | -4.96±5.14| 0.52 Pc4|
| ES  | 81 | 387.29±4.84| 14.27±0.48 | -0.01±0.01             | 19.43±4.34| 0.13    |
| CA  | 55 | 411.75±6.09| 10.74±0.44 | 0.007±0.009            | 8.03±4.09 | 0.09    |

| FA  | 180| 399.45±4.58| 14.11±0.52 | 0.03±0.008             | 4.37±3.38 | 0.22    |
| SA  | 162| 395.98±4.60| 12.29±0.48 | 0.03±0.008             | -1.02±3.12| 0.32    |
| OL  | 175| 391.21±4.61| 14.01±0.56 | 0.05±0.008             | -7.16±3.26| 0.45 Pc3,4|
| ES  | 101| 393.34±4.62| 12.75±0.55 | -0.01±0.01             | 18.03±4.65| 0.11    |
| CA  | 121| 419.18±4.44| 10.02±0.36 | -0.003±0.007           | 11.06±3.14| 0.03    |
The two stations of lower latitudes, namely Cambridge and Eskdalemuir have weak magnetic energy and both stations show relatively poor $E-V_{SW}$ relation. Cambridge which is at the lowest geomagnetic latitude ($52^\circ N$) in the array of five stations is the worst affected. It exhibits almost a flat $E-V_{SW}$ relation for all the period bands examined, the Pc 3, Pc 4 and Pc 3,4 bands. The three stations at higher latitudes, Faroe, St Anthony and Oulu have comparatively strong magnetic energy especially in the Pc 4 band, and have good $E-V_{SW}$ relation. In particular the Pc 3 data at St Anthony illustrates a convincing $E-V_{SW}$ relation, see Figure (4:13a).

Generally there is a large scatter in the $E-V_{SW}$ relation at all five stations. The large scatter is indicative of many factors that may be responsible for the generation of the Pc 3,4 activity at the ground stations. The problems of scatter will be discussed in Chapter 7.

**Effect of IMF cone angle**

(a) General occurrence distribution pattern

The occurrence distribution pattern of the Pc 3,4 events at the five stations is shown in the form of the polar diagrams in Figure (4:17). The radius of each shaded sector, which is $15^\circ$ represents the number of the Pc events ($N$). It is noticeable that, at all ground stations, most events were observed when the cone angle ($\theta_{xB}$) was $15^\circ-45^\circ$ and hardly any events occurred when the cone angle was $60^\circ-90^\circ$.

It may be thought that the occurrence distribution of the Pc 3,4 events presented here merely reflects the natural IMF orientation according to Parker's spiral angle. The distribution pattern of the natural IMF cone angle is inserted in the bottom part of Figure (4:17). The natural IMF orientation pattern was determined from 1053,30-minute data points regardless of whether or not there were pulsations activity observed at any of the five ground stations.
FIGURE 4:17
The natural IMF orientation pattern is totally different from the general occurrence distribution pattern of the Pc 3, 4 pulsations events. The distribution of the natural IMF orientation peaks at $\Theta_{XB} \sim 50^\circ$, whereas the general occurrence distribution for the Pc 3, 4 events peaks well below the cone angle of $45^\circ$. It is evident that the occurrence of the ground pulsations takes place preferably at the small cone angle of $15^\circ-45^\circ$. The mostly preferred values of the cone angle for the occurrence of ground Pc 3,4 pulsations are shown in another way, by means of cumulative distribution in Figures (4:18-4:20).

The same number of Pc 3,4 events as used in Figure (4:17) were used to produce the cumulative distribution curves. The distribution was made by determining for each station the number of Pc 3,4 events which fell below every $15^\circ$ increment in the $\Theta_{XB}$ from $0^\circ$ to $90^\circ$. Such cumulative distribution is known as 'less than' cumulative distribution. This format is convenient for showing the general occurrence distribution pattern of the Pc 3,4 events at once for all five stations. The median of the occurrence distribution can easily be deduced straight away from the cumulative distribution curves.

It is noticeable from Figure (4:18) that the medians (the intersection of dotted line with the distribution curve) of the occurrence distributions at all the stations are at the cone angle range of $27^\circ-37^\circ$. This means that for all the stations at least 50% of the Pc 3,4 pulsations occur when the cone angle is less than $27^\circ-37^\circ$.

It is not clear from the above illustrations how the cone angle operates at different periods of the ground pulsations. For the investigations of effects of cone angle at different period bands the Pc pulsation events were separated into their conventional classes of Pc 3 and Pc 4. For each class the cumulative distributions were
FIGURE 4.18

Cumulative Frequency, \( \phi \)

Median Range (MR) \( 27^\circ \pm 37^\circ \)

\[ \text{Pc 3,4} \]

Legend:
- FA
- SA
- OL
- ES
- CA
FIGURE 4:19

Cumulative Frequency, %

Median Range (MR) 33°-43°
Figure 4:20

Cumulative Frequency, %

Median Range (MR) 24°-32°
made for all five stations. Figure (4:19) and Figure (4:20) show the cumulative distribution for the Pc 3 band and Pc 4 band respectively. Comparing the two figures it is noticeable that the range of medians for the two period bands are quite different. While the range for the Pc 3 band is $33^\circ$-$42^\circ$, the range for the Pc 4 band is $24^\circ$-$32^\circ$. This implies that the cone angle effect is different at different period bands.

(b) The cone angle effect on Pc 3 and Pc 4 pulsations

The effect of the cone angle on the two period bands designated by Pc 3 and Pc 4, separately is investigated below.

The investigation of the dependence of the magnetic energy on the cone angle was carried out by the similar regression procedure as described previously for the solar wind velocity. The dependence of the ground magnetic energy in the two period bands, ie, Pc 3 and Pc 4 on the cone angle is shown in Figures(4:21-4:25). The top panel (a) shows the Pc 3 data, the bottom panel (b) shows the Pc 4 data. The number in each scatter diagram is the number of data points (N) in each of the scatter plots. The effect of the cone angle on the magnetic energy at each of the ground stations is described below.

Faroe

The magnetic energy in each period band was observed to decrease with an increase in the cone angle as shown in Figure (4:21). The Pc 3 pulsations show the trend of the relation more clearly than the Pc 4 pulsations. A high negative correlation coefficient of -0.52 was found for the best fit line for the Pc 3 activity (the negative sign of the correlation coefficient signifies the negative correlation between the two variables involved). The standard error of estimate (SEE) of the regression line was 3.96 dB. For the Pc 4 pulsations the linear correlation coefficient was found to be lower $R = -0.31$. The degree of scatter (SEE = 7.74 dB) almost doubled. The correlation coefficients for the Pc 3 and
Pc 4, both were significant at the 99.9% confidence level. The comparison of the two linear correlation coefficients is justified both by the 95% confidence limits and the Z-transformation, which indicated that the coefficient for Pc 3 activity differed significantly from that for the Pc 4 activity.

St Anthony

The negative correlation between the energy of the ground pulsations and the cone angle is displayed very clearly by the Pc 3 band in Figure (4:22a). The high negative correlation coefficient of -0.56 establishes the best fit line to be significant at the 99.9% confidence level. The degree of scatter about the regression line is relatively small, SEE = 3.22 dB.

The Pc 4 band shows the trend of dependence between the energy and the cone angle rather poorly, see Figure (4:22b). The correlation coefficient is relatively low $R = -0.31$, as found at Faroe. The correlation coefficient establishes the best fit line to be significant at the 99.9% confidence level. There is a large scatter (SEE = 7.79 dB) about the regression line.

Oulu

The dependence of the ground magnetic energy, in the two period bands, on the cone angle at this station was found to be similar to what has been described for the two stations above (Faroe and St Anthony). The Pc 3 band was observed to have a better correlation with the cone angle than the Pc 4 band as shown in Figure (4:23). The Pc 3 pulsations show a high negative correlation coefficient of -0.55 which establishes the best fit line to be significant at the 99.9% confidence level. There is relatively small scatter (SEE = 3.22 dB) about the regression line. The Pc 4 band energy, on the other hand, responds rather mildly to the changes in the cone angle.
The correlation coefficient is low, $R = -0.26$ and there is a large scatter (SEE = 7.22 dB) about the regression line. The correlation coefficient establishes the best fit line to be significant at the 95% confidence level.

Eskdalemuir

A slightly different situation was observed at this station. There is an improved relationship between the energy of the ground Pc 4 pulsations and the cone angle as shown in Figure (4:24). The correlation coefficient is $-0.46$ (the correlation coefficient is significant at the 99.9% confidence level). There is a reasonable scatter (SEE = 4.15 dB) about the regression line. The Pc 3 pulsations observed at this station are few (only 17 events were available for comparison with the cone angle) for the reason that has already been mentioned in section 4:3-4. The correlation coefficient for the Pc 3 band is exceptionally poor, $R = -0.20$ and is not significant at the 95% confidence level.

Cambridge

The usual trend of the behaviour of the magnetic energy with the changes in the cone angle was observed at this station, that is the Pc 3 band displays better relation to the cone angle than the Pc 4 band. The difference between the energy response of the Pc 3 band and that of the Pc 4 band to the changes in the cone angle is remarkable, as shown in Figure (4:25). The Pc 3 band energy shows a typical trend of negative correlation $R = -0.51$ with the cone angle while the Pc 4 band displays the poorest correlation, $R = -0.14$ of all the stations considered. The confidence level for the high correlation coefficient is 99.9% and the poor correlation coefficient is not significant at the 95% confidence level. The difference displayed is apparently reliable since the number of degrees of freedom and consequently the number of data points, and the amount of
FIGURE 4:21 CONE ANGLE (DEG)

- **Pc 3**
  - N = 115
  - R = -0.52

- **Pc 4**
  - N = 117
  - R = -0.31
ST ANTHONY

Pc 3
N = 114
R = -0.56

Pc 4
N = 68
R = -0.31

FIGURE 4:22
CONE ANGLE (DEG)
Figure 4.23

(a) Pc3
- N=110
- R=-0.55

(b) Pc4
- N=84
- R=-0.26

Log Power (dB) vs Cone Angle (deg)
ESKDALEMUIR

\[ R = -0.20 \]

\[ N = 18 \]

\[ R = -0.46 \]

\[ N = 71 \]
FIGURE 4:25

CONE ANGLE (DEG)

LOG POWER (DB)

N = 51
Pc 3
R = -0.51

N = 46
Pc 4
R = -0.15
scatter about the regression lines for the two period bands are quite comparable. The number of degrees of freedom (NDF) and the SEE for the Pc 3 band are 48 and 3.06 dB respectively; the NDF and SEE for the Pc 4 band are 44 and 3.09 respectively.

Strong dependence of the ground Pc 3 pulsations on the cone angle is further illustrated in Figures (4:26-4:27). The figures show the plot of high time resolution ground magnetic data along with the cone angle calculated from 64 sec. IMF data. The H-component of the ground magnetic fields were used for the plots. The ground data were band-pass filtered, with the flat frequency response of the digital filter centered at the middle of the Pc 3 band (30 sec.).

Figure (4:26) shows the records for day 325 (12.00-14.00 UT). There is a monochromatic Pc 3 type activity (T ~ 42 sec.) at almost all the stations, which 'switches off' (disappears) at about 13.11 UT. [There is data gap at St Anthony between 13.30 UT and 14.00 UT; even the rest of the interval does not have as good magnetic records as other stations. It is to be noted that St Anthony is in a different local time zone so it might be expected to look different considering the wavelength of the Pc 3,4 activity; other stations are nearer in their local noon]. From the beginning of the records until about 13.11 UT the cone angle is relatively constant at about 35°. At 13.11 UT the cone angle increases abruptly and thereafter is large and variable.

Figure (4:27) shows the records for day 302 (09.00-11.00 UT). There is a good Pc 3 pulsation activity appearing at all four ground stations from the beginning of the records until about 09.48 UT when the activity switches off. The record from Eskdalemuir is missing because of the reason given in the previous sections. From the beginning of the records until the time for the switch off of the ground activity the cone angle is apparently small
FIGURE 4:26

ISEE 2  64 SEC  DAY 325, 1977

FA  3.45 nT

SA  2.39 nT

OL  2.68 nT

ES  1.18 nT

CA  2.44 nT
and constantly around 35°. The data gap of 20 minutes duration appears on the cone angle record between 09.15 and 09.35 UT. After 09.48 UT the cone angle markedly increases and thereafter remains large and variable.

Further clarification of strong dependence of the Pc 3 ground pulsations on the cone angle is presented in Figures (4:28-4:30). One good event in terms of large amplitude and regularity in the wave form was chosen from the five ground stations on each of the two days (325 and 302). Oulu was for day 325 and Cambridge for day 302; both events were in the Pc 3 band. The chosen events were used to compute power spectra. The power spectra were calculated at 10-min segments. A low pass digital filter was applied to the data for the two events before calculating the spectra using FFT algorithm. The variation of the spectral content with times was presented as a contour plot of dynamic spectrum. Contour lines of the dynamic spectra were in 3 dB interval. The maximum power level is indicated in each case and the zero decibel (0 dB) power is 1 nT^2/Hz.

The dynamic power spectra were compared with the cone angle as shown in Figure (4:28) for day 325 (12.00-14.00 UT) and in Figure (4:29) for day 302 (09.00-11.00 UT). It is clearly noticeable that the energy in the Pc 3 band switches off when the cone angle begins to increase. The dynamic spectrum for day 302 is more complicated than for day 325. After the switch off, there is a short duration, approximately 15 min of energy burst after 10.20 UT, this, however, corresponds well with the temporary change of cone angle from high value (> 45° margin) to low value (< 45° margin). The response of the Pc 4 band to the cone angle is not very clear but it is evident that the long period activity remains unaffected with the change in the cone angle. To show this more clearly the cross section of power level of the dynamic spectrum for day 325 (12.00-14.00) at 12 different periods are presented in Figure (4:30). It is
FIGURE 4:30
clearly noticeable that the pulsation energy in the Pc 3 range (T = 37 sec and T = 40 sec) 'switch off' (cutoff) completely when the cone angle rises; the energy level remains below zero as long as the cone angle is large and variable. The Pc 4 pulsation energy corresponding to the period T = 50 sec, T = 60 sec, T = 70 sec, etc onwards is generally high and variable throughout the interval and does not show any obvious correspondence with the variation in the cone angle.

Although the Pc 4 pulsations are not strongly affected by the changes in the cone angle it is apparent that when they occur the cone angle is mainly small and fairly constant. Figure (4:31) and Figure (4:32) show 4-hr records of large amplitude Pc 4 pulsations (H component) with the period range 70-90 sec along with the simultaneous records (64 sec data) of the cone angle on day 337. The ground data were band-pass filtered, with the flat frequency response of the filter centred around the middle of the Pc 4 band (70 sec period). For the whole of the intervals the cone angle remains literally below 20°; there are data gaps in the cone angle in Figure (4:32). It is noted that there is a difference in period and signal strength among the stations, Figure (4:31) and Figure (4:32), probably due to latitudinal effect. Three stations at the higher latitudes (FA, SA, OL) have strong signals with periods of about 90 sec, whereas the stations at the lower latitudes (ES and CA) have comparatively weak signals with periods of about 60 sec.

The small cone angles correspond to strong energy in the pulsations activity as indicated by the dynamic spectrum shown in Figure (4:33). Power spectra for the dynamic spectrum were calculated at 20 mins intervals for a period of 4 hours, from 07.00 UT to 11.00 UT on day 337 at Faroe; the dynamic power spectrum is representative of the rest of the stations. Close examination of the diagram shows that while the cone angle remains consistently low, on the average < 20°,
there is a spread of high energy of the pulsation throughout the interval.

Table (4:6) summarizes the results described above. The general negative correlation between the energy of pulsations and the cone angle is clearly indicated by negative slopes \( (C_1) \) at the five stations and for all the three period bands (Pc 3, Pc 4 and Pc 3, 4). That the Pc 3 pulsations have better correlation with the cone angle than the Pc 4 is brought out clearly by generally higher linear correlation coefficient for the Pc 3 band than for the Pc 4 band. The Pc 3, 4 band shows intermediate (between the two extremes) correlation coefficient which is fairly constant among the stations. Another important feature revealed in the table is that the Pc 4 pulsations which have generally higher average energy level (E) are detected at each station when the average value of the cone angle \( (\Theta_{XB}) \) is less than that for the Pc 3 pulsations; that is for the Pc 4 pulsations, the average cone angle is about 30°; for the Pc 3 the average is \(~39°\). This result agrees well with the previous results shown in Figures (4:19) and (4:20) where the mean value of the medians is 28° for the Pc 4 and 36° for the Pc 3, at the five stations.

The results of the analysis of dependence of the pulsations activity on the cone angle will be summarized in Chapter 7 but it is prefaced here by noting that there is a strong negative correlation between the energy of ground pulsations and the IMF cone angle; the magnetic energy decreases as the cone angle increases. The Pc 3 band is more strongly related to the cone angle than the Pc 4 band. Oulu and St Anthony are good examples of showing the difference in effect of cone angle on the two frequency
TABLE (4.6): Summary of the cone angle effect on the pulsation energy

<table>
<thead>
<tr>
<th>STN</th>
<th>N</th>
<th>$\bar{\tilde{E}}_{XB}$</th>
<th>$\bar{E}$</th>
<th>$E = C_1 \tilde{E}_{XB} + C_0$</th>
<th>$C_1$</th>
<th>$C_0$</th>
<th>$R$</th>
<th>TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>FA</td>
<td>115</td>
<td>4.45±1.52</td>
<td>8.69±0.43</td>
<td>-0.15±0.02</td>
<td>15.31±1.08</td>
<td>0.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SA</td>
<td>114</td>
<td>39.03±1.53</td>
<td>10.79±0.40</td>
<td>-0.14±0.02</td>
<td>16.39±0.85</td>
<td>0.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OL</td>
<td>110</td>
<td>37.89±1.41</td>
<td>10.56±0.37</td>
<td>-0.14±0.02</td>
<td>15.96±0.86</td>
<td>0.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ES</td>
<td>18</td>
<td>37.46±1.0</td>
<td>8.65±1.43</td>
<td>-0.08±0.09</td>
<td>11.47±3.68</td>
<td>0.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CA</td>
<td>51</td>
<td>33.86±2.49</td>
<td>11.07±0.5</td>
<td>-0.10±0.02</td>
<td>14.57±0.95</td>
<td>0.51</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FA</td>
<td>117</td>
<td>35.62±1.61</td>
<td>15.77±0.75</td>
<td>-0.14±0.04</td>
<td>20.90±1.63</td>
<td>0.31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SA</td>
<td>68</td>
<td>36.72±2.17</td>
<td>14.59±0.98</td>
<td>-0.23±0.05</td>
<td>22.91±1.97</td>
<td>0.31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OL</td>
<td>84</td>
<td>30.43±1.72</td>
<td>19.03±0.81</td>
<td>-0.12±0.05</td>
<td>22.78±1.73</td>
<td>0.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ES</td>
<td>71</td>
<td>27.62±1.65</td>
<td>14.45±0.55</td>
<td>-0.15±0.04</td>
<td>18.65±1.10</td>
<td>0.46</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CA</td>
<td>46</td>
<td>23.58±1.33</td>
<td>11.76±0.46</td>
<td>-0.05±0.05</td>
<td>12.92±1.28</td>
<td>0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FA</td>
<td>232</td>
<td>39.89±1.14</td>
<td>12.31±0.49</td>
<td>-0.19±0.03</td>
<td>19.87±1.11</td>
<td>0.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SA</td>
<td>182</td>
<td>38.30±1.25</td>
<td>12.19±0.46</td>
<td>-0.19±0.02</td>
<td>19.28±0.99</td>
<td>0.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OL</td>
<td>194</td>
<td>34.61±1.12</td>
<td>14.23±0.50</td>
<td>-0.19±0.03</td>
<td>20.75±1.13</td>
<td>0.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ES</td>
<td>89</td>
<td>29.63±1.57</td>
<td>13.20±0.60</td>
<td>-0.17±0.04</td>
<td>18.24±1.17</td>
<td>0.46</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CA</td>
<td>97</td>
<td>29.25±1.55</td>
<td>11.35±0.34</td>
<td>-0.09±0.02</td>
<td>14.04±0.67</td>
<td>0.42</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
bands, see Figures (4:22a, b) and (4:23a, b). Whenever there are Pc 4 pulsations on the ground the cone angle is usually small ($\leq 20^\circ$) and constant.

Effect of IMF magnitude on the frequency of Pc 3, 4 pulsations

The relationship between the frequency of the ground pulsations and the IMF magnitude was tested. As before two separate bands of the ground magnetic activity, that is the Pc 3 and Pc 4 were considered. The frequency of the ground pulsations was determined from the peak of the power spectrum calculated for the 30-min intervals. 30-min values of the IMF magnitude (nT) were plotted against the frequencies of the pulsation activity for the five stations: the resulting scatter diagrams are shown in Figures (4:34-4:38). The horizontal dotted line across each scatter diagram marks the boundary between the Pc 3 and Pc 4, N is the number of data points. Then the same procedure of linear regression analysis already described in the previous sections was applied to these data.

The results generally indicate that the frequency of the ground pulsations increases with rise in the IMF magnitude. The frequencies of the Pc 3 band show strong dependence on the IMF magnitude, whereas for the Pc 4 band the dependence is considerably weaker. This general trend is common to all the five stations in the network, although individual stations show different degrees of the relationship. Specifically, St Anthony has a very high value of linear correlation coefficient ($R = 0.66$) for the Pc 3 pulsations; the high correlation coefficient establishes the best fitted line to be significant at the 99.9% confidence level, but the degree of scatter about the regression line is comparatively high, on the average SEE = 5.44 mHz, see Figure (4:35). The Pc 4 band at this station shows very little or no correlation at all with the IMF magnitude; the least square best fitted line is
Figure 4.34

(a) Pc 3
N = 126

F (millihertz) vs. B (nanotesla) with correlation coefficient R = 0.64

(b) Pc 4
N = 124

F (millihertz) vs. B (nanotesla) with correlation coefficient R = 0.13
FIGURE 4.35

(a) Pc 3
N=137
R=0.66

(b) Pc 4
N=68
R=0.01
**FIGURE 4:36**

(a) $P_c^3$

$N = 149$

$R = 0.35$

(b) $P_c^4$

$N = 85$

$R = 0.16$
(a) 

Pc 3  
N = 18  

R = 0.34  

(b) 

Pc 4  
N = 76  

R = 0.09  

FIGURE 4:37
almost horizontal, and the coefficient of linear
correlation is very little above zero, $R = 0.01$,
establishing the best fitted line to be not significant
at the 95% confidence level.

Detailed results for the rest of the stations can be
obtained from the summary given in terms of regression
lines in Figure (4:39) and in tabular form, Table (4:7).
The table also contains the results of the same analysis
performed on the combined Pc 3 and Pc 4 bands (Pc 3, 4).

Examination of the diagram for the regression lines
indicates that there are two distinct groups of the
regression lines, that is the 'inclined' regression lines
representing the Pc 3 band and the 'near horizontal'
regression lines representing the Pc 4 band. The table
indicates that the Pc 3 magnetic activity has generally
good correlation with the IMF magnitude at the five
ground stations; the slope ($C_1$) of the linear regression
line is fairly consistently about 3 mHz/nT among the
stations. The Pc 4 band has consistently flat but
positive slope $C_1 < 1$ mHz/nT at all five stations
considered here, implying that the Pc 4 pulsations have
poor correlation with the IMF magnitude. Combined Pc 3
and Pc 4 band (Pc 3, 4) has different feature from either
Pc 3 band or Pc 4 band taken separately: the slope of
the linear regression line for the Pc 3, 4 band varies
considerably from station to station. For instance
Cambridge has the highest value for the slope
($C_1 = 3.6$ mHz/nT) whereas Oulu has the lowest ($C_1 = 2.14$
mHz/nT). Similarly the intercept ($C_0$) is not consistent
among the stations as clearly indicated in the table.

It is to be noted that few Pc 3 events from Eskdalemuir
were available for analysis for the reasons that have
already been mentioned; so it is thought that the analysis
TABLE (4:7) Summary of the F-B relation of the Pc3, 4
pulsations on the ground

<table>
<thead>
<tr>
<th>Stn</th>
<th>N</th>
<th>(\overline{B})</th>
<th>(\overline{F})</th>
<th>(F = C_1 B + C_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(C_1)</td>
</tr>
<tr>
<td>CA</td>
<td>67</td>
<td>5.22±0.13</td>
<td>27.5±0.7</td>
<td>2.75±0.59</td>
</tr>
<tr>
<td>ES</td>
<td>18</td>
<td>5.65±0.28</td>
<td>29.8±2.7</td>
<td>3.31±2.21</td>
</tr>
<tr>
<td>FA</td>
<td>126</td>
<td>5.83±0.15</td>
<td>32.3±0.8</td>
<td>3.19±0.35</td>
</tr>
<tr>
<td>OL</td>
<td>149</td>
<td>5.43±0.10</td>
<td>33.0±0.6</td>
<td>2.18±0.49</td>
</tr>
<tr>
<td>SA</td>
<td>137</td>
<td>5.92±0.15</td>
<td>32.3±0.6</td>
<td>2.61±0.27</td>
</tr>
<tr>
<td>CA</td>
<td>52</td>
<td>4.27±0.13</td>
<td>16.1±0.4</td>
<td>0.14±0.49</td>
</tr>
<tr>
<td>ES</td>
<td>76</td>
<td>4.36±0.13</td>
<td>14.4±0.4</td>
<td>0.33±0.40</td>
</tr>
<tr>
<td>FA</td>
<td>124</td>
<td>4.91±0.13</td>
<td>14.3±0.4</td>
<td>0.43±0.27</td>
</tr>
<tr>
<td>OL</td>
<td>85</td>
<td>4.96±0.19</td>
<td>13.6±0.5</td>
<td>0.40±0.26</td>
</tr>
<tr>
<td>SA</td>
<td>68</td>
<td>5.19±0.22</td>
<td>15.5±0.6</td>
<td>0.10±0.31</td>
</tr>
<tr>
<td>CA</td>
<td>119</td>
<td>4.80±0.10</td>
<td>22.5±0.7</td>
<td>3.60±0.52</td>
</tr>
<tr>
<td>ES</td>
<td>94</td>
<td>4.60±0.13</td>
<td>17.4±0.9</td>
<td>2.82±0.66</td>
</tr>
<tr>
<td>FA</td>
<td>250</td>
<td>5.38±0.10</td>
<td>23.4±0.7</td>
<td>3.46±0.38</td>
</tr>
<tr>
<td>OL</td>
<td>234</td>
<td>5.26±0.10</td>
<td>26.0±0.8</td>
<td>2.14±0.49</td>
</tr>
<tr>
<td>SA</td>
<td>205</td>
<td>5.68±0.13</td>
<td>26.7±0.7</td>
<td>2.49±0.35</td>
</tr>
</tbody>
</table>
of only 17 events might have jeopardized the statistical results for the Pc 3 band at this station. Nevertheless, the station still displays the general trend of the frequency dependence on the IMF magnitude as shown in Figure (4:37). If there is a good correlation between IMF magnitude and frequency of pulsation, even the few events should show this anyway.

Further investigation was made on the effect of the IMF magnitude on the Pc 3 band only, by forcing the least square best fitted line through zero origin. The regression line passing through origin is defined by \( F = CB \), the constant \( C \) gives the slope of the F-B dependence. The Pc 3 band was chosen for the examination because the results described above indicate that the relationship between the IMF magnitude and the frequency of pulsations in the Pc 3 band is promising. The following relations were derived for the five stations: \( F = 5.36 \pm 0.40 \) B (Faroe); \( F = 5.25 \pm 0.35 \) B (St Anthony); \( F = 5.90 \pm 0.58 \) B (Oulu); \( F = 5.20 \pm 2.29 \) B (Eskdalemuir); and \( F = 5.16 \pm 0.67 \) B (Cambridge). The least square best fitted lines representing above functional relation are shown in Figure (4:40) along with the empirical relation, \( T = 160/B \), or \( F = 6.25 \) B of Gul'elmi et al. (1973). The lines for all the stations certainly indicate a clear frequency dependence on the IMF magnitude and are fairly close to the empirically established relation at least when the regression lines are forced through origin.

However, forcing the regression line through origin is not statistically good fit to the data. To illustrate this, the results of the regression analysis for the Pc 3 expressed in the form of \( F = C_0 + C_1B \) in Table (4:7) were compared with the results obtained by forcing the regression lines through origin (ie \( F = CB \)), see Table (4:8).
Table (4:8)  Pc3 Regression results

<table>
<thead>
<tr>
<th>Data</th>
<th>N</th>
<th>$\overline{B}$</th>
<th>$\overline{F}$</th>
<th>$F = CB$</th>
<th>$F = C_0 + C_1B$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>FA</td>
<td>126</td>
<td>5.83 ± 0.15</td>
<td>32.3 ± 0.8</td>
<td>5.36 ± 0.40</td>
<td>7.74</td>
</tr>
<tr>
<td>SA</td>
<td>137</td>
<td>5.92 ± 0.15</td>
<td>32.3 ± 0.6</td>
<td>5.25 ± 0.35</td>
<td>7.16</td>
</tr>
<tr>
<td>OL</td>
<td>147</td>
<td>5.43 ± 0.10</td>
<td>33.0 ± 0.6</td>
<td>5.9 ± 0.58</td>
<td>8.68</td>
</tr>
<tr>
<td>ES</td>
<td>18</td>
<td>5.65 ± 0.28</td>
<td>29.8 ± 2.7</td>
<td>5.2 ± 2.29</td>
<td>11.25</td>
</tr>
<tr>
<td>CA</td>
<td>67</td>
<td>5.22 ± 0.13</td>
<td>27.5 ± 0.7</td>
<td>5.16 ± 0.67</td>
<td>5.96</td>
</tr>
</tbody>
</table>
A measure of the statistically good fit to the data is chosen to be the standard error of estimate (SEE) of the regression lines, (the SEE has been described previously as a measure of degree of scatter).

A critical look at Table (4:8) reveals that the regression lines of the form $F = C_0 + C_1 B$ have less SEE than those of the lines $F = CB$. The ES data are rather unusual and may be considered unreliable in this respect probably because of small number of degrees of freedom. It is implied that the form $F = C_0 + C_1 B$ is statistically better fit to the data than the form $F = CB$, we shall return to this for further discussion in Chapter 7.

**Simultaneous Pc 3 and Pc 3,4**

The exercise described in the preceding paragraphs considers any Pc 3,4 pulsations activity regardless of whether the event is seen at only one station or simultaneously at, at least, two stations in the network of five stations. Now the simultaneous events at station - pairs in the E-W and N-S profile are analysed. The simultaneous events were selected on the basis of coincidence in their frequencies within $\pm 10\%$ error. The justification of this selection is that if the IMF does determine the frequency of magnetospheric pulsations it is expected, from geometry, that it is a wide source in longitude and therefore the stations with large longitudinal separation ($> 2$ hrs) would see the same frequency of pulsations. In the E-W profile the following pairs were considered, Oulu and St Anthony separated by approximately 6 hrs; Faroe and St Anthony separated by $\sim 4$ hrs; Oulu and Faroe separated by $\sim 2$ hrs; (the local time difference between the stations are expressed to the nearest hour). In the N-S profile Faroe and Cambridge (separated by geographic latitude $\sim 10^\circ$) were considered.
It is noted that the events which were simultaneously recorded among the stations were largely Pc 3 pulsations; however, in the analysis, a few Pc 4 that were also recorded simultaneously at the station-pairs are included.

The results of the linear regression analysis show that there is a considerable improvement in the relationship between the frequency of the ground pulsations and the IMF magnitude when the same frequency is recorded simultaneously over a large distance separating the ground stations. The results for the Pc 3 and Pc 3,4 bands are summarized in Table (4:9). The first column of the table contains pairs of the stations that saw the same period of pulsations activity simultaneously; for example TSA = TOL means the same period measured at St Anthony and Oulu simultaneously; the second column of the table contains the distance of separation between the stations (in the pair) expressed in terms of local time in case of E-W profile and degrees latitudes in case of N-S profile; the rest of the columns contains the same statistical quantities that have already been described.

The least square best fitted lines for the simultaneous events are shown in the scatter diagrams in Figures (4:41-4:44). The top panel shows the Pc 3 data, and the bottom panel shows the Pc 3,4 data. The regression lines exhibit a convincing fit to the data suggesting that the F-B relation for the station pairs is better than that for the single stations.

The correlation coefficient is very high (R ≈ 0.8) particularly for the stations separated by more than two hours, local time. The improved relation is also indicated by a steep slope, on the average C₁ = 4.2 mHz/nT for the Pc 3 and C₁ = 4.8 mHz/nT for the Pc 3,4 band. Generally there is not much difference in the improved relationships for the case of Pc 3 and Pc 3,4 probably because the Pc 3 dominate in every case as noted above.
### TABLE 4:9  Regression results of simultaneous events

<table>
<thead>
<tr>
<th>DATA</th>
<th>SEPARATION</th>
<th>N</th>
<th>$\bar{B}$</th>
<th>$\bar{F}$</th>
<th>$F = CB$</th>
<th>$F = C_0 + C_1B$</th>
<th>TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{SA} = T_{OL}$</td>
<td>6 Hrs</td>
<td>19</td>
<td>$5.12 \pm 0.30$</td>
<td>$32.39 \pm 1.73$</td>
<td>6.23</td>
<td>4.95</td>
<td>4.65 $\pm$ 0.83</td>
</tr>
<tr>
<td>$T_{SA} = T_{FA}$</td>
<td>4 Hrs</td>
<td>24</td>
<td>$5.82 \pm 0.42$</td>
<td>$31.61 \pm 2.09$</td>
<td>5.28</td>
<td>6.85</td>
<td>3.97 $\pm$ 0.65</td>
</tr>
<tr>
<td>$T_{OL} = T_{FA}$</td>
<td>2 Hrs</td>
<td>42</td>
<td>$5.43 \pm 0.19$</td>
<td>$30.98 \pm 1.21$</td>
<td>5.65</td>
<td>5.26</td>
<td>4.69 $\pm$ 0.63</td>
</tr>
<tr>
<td>$T_{CA} = T_{FA}$</td>
<td>10° Lat</td>
<td>28</td>
<td>$4.89 \pm 0.18$</td>
<td>$26.66 \pm 0.90$</td>
<td>5.38</td>
<td>6.17</td>
<td>3.47 $\pm$ 0.78</td>
</tr>
<tr>
<td>$T_{SA} = T_{OL}$</td>
<td>6 Hrs</td>
<td>20</td>
<td>$4.99 \pm 0.31$</td>
<td>$31.66 \pm 1.80$</td>
<td>6.24</td>
<td>6.83</td>
<td>4.88 $\pm$ 0.75</td>
</tr>
<tr>
<td>$T_{SA} = T_{FA}$</td>
<td>4 Hrs</td>
<td>26</td>
<td>$5.57 \pm 0.42$</td>
<td>$30.03 \pm 2.22$</td>
<td>5.25</td>
<td>6.92</td>
<td>4.27 $\pm$ 0.62</td>
</tr>
<tr>
<td>$T_{FA} = T_{OL}$</td>
<td>2 Hrs</td>
<td>57</td>
<td>$5.22 \pm 0.16$</td>
<td>$26.11 \pm 1.43$</td>
<td>5.03</td>
<td>8.15</td>
<td>5.71 $\pm$ 0.87</td>
</tr>
<tr>
<td>$T_{CA} = T_{FA}$</td>
<td>10° Lat</td>
<td>35</td>
<td>$4.75 \pm 0.15$</td>
<td>$24.61 \pm 1.03$</td>
<td>5.15</td>
<td>6.62</td>
<td>$4.49 \pm 0.88$</td>
</tr>
</tbody>
</table>
(a) 

**Pc 3**

\[ R = 0.80 \]

(b) 

**Pc 3,4**

\[ R = 0.83 \]

**FIGURE 4:41**
FIGURE 4:42

(a) 
Pc 3
\[ R = 0.79 \]

\[ F \text{ (MILLIHERTZ)} \]

B (NANOTESLA)

(b) 
\[ T_{SA} = T_{FA} \]
Pc 3.4
\[ R = 0.82 \]
(a) \[ \text{Pc 3} \]
\[ R = 0.76 \]

(b) \[ T_{FA} = T_{OL} \]

\[ \text{Pc 3.4} \]
\[ R = 0.66 \]

FIGURE 4.43
FIGURE 4.44

(a) Pc 3
    \[ R = 0.65 \]

(b) T_{CA} = T_{FA}
    Pc 3.4
    \[ R = 0.66 \]
Looking at the Table (4:9) more closely, once again the regression lines of the form $C_0 + C_1B$ fit the data better than the form $F = CB$. This is judged from values of the standard error of estimates (SEE). Another point revealed by the table is that the SEE values for the simultaneous data are significantly lower than those for the single stations data, shown in Table (4:8).

The results for the simultaneous events, particularly the $T_{SA} = T_{OL}$ data ($F = (7.28 \pm 3.89) + (4.88 \pm 0.75)B$) compare quite well with the derived relationship by Gul'elmi and Bolshakova (1973) ($F = 11.8 + 5.1B$) also using the simultaneous records with coincident frequencies from a pair of stations - Borok and Petropavlovsk. This relationship was, as already mentioned, the original basis for the Borok B index. The relationship has been confirmed by Green et al. (1982) who used one year data from a pair of stations - Hartland and Borok to obtain $F = (10.1 \pm 1.5) + (5.16 \pm 0.21)B$.

The differences in the values of $C_1$ and $C_0$ obtained from the single stations data sets are significant at the 95% level for both $C_1$ and $C_0$. The differences in the values, between the data from the single stations and those from the station pairs are also significant at the 95% level; but the differences obtained from the station pairs themselves are not significant at the 95% level. The reason for these differences has been suggested by Green et al. to be the different distributions of pulsation frequencies for different data sets. Our five ground stations are spread both in longitude and latitude, so they should have different distributions of frequencies. [Such difference in frequencies distributions among various data sets is illustrated, for IMF data, in the next Chapter, Figure (5:25)].

Generally there is a large scatter in the F-B relation and it is reasonable to assume that there are pulsations (particularly the lower frequency pulsations) whose frequency does not depend upon the IMF magnitude. These pulsations
would tend to reduce the overall correlation of a single station data set. It is suggested, therefore, that the dependence of the frequency of pulsations on the IMF magnitude obtained from the use of coincidental frequencies at a pair of stations is the most reliable. The separation between the two stations, in longitude, should be preferably more than 4 hours local time.

It is, however, noted that the division of the Pc pulsations activity into the two separate frequency bands, the Pc3 and the Pc4 is artificial and is adopted merely to maintain consistency in the analysis. Assuming that the artificial boundaries defined by the Pc3 and the Pc4 do not exist and looking carefully at individual scatter diagrams Figures (4:34 - 4:38) there is no obvious evidence that the plots divide into two sections, and if there is such a division it is not clear where the boundary lies. The justification of the division is that the preliminary results reported by Odera and Stuart (1980) suggest that there is frequency dependence in the effects of the IMF parameters on the ground pulsations. One of the intentions in this chapter has been the investigation of the frequency dependence of the effects of the three major solar wind parameters ($\mathbf{V_{SW}}$, $\mathbf{\Theta_{XB}}$, $\mathbf{B}$) on the Pc pulsations activity on the ground. We use the higher frequency Pc activity defined by the Pc3 and the lower frequency activity defined by the Pc4.
CHAPTER 5
LOW FREQUENCY WAVES IN THE INTERPLANETARY MEDIUM

5:1 Introduction

Early satellite measurements, notably by Heppner et al. (1967) and Greenstadt et al. (1968) confirmed a suggestion by Axford (1966) that waves may be found in the interplanetary medium. Long period (20 - 100 sec) magnetic fluctuations were studied by Fairfield (1969) who showed that they were associated with the interplanetary magnetic field (IMF) connection to the Earth's bowshock. Fairfield identified the magnetic fluctuations as transverse Alfvén waves locally generated probably by a resonant wave particle interaction involving the 4-7 KeV protons which had been detected by Asbridge et al. (1968) in the solar wind upstream of the bowshock. The typical energy of quiet day solar wind protons is 300 – 800 eV.

Measurements of energies up to 20 KeV by Asbridge et al. and Scarf et al. (1970) revealed that a small fraction of the solar wind ions incident on the bowshock are reflected and accelerated there by process such as the one described by Sonnerup (1969) to energies approximately 3 KeV and emitted upstream along the IMF as suprathermal ions. The suprathermal particles are produced by collisionless acceleration mechanism at the bowshock or at other discontinuities within the magnetosheath, and it is plausible to interpret the waves which are observed in terms of some interactions of energetic ions flowing in the opposite direction to the solar wind with the solar wind itself. Ions of considerably higher energies were also observed in the upstream region. Lin et al. (1974) reported the nearly continuous presence of protons with energies in the range of 30 – 100 KeV on the field lines likely to be connected to the bowshock. It was suggested by Lin et al. that the 3 KeV protons and the long period waves noted above conspired, in a way left unspecified, to produce the more energetic protons.
Although Lin et al. (1974) reported that the upstream energetic protons spectrum cuts off sharply (in terms of energy level) at about 100 KeV, bursts of protons with energies between 100 KeV and 200 KeV are quite common in the upstream region (West and Buck, 1976).

Several theories describing the generation of upstream waves by processes involving the backstreaming ions have been proposed. For example Barnes (1970) proposed a model to account for the presence of transverse hydromagnetic waves far upstream of, but associated with, the Earth's bowshock. This model was based on the ion-cyclotron resonant instability associated with a stream of protons flowing upstream (along interplanetary magnetic field) from the bowshock: beam particles can interact strongly only with hydromagnetic waves whose frequency, as seen in the rest frame of the beam, has been Doppler shifted up to ion gyrofrequency. According to the model, a proton streaming velocity of two or three times the solar wind speed would efficiently generate hydromagnetic waves far upstream ~ 20 RE. Considering wave-particle momentum exchange (pitch angle scattering) as the wave-particle interaction that quenches the instability, Barnes derived the growth rate of unstable wave and predicted the wave amplitudes to be proportional to the product of beam density and its speed. He concluded that the observed magnetic fluctuations which are left circularly polarized in the spacecraft frame of reference, are actually right circularly polarized in the rest frame of the solar wind, and that they are magnetoacoustic waves propagating nearly parallel to the ambient magnetic field and so are essentially transverse waves.

Another theoretical model for generation of upstream hydromagnetic waves by reflected proton beams from the bowshock was proposed by Fredricks (1975). This model
assumes without proof that the reflection process is capable of producing some degree of gyrophase bunching of protons thus creating a disturbance that propagates with the beam as it streams back along IMF lines. This conjectured phase organization leads to production of driven hydromagnetic waves in the left hand mode. Fredricks predicted a wave amplitude which depends upon the group of protons assumed to be coherent in their gyromotion and on the beam velocity, temperature and the Alfvén Mach number. Furthermore he noted that the observed frequency and polarization depend upon Doppler shifting due to solar wind flow and that observed polarization could be either left hand or right hand depending upon the vector properties of the solar wind velocity and magnetic fields. In a sense Fredricks (1975) theory and Barnes (1970) theory are complementary since in the absence of any gyrophase organization of the reflected protons, the driven waves cannot exist and only an instability theory such as that of Barnes would explain the observation of upstream waves. The authors of these theories assumed that any reflected ions/protons would travel back along the IMF through the upstream region now called the foreshock region.

Upstream wave phenomena are associated with the IMF connection to the bowshock. The upstream region where the waves occur has a sunward boundary whose location is critically dependent upon the orientation of IMF. The location of the boundary defines the foreshock region. It is consistent with disturbance propagating along the magnetic field direction with a velocity of $\sim 2.7 V_{SW}$ while being convected away from the Sun at the solar wind speed ($V_{SW}$). Sunward of this boundary waves do not occur, even for the field lines that connect to the bowshock. The geometry that fits the description cited here is shown schematically in Figure (5:1) (adapted from Rodríguez, 1981) for an upstream magnetic field oriented in Parker's spiral angle (typically $45^\circ$ to X-ecliptic axis). The
REGION OF LOW FREQUENCY WAVES

INTERPLANETARY MAGNETIC FIELD $\mathbf{B}$

Foreshock Region; Schematic

FIGURE 5:1
vector sum of the disturbance velocity and the solar wind velocity determines the location of the boundary indicated by Q, behind which energetic protons and electrons occur. The boundary denoted by P is nearly coincident with the first magnetic field line to connect with the bowshock and marks the upstream boundary for energetic electrons. The typical value of $V_P \sim 2.5 - 3 V_{SW}$ is consistent with upstreaming 4 to 7 KeV protons.

The figure shows that the boundary for energetic electrons, labelled P extends further sunward than the boundary for energetic protons, labelled Q. One important implication of this geometry described by Figure (5:1) is that the whole connected surface of the bowshock to the foreshock regions can emit energetic electrons and protons. The regions for the electrons and protons overlap with both energetic electrons and protons found behind the boundaries Q and only energetic electrons in the region bounded by P and Q. Sunward of the boundary P, the solar wind is undisturbed by the shock.

Further theoretical treatment of waves generated in the foreshock region was given by Kovner et al. (1976) on a slightly different basic formation from the one used in the two models already mentioned above. Unlike Barnes (1970) and Fredricks (1975) who both considered the condition for cyclotron instability of the system consisting of solar wind plasma and a flux of protons accelerated by reflection at the bowshock, Kovner et al. (1976) considered the instability of a system involving the solar wind plasma and protons accelerated in the magnetosheath, some of which cross the bowshock into the foreshock region. Earlier Kovner (1974) had studied acceleration of the solar wind protons in the magnetosheath and showed that the distribution function of particles accelerated there and returning from the bowshock to the solar wind agreed
satisfactorily with the experimental data of Fairfield (1969).

According to Kovner's theory the generated waves are righthand polarized in the rest frame of solar wind, but left hand polarized as seen in the Earth's frame of reference. Kovner showed that the growth rate of the waves in the solar wind is maximal when the angle ($\theta$) between the direction of IMF and the bowshock front is not equal to 90° and that although the waves can be generated in a large frequency range the spectrum of more stable oscillations with large amplitudes depends upon the ions gyrofrequency in consistent with the relation $T = 160/B$. Furthermore the work indicated that the growth rate of the perturbation increases with the growth of solar wind velocity whereas the influence of IMF magnitude on the amplitudes of generated waves is not significant. The positive growth rate for the waves was shown to be possible for the waves travelling towards the Earth in the reference frame of the Earth.

The high sensitivity and time resolution of plasma and field instrumentation aboard the ISEE 1 and 2 satellites revitalised interest in upstream waves and their association with the energetic ions backstreaming from the bowshock against the solar windflow direction. Many more new results have been produced from the ISEE data. For example, two distinctly different populations of upstream ions at energies between 1 KeV and 40 KeV have been reported by Gosling et al. (1978) who referred to them as 'reflected' and 'diffuse' ions. These two tend to be mutually exclusive. The reflected ions are distinguished by their sharply peaked energy spectrum which seldom extends much above ~ 10 KeV/ion and relatively collimated flow coming from the direction of the bowshock, i.e. they form a beam directed outwards from the shock along interplanetary field
lines. The diffuse ions, on the other hand, are characterized by their relatively flat energy spectrum and broad angular distribution. They are the most commonly observed upstream ion events. Paschmann et al. (1981) studied the characteristics of the two ion populations in greater details and added that at times transitions between the two extremes represented by the reflected and diffuse ions exists. This was referred to as an 'intermediate' ion population. The three types occur at different angles ($\theta_{BN}$) between the local shock normal and the interplanetary magnetic field. Earlier Paschmann et al. (1980) had shown that the energies of reflected ion beams are in good agreement with ion energies predicted by a model in which energization occurs because the ions are displaced parallel to the interplanetary electric field as they are reflected from the bowshock. Further description of the three types of ion distribution was given quantitatively by statistical method described by Bonifazi and Moreno (1981).

The occurrence of the three established types of ion populations correlate well with different modes of upstream waves. Reflected ions are observed in conjunction with small amplitude magnetic fluctuations at frequencies near 1 Hz (Hoppe et al. 1981). Sometimes these fluctuations are observed superposed upon low frequency waves when intermediate ions are present. Diffuse ions are observed in conjunction with large amplitudes of low frequency fluctuations in the field magnitude and plasma density with periods (in the spacecraft frame) of 10 - 60 sec (Paschmann et al. 1979). A strong correlation exists between these fluctuations and the diffuse ions and it has been noted by Sentman et al. (1981) that for typical diffuse ion energies the field fluctuations and particles are in near cyclotron resonance.
The results summarised above together with many more detailed conclusions have clarified the association of observed energetic ions in the solar wind with the upstream waves. Most of the research which has been done on this subject until now has been based on small numbers or even single short duration events and although the work has been effective in advancing understanding of the problems involved it may not be representative of the general morphology of the waves in the foreshock regions. The large amount of high time resolution data available from the ISEE-2 spacecraft is ideal for studying the morphology of upstream waves, thus broadening the base for future interpretation. This chapter summarizes such a morphological study. The waves in the IMF will be referred to as low-frequency waves in the solar wind or simply pulsations in the interplanetary medium/solar wind. Their study is conducted in such a way as to expose the possibility of IMF waves being responsible for at least some of the Pc 3, 4 observed on the surface of the Earth.

5:2 Interplanetary magnetic field data selection and processing

5:2-1 Introduction

The satellite data used in this work were obtained from UCLA fluxgate magnetometers aboard the ISEE-2 spacecraft. The magnetic field experiments and the instrumentation system has been outlined in section 4:2-2. The 4-sec data were used in this study; covering the period from 22 October, 1977 to 31 December, 1977. This interval covered the first 30 orbits of the ISEE-2 satellite; the apogee of the orbits was in the interplanetary medium and in the morning sector most of the time, see Figure (4:4).
Selection procedure

Before the selection of wave events in the interplanetary medium was done the raw data (4 sec) were edited in two stages using computer programmes. The first stage involved removing large and artificial spikes contained in the raw data. The second stage was the removal of times when the spacecraft was not in the interplanetary medium (i.e., the bowshock region, magnetosheath and within the magnetopause). Average positions of the boundaries such as the bowshock and the magnetopause were assumed for selecting data which were in the interplanetary medium in the day-side of the Earth's bowshock. Satellite position was verified by visual inspection of the 64 sec data from which it was possible to identify the interplanetary medium and the encounters of the bowshock and the magnetopause.

The magnetic field is fairly undisturbed in the interplanetary medium. The magnetic signature of the position of the bowshock encounter is an abrupt increase in the total field (B). In the magnetosheath which is the transitional region between the interplanetary medium and the magnetosphere and bounded by the bowshock and the magnetopause, the magnetic field is disturbed and exhibits large amplitude fluctuations. The magnetopause crossing is signified by a sharp jump in the total field. The increase of the total field at the magnetopause crossing is well defined and takes place at higher field magnitude than that at the bowshock crossing.

A typical feature of the magnetic field in the interplanetary space is shown on day 313 in Figure (5:2). An occasion of the bowshock and the magnetopause crossing is shown on day 316 in Figure (5:3). Satellite positions in geocentric solar magnetospheric (GSM)
FIGURE 5:2
FIGURE 5:3
FIGURE 5:4
coordinates are shown every two hours by numbers on top of the panel. The GSM system, as with the GSE system, has its x-axis positive from the Earth to the Sun. The y-axis is defined to be perpendicular to the Earth's magnetic dipole so that the x-z plane contains the dipole axis. The positive z-axis is chosen to be in the same sense as the northern magnetic pole. The difference between the GSM and the GSE is simply a rotation about the x-axis, see Figure (5.4). The x-axis in both of these orthogonal systems is formed by the Earth-Sun line (ecliptic x-axis). The solar ecliptic Z_gse axis is normal to the plane of the ecliptic and the orbital motion of the Earth is along the -Y_gse direction. The YZ planes in both systems are coincident; the solar magnetospheric Z_GSM axis is formed by projecting the geomagnetic dipole axis into the YZ plane.

On day 313 the satellite is in the interplanetary medium the whole day. Artificial spikes are seen clearly on the plot. On day 316 there is a bowshock crossing at a few minutes before 20.00 UT and a magnetopause crossing at around 23.00 UT; the crossings are marked by arrows in the diagram.

The selection procedure for the wave events in the interplanetary medium was as follows. The edited 4 sec data were plotted at a time scale of 3mm/min, thus enabling the shortest possible period events (~10 sec) to be clearly identified. Plots of approximately 800 hours of data were produced. The absence or presence of wave events was then determined by visual inspection.
Results

Classification of waves in the IMF

From the visual examination of 800 hours of IMF data three classes of the waves were identified.

(i) Waves which were fairly regular in form and almost monochromatic, persisting for up to or more than one hour. These waves are referred to as Pc-like pulsations. They occurred in about 116 hours of recording.

(ii) Quasi-periodic oscillations distinguished by mixed-period signals which often last for several hours. These waves were the most commonly observed ones in the interplanetary medium. There were ~ 200 hours of these waves.

(iii) Irregular oscillations with relatively short duration (about 10 minutes) which usually occurred in a generally quiet IMF background. The wave structure within each packet may be monochromatic or have mixed periods. These wave forms are referred to as discrete wave 'bundles'. These waves would be described better as discrete wave packets; but Russell et al. (1971) and Hoppe and Russell (1980) have already used the expression discrete wave packets to describe entirely different IMF wave phenomena from those reported here and so we adopt 'bundle' to avoid confusion.

Figures (5:5a) and (5:5b) show examples (day 325 and 337 respectively) of the Pc-like pulsations observed in the solar wind. Figure (5:6) shows an example (day 304) of the quasi-periodic and incoherent oscillations commonly observed just upstream of the Earth's bowshock. These fluctuations usually persist for several hours in the foreshock region although only a section of one hour activity is shown in the figure. Figures (5:7a) and (5:7b) show discrete wave bundles on day 328 and 306 respectively. The average positions of the ISkE-2 spacecraft during the
FIGURE 5:5
FIGURE 5.6
events shown above are indicated in Figure (5:8). The encircled numbers mark the positions of the spacecraft for the events shown in Figures (5:5 to 5:7) which are also marked with the corresponding numbers. The average IMF direction in the equatorial plane for each event is shown by the arrow through the spacecraft position. Average positions in the X-Y plane were determined from hourly value of the 64 sec X and Y components of the GSE coordinate system. The average IMF direction was determined in a similar way.

It is noted that within one hour, both IMF direction and spacecraft positions can change considerably thus the average values represent approximate position of the satellite. Even using the average positions and IMF directions it can be seen that the field line connects the spacecraft to the bowshock for all cases of the five events. These examples illustrate the range of variation in wave form which the low frequency fluctuations in the solar wind exhibit. It is clear in the illustrations that the transverse components of the waves are more pronounced than the compressional components, a feature which is generally true of the IMF waves. The transverse feature of the IMF waves will be discussed in Chapter 7.

Period and amplitude of waves in the IMF

In the study of the properties of the waves, periods and amplitudes of all events were catalogued for the duration of the study, i.e. day 295-365, 1977. IMF oscillations were categorized as either continuous type events or irregular wave bundles. Continuous type events were considered to be those that met the following criteria.

(a) Continuous and fairly regular and monochromatic pulsations persisted for at least 10 minutes and at most for 30 minutes.
FIGURE 5:8
Continuous and quasi-periodic oscillations persisted for 10-30 minutes.

The amplitude of oscillations in (a) and (b) were sufficiently above the level of the background noise which was less than 1nT all the time.

In the maximum interval of each event (~ 30 mins) the variation of period of the waves did not change by more than 10%.

Waves with the following characteristics were categorized as irregular wave bundles.

(a) The waves were monochromatic or quasi-periodic oscillations lasting over three cycles.

(b) The amplitude of the wave bundles were sufficiently above the level of background noise.

(c) The wave bundles occurred clearly against a background of quiet interplanetary magnetic field activity.

Two continuous type events cover the two classes of waves, that is the Pc-like and the quasi-periodic oscillations. The continuous type events are distinguished as the continuous wave phenomena.

A total of 286 events of the continuous wave phenomena and 84 events of the discrete wave bundles were identified in the whole period of study. The average positions of the ISEE-2 satellite (projected on x-y ecliptic plane) when the continuous waves and the discrete wave bundles were observed are shown in Figure (5:9a) and Figure (5:9b) respectively. Examination of the two diagrams indicates that the two classes of waves are found at almost all local times in the morning sector of the foreshock region. The period range and the amplitude of enhanced components of the IMF oscillations from the 370 events were estimated by handscaling plots made at a time and amplitude scale of 3mm/min and 1.5mm/nT respectively. The period was estimated
ISEE-2 POSITIONS

(a) CONTINUOUS WAVES

(b) WAVE BUNDLES

FIGURE 5:9
by handscaling over a chosen number of cycles within the duration of each event. For continuous waves 10 cycles were usually chosen, and for the wave bundles a minimum of 5 cycles were counted. Results are presented for the continuous wave phenomena in Figure (5:10, a, b) and for the discrete wave bundles in Figure (5:11, a, b) as the percentage of frequency of occurrence of amplitude and period ranges. The dominant period band and amplitude range of the continuous wave phenomena are 30 - 40 sec. and 4 - 5 nT respectively. For the discrete wave bundles the period band of 25 - 35 sec dominates, and the amplitude range of 4 - 5 nT is also the most significant.

It is to be remembered that period determination was the more difficult operation particularly for the quasi-periodic oscillations than for the more monochromatic Pc-like oscillations. The period was estimated only for fluctuations which were clearly identifiable. Where there was any doubt no measurement was done. Under these conditions, the period range of the waves between 20 seconds and 80 seconds was recorded. However, it should be noted that the shorter periods (below 20 sec) are affected by the pre-processing of the high time resolution of satellite data. The longer period range (about 80 sec) is not biased in any way. The amplitudes of waves were found to vary from approximately 2nT to 10nT.

5:3-4 **Effect of IMF orientation**

Examinations of three components x, y and z of the IMF for the high resolution (4 sec) data in Figure (5:12) indicates that the y and z components are fluctuating with large amplitude about zero whereas x (or radial) component fluctuates well above zero. The radial or x-component of the IMF was used for comparison with the wave forms. We
FIGURE 5:10

(a) Amplitude (nT)


(b) Period (sec.)

**FIGURE 5.11**

(a) Frequency vs. Amplitude (nT) for OCT-DEC 1977

(b) Frequency vs. Period (sec) for OCT-DEC 1977
FIGURE 5:12
considered cases (a) when the waves were present in the solar wind and (b) when there were no waves in the solar wind in conjunction with the sunward and ant.sunward orientation of the IMF. Sunward or antisunward orientation depends on whether x-component was positive or negative. Table (5.1) summarizes the results of this analysis. It is evident the sunward orientation of the IMF is more favourable for the appearance of waves in the solar wind. Cases of no pulsations in the solar wind were more common (62%) when the IMF direction was antisunward.

According to established theory of generation of waves in the foreshock region only the orientation of IMF field line to the local bowshock normal should determine the generation of the waves. The normalcy does not depend on the sense of the field direction, towards or away from the Sun. Nevertheless, the results above show that a particular sense of IMF orientation is favoured for detection of the low frequency waves in the solar wind. A similar sense of IMF orientation had been found by Pjyasova-Bakounina et al. (1978) to be favourable for the upstream waves whose period (T) depended on the IMF magnitude (B).

A detailed and more specific effect of the IMF orientation was examined using the IMF cone angle described in Chapter 4. The average values of the cone angle (θXB) were computed for the exact duration of each wave event (the maximum duration of a continuous wave event was chosen to be 30 min); only the continuous wave phenomena (286 events) were considered in this exercise. The standard deviation of the resulting cone angles was sufficiently small to lend confidence to their interpretation. The results of the investigation into the
TABLE 5:1 Statistics of Sunward/Antisunward IMF in relation to the presence of pulsations in the interplanetary medium

**Pulsations Present**

<table>
<thead>
<tr>
<th>IMF Orientation</th>
<th>No. of Events</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunward</td>
<td>209</td>
<td>68.5</td>
</tr>
<tr>
<td>Anti-Sunward</td>
<td>96</td>
<td>31.5</td>
</tr>
</tbody>
</table>

**No Pulsations**

<table>
<thead>
<tr>
<th>IMF Orientation</th>
<th>No. of Events</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunward</td>
<td>150</td>
<td>37.8</td>
</tr>
<tr>
<td>Anti-Sunward</td>
<td>247</td>
<td>62.2</td>
</tr>
</tbody>
</table>
cone angle effect on the presence of waves in the solar wind is shown in Figure (5:13). The radius of each shaded 15° sector represents the number of events in that sector. It is noticeable that most events were detected when the cone angle was 30° - 45°, and hardly any event occurred when the cone angle was 60° - 90°. There seems to be some evidence for a cut-off at a cone angle of 45° - 60°.

It is noted that the IMF cone angle orientation when the upstream waves are present is not just the natural orientation (i.e., the IMF cone angle orientation in the whole period of study regardless of whether there are upstream waves or not). The distribution pattern of the natural IMF cone angle is inserted at the top left hand side of Figure (5:13). It is clearly noticeable that the natural IMF orientation as presented by the cone angle distribution pattern is very different from the IMF orientation which favours observation of upstream waves: the peak of the distribution of the natural IMF orientation is at 50° - 60°, whereas the peak of the cone angle distribution is at 30° - 45° when the upstream waves are observed.

Figures (5:14 - 5:17) illustrate the cone angle effect for single events on four different days (308, 325, 335, 359). The four day-events were chosen to represent the varying amplitudes and waves forms exhibited by the low frequency pulsations in the interplanetary medium. Day 325 represents the regular and almost monochromatic Pc-like waves; day 308 represents the quasi-periodic oscillations; and days 335 and 359, both represent the wave forms in between the quasi-periodic oscillations and the Pc-like waves.
FIGURE 5:13
On day 325 (12.00 - 14.00 UT) Figure (5:114) there are continuous and almost monochromatic Pc like pulsations from the beginning of the interval until about 12.55 UT after which the activity 'switches off' and remains quiet for the rest of the time interval. Correspondingly, the cone angle remains relatively small (about 30°) from 12.00 UT to 12.55 when it begins to rise up to more than 60° and remains at relatively high level, although fluctuating considerably during the rest of the interval.

Day 308 (03.00 - 05.00) Figure (5:15) is a little more complicated and gives a remarkable picture of 'switch off' and 'switch on' of the waves in sympathy with rise and fall of the IMF cone angle. There is a distinct 'hump' in the cone angle corresponding to the interval of no waves superposed between the intervals of active pulsations. More pointedly, there are quasi-periodic oscillations from the beginning of the time interval up to about 03.40 UT, after which the pulsations disappear (switch off) and remain absent till about 04.28 UT, Thereafter the pulsations re-appear (switch on) and continue for the rest of the time interval. Correspondingly the cone angle remains essentially below 40° from 03.00 UT to 03.40 UT. After 03.40 UT the cone angle rises considerably to about 80° and remains there till about 04.28 UT when it dramatically falls to about 20° and on the average, remains there for the rest of the interval; the cone angle configuration, resembles a hump. This configuration has a very convincing one-to-one correlation with appearance and disappearance of waves in the interplanetary medium.
Day 359 (00.00 - 01.00 UT), Figure (5:16), and day 335 (05.00 - 07.00 UT), Figure (5:17) amplify what has been described above and illustrate the various time scales at which the cone angle can be effective. Day 359 (00.00 - 01.00 UT) shows a short period (about 7 minutes), at the beginning of the interval, when there are no pulsations, followed by a relatively longer period (about 53 minutes) with pulsations activity; the cone angle varies in sympathy. Day 335 (05.00 - 07.00 UT) shows one hour of no pulsations at all followed by another hour with pulsations activity; once again the cone angle varies in sympathy.

The main points illustrated in this section indicate that there is a good correlation between the IMF cone angle ($\theta_{xB}$) and the pulsations activity in the interplanetary medium. Most of the low frequency waves are observed when the cone angle is between $15^\circ$ and $45^\circ$. The amplitudes of the waves are modulated by changes that occur in the cone angle. The continuous and stable oscillations occur when the cone angle is generally below $45^\circ$. The amplitudes of the oscillations decay when the cone angle increases and rise when the cone angle decreases. The 'switch off' (cut off) and the 'switch on' (appearance) of the amplitudes are coincident with the rise and fall in the cone angle.

Spectral character of the IMF waves

Relationships between the period of the waves and the magnitude of the interplanetary magnetic field was investigated. The period was determined as described previously. The average values of the IMF magnitude ($BnT$) were calculated, from the 4 sec data, for the duration corresponding to exact length of each wave event.
FIGURE 5:17
Figure (5:18) shows the average activity in thirteen period bands of the solar wind pulsations for different IMF magnitude ranges. The peak of the distribution of activity moves systematically to the left from the shorter period bands to the longer period bands up to ~ 50 sec, after which it remains approximately constant - a feature likely to be interpreted as an inverse proportion of the period (T sec) to the IMF magnitude (BnT). There is a spread of measured field magnitude corresponding to each period (T). The center of each period band was plotted against the peak of the IMF distribution and the plot was compared with the empirical relation, \( T = \frac{160}{B} \) established from ground pulsations by Gul'elmi et al. (1973), see Figure (5:19). Examination of the diagram indicates there is a reasonable fit between the plotted points and the superimposed curve \( T = \frac{160}{B} \); implying that the spectrum of the waves in the solar wind may follow the relation \( T = \frac{160}{B} \). This is examined below.

The frequency of occurrence of the measured periods was compared with that of the predicted periods calculated from the empirical relation \( T(\text{sec}) = \frac{160}{B(\text{nT})} \). The \( B(\text{nT}) \) was computed from the 4 sec data and averaged over an exact duration of the IMF wave event. It was found that the occurrence distributions for the measured and predicted periods are quite different.

The comparison is illustrated in Figure (5:20). The continuous and dashed lines are the frequency polygons corresponding to the measured and predicted periods, respectively.

Examination of the diagram indicates that the difference between the frequency occurrence of the measured periods and that of the predicted periods is considerable. The
FIGURE 5:19

\[ T = \frac{160}{B} \]
Figure 5:20
difference is illustrated more clearly by the curve in the top panel. The curve is drawn from arbitrary numbers that are in proportion to the difference between the two distributions curves (the frequency polygons) at different periods: the positive numbers indicate the extent of the distribution curve for the predicted periods above that of the measured ones; the negative numbers indicate the extent of the distribution curve for the predicted periods below that of the measured ones; zero means no difference between the two distribution curves.

For \( T < 30 \text{ sec} \) the frequency of occurrence of the predicted periods is above that of the measured periods. There is a change at period \( T = 30 \text{ sec} \); for \( T > 30 \text{ sec} \) the frequency of occurrence of the predicted periods is below that of the measured ones. The small differences at the period range \( 80 > T > 55 \text{ sec} \) mean that a few data in this range were available, see Figure (5:10b) and that there are always fewer IMF records for the range \( 1.5 B < 3nT \) as is already shown in the previous Chapter, Figure (4:8b).

It is to be remembered that Vero (1980) has reported a change at \( T = 30 \text{ sec} \) in connection with effects of solar wind parameters on the ground pulsations. Perhaps Vero's change is related to the one above, but it is not possible to specify the relations because of lack of relevant data.

The relation of the measured period of the IMF waves with the empirically established period \( T = 160/B \) was further examined by using only those events which were thought to have periods very nearly the predicted periods according to the empirical relation. The continuous
wave events whose periods corresponded to the predicted period \( T_{pr} = 160/B \) within \( \pm 10\% \) errors were selected. There were only 42 events (~15\% of the continuous wave events observed in the interplanetary medium) that fitted the selection criterion. The periods of the selected events were re-measured, the differences between the initial measurements and the second readings of the periods gave an indication of errors in measuring the periods. The second readings were also within the \( \pm 10\% \) errors. Figure (5:21) shows the plot of the measured period \( T_{(sat)} \) versus the predicted period \( T_{pr} \).

It is clearly noticeable in Figure (5:21) that the relationship between the satellite period \( T_{(sat)} \) and the predicted period \( T_{pr} \) is linear when \( T > 30 \text{ sec} \), although a straight line representing the data does not pass through origin. For \( T < 30 \text{ sec} \) the relationship is non-linear. The picture presented shows that the data do not fit the \( T = 160/B \) relation very well and that the straight line representing the data hardly passes through origin.

It is not sufficient to judge the actual relationship of the period of waves in the solar wind with the IMF magnitude from such a small percentage of the total events as presented in Figure (5:21). Moreover, the presentation cannot be precise because the assumption that \( 160/B \) relation exists (in the solar wind) is made first before it is actually determined.

To try and establish the precise relationship between the waves in the solar wind and the IMF magnitude the regression and correlation analysis was used. Before performing the analysis the wave events were divided into three overlapping groups (A, B and C). The division was made on the basis of visual judgement
Predicted Period ($T_{pr}$) in seconds

**FIGURE 5.21**

Measured Period ($T_{sat}$) in seconds

Predicted Period ($T_{pr}$) in seconds
of the quality of the event in terms of uniformity in the wave-form. Group (A) consists of the best examples of very regular and almost monochromatic waves whose periods could be determined most accurately; there are 30 events in this group. Group (B) consists of the waves whose wave-form is 'intermediate' between monochromatic and quasi-periodic oscillations plus the waves in group (A); the period of the intermediate waves could be measured with small errors. There are 86 events in group (B). Group (C) is common and consists of all the wave events (286), that is, it is made up of events from groups (A) and (B) plus the mixed frequency oscillations whose periods could be measured with large errors. Such grouping was necessary to examine the effect of accuracy in the measurements of period on the overall statistical results. For statistical calculations frequency $F$ (mHz) was used instead of period, as the dependent variable.

Scatter diagrams are shown for group (A) in Figure (5:22), for group (B) in Figure (5:23) and for group (C) in Figure (5:24). They indicate that generally there is a good correlation between the frequency of waves in the solar wind and the IMF magnitude, although there is considerable scatter of points. Assuming a linear relationship exists between the frequency of the waves and the IMF magnitude, a regression analysis was performed whereby the following quantities were determined; the least square best fitted line, the standard error of estimate (SEF) of the regression line as a quantitative measure of scatter, and the coefficient of linear correlation with its level of significance. The results of the statistical
FIGURE 5:22

$N = 30$

$R = 0.79$

$F (\text{MILLIHERTZ})$

$B (\text{NANOTESLA})$

$F = 5.22 \pm 0.59B$

$F = (11.75 \pm 2.69) + (3.27 \pm 0.47)B$
\[ F = 4.77 \pm 0.21B \]

\[ F = (12.25 \pm 0.98) + (2.73 \pm 0.17)B \]

FIGURE 5:24

C
N=286
R=0.69
calculations are described below.

**Group (A):** The regression line shown in the Figure (5:22) by the continuous line is

\[ F = (11.75 \pm 2.69) + (3.27 \pm 0.147)B; \]

the standard error of estimate of the best fitted line was 3.93 mHz. A very high positive correlation coefficient of 0.79 was found for the line, the coefficient of correlation is significant at the 99.9% confidence level for the number of data points used.

**Group (B):** The regression line (continuous line in Figure (5:23)) is

\[ F = (12.20 \pm 1.57) + (3.18 \pm 0.27)B. \]

The standard error of estimate of the regression line was found to be 4.22 mHz. A very high positive correlation coefficient of 0.80 was found for the line; the coefficient of correlation establishes the best fitted line to be significant at the 99.9% confidence level.

**Group (C):** The regression line for this group is shown in Figure (5:24) and is defined by

\[ F = (12.25 \pm 0.98) + (2.73 \pm 0.17)B, \]

the standard error of estimate of the regression line was found to be 5.15 mHz. A high positive coefficient of linear correlation of 0.69 was found; the coefficient of correlation establishes the best fitted line to be significant at the 99.9% confidence level for the number of data points used.

The statistical results described above are summarized in Table (5.2). The statistical quantities in the table are already familiar since similar quantities have been discussed on different occasions in Chapter 4; added to this table, are values of the standard error of estimate (SEE) of the regression lines. Examination of the table clearly
### TABLE (5:2) Summary of result of regression analysis

<table>
<thead>
<tr>
<th>Data</th>
<th>N</th>
<th>F (±SE)</th>
<th>B (±SE)</th>
<th>F = CB</th>
<th>F = C₀ + C₁B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>C (±SE)</td>
<td>SEE</td>
<td></td>
<td>C₁ (±SE)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C₀ (±SE)</td>
<td>SEE</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>30</td>
<td>30.0±1.2</td>
<td>5.58±0.29</td>
<td>5.22±0.59</td>
<td>3.27±0.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.00</td>
<td>11.8±2.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.93</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.79</td>
</tr>
<tr>
<td>B</td>
<td>86</td>
<td>29.0±0.8</td>
<td>5.60±0.33</td>
<td>4.98±0.33</td>
<td>3.18±0.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.46</td>
<td>12.2±1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.79</td>
</tr>
<tr>
<td>C</td>
<td>286</td>
<td>27.2±0.4</td>
<td>5.46±0.10</td>
<td>4.77±0.21</td>
<td>2.73±0.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.38</td>
<td>12.3±1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.69</td>
</tr>
</tbody>
</table>
indicates (as would be expected from the criterion adopted here for grouping the event) that the degree of scatter increases progressively from group (A) to group (C). Another feature noticeable in the table is that the slope \( C_1 \) decreases systematically from group (A) through group (B) to group (C) whereas the intercept \( C_0 \) varies only very slightly. The change of slope is not, however, statistically significant at the 95\% level.

The trend towards higher values of \( C_1 \) as the choice of the wave events becomes more selective is suggestive. It may reflect the change in distribution of frequencies of the data sets. These distributions, for the three groups, are shown in Figure (5:25). Increased selectivity results in a change to higher mean value of frequency. The change is, however, expected because the higher frequency wave events tend to be more sinusoidal in wave form. It is interesting to note that each of the three distributions of frequencies is different from the distribution exhibited by UCLA data (also shown in the figure). The difference in the frequency distribution of individual data sets may be a complicating factor that would indicate that the parameters of any derived relationship between the frequency and the IMF magnitude (the F-B relation) are strongly affected by the distributions of frequency in the data set.

It was suspected that the differences in slopes, intercepts and correlation coefficients between three groups were not statistically significant, so significance tests were performed to confirm this. To evaluate significant difference (to two standard deviation) of
Figure 5.25

- **Category C:**
  - N = 286

- **Category A:**
  - N = 30

- **Category B:**
  - N = 86

- **UCLA:**
  - N = 85

The histograms represent the percentage occurrence of events in different categories. The x-axis is labeled as f(mHz) and the y-axis as Percentage Occurrence.
the slopes and intercepts among the three groups
the principle of errors was used. The statistical
difference for the coefficient of linear correlation
was determined using Fisher's Z-transformation.
Results of the significance test are shown in Table
(5:3) where NS means no significant difference and
S means the significant difference was found. Table
(5:3) confirms that the differences were not
significant.

A general way of looking at the relationship
between the frequency of pulsations and the IMF magnitude
is by 'forcing' the regression line through zero origin.
The approach is based on the assumption that a direct
proportionality exists between the frequency of waves
and the IMF magnitude. The direct proportionality has
been indicated in the theory proposed by Gul'elmi (1974)
and developed by Kovner et al. (1976) who justified the
relation in the form of \( F = CB \) corresponding to a
functional relationship between the frequency \( F \) of
waves and the IMF magnitude \( B \) of the form \( F = CB \),
\( C \) is a constant relating to the slope of the function
\( F-B \) passing through zero:

The least square best fitted lines forced through
origin were derived for the three groups of wave events.
The results are summarized in Table (5:2). The least
square best fitted lines are shown by dashed lines in
Figure (5:22) for group (A), Figure (5:23) for group (B)
and Figure (5:24) for group (C). Significance tests on
the values of slopes shown in the table were performed
and it was found that there is no significant difference
between them, see Table (5:4).

Looking at the Table (5:2) more closely and remembering
that the criterion of goodness-of-fit adopted in this work
TABLE (5:3) Significance test of the slopes and intercepts of the regression lines for the F - B relation

Slope

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td>NS</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Intercept

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td>NS</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NS - not significant difference

Correlation Coefficient

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td>NS</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE (5:4) Significance test:
Regression lines forced through origin
Slope

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
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</thead>
<tbody>
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<td>NS</td>
<td>NS</td>
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<td></td>
<td>NS</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NS - No significant difference
is the standard error of estimate (SEE) the expression \( F = C_0 + C_1B \) is a better fit to the data than the \( F = CB \) (as indicated by SEE). It is already shown in section 4:3-6 of the previous chapter that this is true with the ground data also.

In summary it is emphasised that there is a spread of measured field magnitudes (B) corresponding to each period (T) see Figure (5:18). Thus rather than draw a single best fit curve through the data points in the Figures (5:22 - 5:24) it may be more correct to draw a band approximately 1.3 nT wide around the best fitting line to produce a true physical representation. In this situation the precise relationship between frequency of waves in the interplanetary medium and the IMF magnitude can be defined preferably by the least square regression line of the form

\[
F = C_0 + C_1B
\]

shown in Table (5:2), where \( C_1 \) is the slope and \( C_0 \) is the intercept. The intercept is significant statistically. A comparison between the IMF (ISEE-2) data set and the ground (Hartland-Borok, 1974) data sets of Stuart and Green (personal communication) indicates that the intercepts for the two data sets are quite comparable particularly when the same frequency of pulsations is seen over a large area on the ground (\( \sim 45^\circ \) longitude), whereas the slopes are considerably different. A similar comparison made with the ground data presented in the previous chapter, section 4:3-6 indicates that the intercepts for the two data sets are comparable. One important implication which is only mentioned here and will be discussed later in Chapter 7, is that the relation \( F = 6.25B \) or \( T = 160/B \) does not properly represent the spectrum of the waves in the interplanetary medium.
CHAPTER 6

CORRELATION OF GROUND AND SATELLITE PULSATIONS

6:1 Introduction

Early studies indicated that dayside Pc 3, 4 recorded on the surface of the Earth are influenced by the state of the interplanetary medium. Their periods were found to correlate with the magnitude of the interplanetary magnetic field. The correlations have been outlined in Chapter 3, section 3:1. In brief, Troitskaya et al. (1971) found the relation between the frequency of ground pulsations and the IMF magnitude to be \( F = 6.15B \). Later, authors derived similar functional relationships eg \( F = 6.25B \) or \( T = 160/B \) (Gul'elmi et al., 1973); \( F = 5.5B \) (Gul'elmi, 1974); \( F = 11.8 + 5.1B \) (Gul'elmi and Bolshakova, 1973). The last expression was used to define the Borok-B index, an hourly number designed to provide an indirect measure of the IMF magnitude from pulsation data. The reliability of the Borok index was tested by Russell and Fleming (1976) who showed that the index was only 27% successful but could be improved to be 54% successful when it was recalibrated. Recently Russell and Hoppe (1981) reported the relation between the frequency of waves in the solar wind and the IMF magnitude as \( F = 5.81B \). In Chapter 4 strong dependence of frequency of ground Pc 3 pulsations on the IMF magnitude is found and in Chapter 5 similar relationship is found for the low frequency waves detected aboard the ISEE-2 spacecraft.

The amplitude of the Pc 3, 4 pulsations on the ground was found to be related to the direction of the IMF, being largest when the IMF makes a small angle.
with the direction of flow of the solar wind (Bolshakova and Troitskaya, 1968; Greenstadt and Olson 1976). Webb and Orr (1976) showed some examples of occasions when the IMF is confined to the ecliptic plane in a radial direction for a long time. In these conditions magnetic activity in the band commonly associated with Pc 3, 4 type pulsations is turned on or off abruptly with each $180^\circ$ shift in the field direction. In an extension to this work, Webb et al. (1977) demonstrated that during these special cases the magnetic activity was enhanced over an azimuthal extent of approximately 5 hours in local time.

The amplitude of the pulsations also increases with the increasing solar wind velocity (Saito, 1964; Vero and Hollo, 1978; Singer et al., 1977; Greenstadt et al., 1979; Saito et al., 1979) and their energy spectra correlate well with the solar wind velocity and solar wind kinetic energy (Wolfe 1980, and Wolfe and Meloni, 1981, respectively).

Also in Chapter 4 it is demonstrated that the Pc activity has good correlation with the IMF cone angle and that the solar wind velocity has some influence on the energy of ground pulsations. An interesting speculation is that some Pc 3, 4 are waves that are originally generated in the solar wind and transmitted into the magnetosphere. The idea is encouraged by the fact that waves have been actually seen in the solar wind, see Chapter 5.

One of the early attempts to study the external origin of Pc 3, 4 pulsations was made by Greenstadt (1972) who showed that for small cone angle ($\theta_{XB}$) shock induced disturbances (now called the quasi-parallel structure) often found in the magnetosheath can be
convected to the magnetosphere by the solar wind flow
where they could produce the Pc 3, 4 pulsations
observed on the surface of the Earth. A more general
theory of the external origin of geomagnetic micro-
pulsations was given initially by Gul'elmi (1974).
His idea was based on an early report by Troitskaya
et al. (1971) that the period of pulsations observed
on the surface of the Earth was proportional to the
gyroperiod (Tp) of protons in the interplanetary
magnetic field, $T = (2.5 \pm 0.5) \, Tp$ and that the waves
discovered in the interplanetary medium had the same
property, namely they are waves that are locally generated
by a cyclotron resonant instability involving a beam
of backstreaming energetic protons reflected from
the bowshock. The waves, therefore, have their frequency
directly proportional to the protons gyrofrequency.
Gul'elmi estimated that the resonance frequency produced
by instability of reflected protons is the same as the
average frequency of the Pc 3 pulsations ($F \sim 30 \, \text{mHz}$).
He also showed that the process could have a large
coefficient of amplification. Important consequence
of Gul'elmi's theoretical consideration is that if the
ground pulsations spectrum was really formed in the
interplanetary medium, the carrier frequency must be
proportional to the magnitude of the interplanetary
magnetic field as follows

$$F = \frac{\Omega p \, V}{2 \, \pi (V+U)} \quad (4:1)$$

where $\Omega p$ is the proton gyrofrequency, $V$ is the solar
wind velocity and $U$ is the resonant velocity of protons
interacting with hydromagnetic waves. For $U = 1.6 \, V$
and for average solar wind conditions, the above expression
simplifies to

$$F_{(\text{mHz})} = 6 \, B_{nT} \quad (4:2)$$
Gul'elmi's idea was fundamental and formed a basis for a more rigorous theoretical treatment by Kovner et al. (1976). Kovner's theoretical consideration is so far the only one which has attempted to give a mathematical explanation of the association of the Pc 3, 4 pulsations with the low frequency waves seen in the interplanetary medium. Kovner's results are already outlined in Chapter 5, section 5:1. One of the important results was that the maximum growth rate of waves in the interplanetary medium occurs at a frequency \( w = 0.4 \Omega_p \) (for average parameters of the solar wind, \( V = 400 \) km/sec, \( N = 3 \) cm\(^{-3}\), \( B = 5 \) nT). This coincides with the relation \( T = (2.5 \pm 0.5) T_p \) which was obtained from ground experiment by Troitskaya et al. (1971). Using the average solar wind parameters Kovner et al. carried out a statistical comparison between theoretical and experimental results and showed that some parameters (e.g., amplitude, occurrence frequency and period) of some Pc 3, 4 observed on the ground agreed well with the quantities predicted by theory. The amplitude of Pc 3, 4 increased with rise in solar wind velocity, and the occurrence frequency of Pc 3, 4 activity depended on the angle between the direction of the interplanetary magnetic field and the normal to the bowshock. Varga (1980) numerically analysed some of Kovner's results and compared them with observations of Pc 3, 4 made on the ground at Nagycenk. He found that in geomagnetically quiet periods the frequency range of interplanetary waves derived from theory corresponds well with that measured on the ground.

Early experimental observations by Plyasova-Bakounina (1972) supported the idea that waves excited in the interplanetary medium may contribute to the spectrum of
Pc 3, 4 pulsations observed on the Earth's surface. She compared the occurrence frequency both of the Pc 2-4 activity on the ground at Borok and of pulsations in the interplanetary medium detected by Explorer 34 to the orientation of IMF. She found that the frequency of occurrence of the waves in space was similar to that of the Pc 2-4 on the ground. A direct comparison of the period of pulsations in the two media (ground and space) indicated good agreement between the periods of the Pc 2-4 pulsations and those pulsations observed simultaneously in the interplanetary medium, although there were only 13 simultaneous events and there was some scatter. Recently Plyasova-Bakounina et al. (1978) made a similar but more detailed study and reported that, when the IMF was directed away from the Sun the peak intensities in the dynamic spectrum of the pulsations at Borok and on a satellite HEOS-1 in the IMF occurred at remarkably similar periods with only a few exceptions. The time delays between the events as recorded at HEOS-1 and Borok were found to be comparable with that reported by Webb and Orr (1976). The time lag depended on the distance between the satellite and the bowshock in a way they thought was consistent with the established idea that the wave events recorded at the satellite are produced locally. They showed by statistical analysis that the pulsation period at Borok was consistently dependent on the IMF magnitude when the field was directed away from the Sun but they could not establish with confidence the same statistical results for sunward directed IMF. The authors, however, noted the difficulties involved in waves in the interplanetary medium propagating directly through the bowshock, magnetosheath and
magnetopause and again being observed within the magnetosphere or at the mid-latitude ground stations. As a consequence it was argued that the waves in the interplanetary medium and those on the ground are probably generated by two separate mechanisms which lead to similar wave spectra being generated in the two media. This idea was developed by Golikov et al. (1980) who offered a modified theoretical treatment of the Kelvin-Helmholtz instability at the magnetopause to explain the similarity of periods of pulsations on the ground and in the interplanetary medium. Golikov's formulation gives an important alternative view on the generation of ground pulsations which may be controlled by parameters of the interplanetary medium.

Golikov applied linear theory to show that the critical flow speed (in the context of the Kelvin-Helmholtz instability) necessary for generating surface waves at the magnetopause was largely dependent on the sum of two Alfvén speeds, one measured inside the magnetopause and another measured outside the magnetopause. He compared his theoretical results with $Pc$ 3, 4 data recorded at Borok during upstream wave events observed by the HEOS 1-2 satellites in the solar wind and demonstrated that the same periods of pulsations seen at the two locations occurred only when the solar wind speed was such that the local magnetosheath flow speed exceeded the sum of the Alfvén velocity just inside the magnetopause and the Alfvén velocity just outside. Using average solar wind parameters the characteristic frequency of surface waves generated by the modified model was estimated to be $\omega = 4 \times 10^{-2}$ $s^{-1}$, which corresponds to typical $Pc$ 3 pulsations on the ground. A direct proportionality was found between the frequency of the ground pulsations and
IMF magnitude, \((w \sim 10^{-3} \text{ B})\). This last result is again consistent with the empirical relation reported by Troitskaya et al. (1971). They speculated that the amplitude of the wave was dependent on the angle \((\psi)\) between the IMF and the flow direction of solar wind. It was concluded that the Kelvin-Helmholtz instability at the magnetopause was the mechanism by which pulsations which are controlled by the solar wind parameters are generated. The location of the source of some of these pulsations controlled by solar wind parameters is generally believed to be in the interplanetary medium and Golikov noted that his results were limited only to a special condition of IMF orientation (ie \(\psi = 0\)) and that more general application of his theory requires the critical condition for wave generation to be determined for \(\psi \neq 0\).

None of the theories and experiments mentioned above attempt to solve the transmission problem of waves from the interplanetary medium passing through the complex boundaries at the bowshock, magnetosheath and magnetopause to the Earth's surface. Moreover there is no experimental evidence to support the idea that the external processes and the internal processes produce waves simultaneously with identical spectra. In particular there has been no evidence of relatively monochromatic waves of 20 - 60 sec observed in satellites deep in the magnetosphere. It is also interesting to note that most of the observations which support a direct relationship between the waves in the solar wind and ground \(Pc_3, 4\) activity have been made from the mid-latitude stations Borok \((L = 2.8)\) and Nagycenc \((L = 1.8)\).

In the following sections comparison is made between waves in the solar wind and pulsations recorded at
midlatitude stations and at a subauroral station. Direct comparisons are made using a high latitude station, Oulu (L = 4.3) and a similar comparison is made using a midlatitude station, Cambridge (L = 2.4). The statistical comparisons are carried out between the periods of waves in the solar wind and those of pulsations measured at another midlatitude ground station, Nagycenk (L = 1.8).

6:2 Direct comparison

The low frequency waves recorded on board the ISEE-2 satellite described in Chapter 5 as continuous wave phenomena were compared with simultaneous ground records of the Pc 3, 4 pulsation events studied in Chapter 4. For the comparison only the Pc 3, 4 events which were recorded simultaneously by at least three stations in the network of five stations were used. These simultaneous Pc events were referred to as 'global'. The global events were chosen because the result presented in section 4:3-6 suggests that their relationship with the interplanetary parameters is better than events selected from only one station. The stations which are used were chosen because they had continuous good and relatively noise free magnetic records during most of the time of this study, and they had good Pc 3, 4 pulsations in terms of amplitude and continuity. In addition, Oulu being at L = 4.3 is suitable for testing the similarity between the solar wind pulsations and the Pc 3, 4 pulsations at higher latitude than Borok and Nagycenk where previous investigations have been made. Cambridge is on about the same L value as Borok and Nagycenk.

6:2-1 High latitude station

Power spectral estimates were performed on both
satellite and ground data sets using the maximum entropy method (MEM). MEM was developed by Burg (1967, 1968). The application of MEM spectral analysis to geophysics has been discussed by Ulrych and Bishop (1975). The MEM permits high frequency resolution in the spectral analysis, particularly for short data length. The resolving power of MEM depends on the percentage length for prediction error filter. Too short a length results in highly smoothed estimates, obviating the resolution advantage of MEM, whereas an excessive length introduces spurious details into the spectrum. Applying the MEM, successive five minute intervals were spectrally analysed giving resolution of wave packets of 10 min duration. Prediction error filters in the range of 10 - 40% (the percentage length for the prediction error filters) were used, this range gives the spectra which are clear and suitable for comparison. A sequence of spectra was presented as contour plot representing the dynamic spectrum. A low pass filter with a cut-off frequency of 100 mHz was used on the ground records before calculating the spectra to eliminate long period contamination and to make the overall spectra similar to those of the IMF waves. Although the estimation of the power spectral density was fairly coarse, the time resolution was sufficient to make reasonable comparison between the satellite data and the simultaneous ground records.

In Figure (6.1) the top panel is the dynamic spectrum for ISEE-2 and the bottom panel is the ground spectrum for day 337 covering the time interval 04.00 - 14.00 UT. Vertical lines in each panel represent hour marks. Start, finish and increment power spectral density contours (dB) along with the percentage of the
FIGURE 6:1
prediction error filter are shown in the top right
hand corner of each panel. Minimum and maximum frequencies
on the ordinate are 10 mHz and 70 mHz respectively,
the frequency resolution is 1 mHz (the same format
is displayed in all subsequent similar figures).
The satellite has good Pc events with the average
frequency of about 30 mHz at 04.00 - 07.30 UT. There is
a sharp 'switch-off' at 07.30 UT followed by a 'switch-
on' (at higher frequency, \( \sim 45 \) mHz) at 08.10 UT. This
'switch-on' at 08.10 UT is clear in the analogue record
which is shown in Figure (5:5b). At about 09.20 UT
the frequency returns back to its earlier value and
the signal gradually dies away from about 10.30 UT.

The average local time of the ISEE-2 satellite
during the time interval 04.00 - 14.00 UT is about 07.30
in the morning, the radial distance of the satellite
being \( \sim 22 \) RE. The average IMF magnitude during the
time interval is 4.1 nT giving a frequency predicted by
the empirical relation \( T = \frac{160}{B} \) of about 26 mHz.
The predicted frequency is lower than the average
frequency measured at the satellite.

The ground spectrum shows no correspondence to
that of the waves in the interplanetary medium. The
Pc activity is strong at much lower frequency and
continues throughout the interval with the frequency
which is not comparable to the predicted one. There
is very little Pc energy in the band-width of the
pulsations in the interplanetary medium and no clear
'switch on' or 'off' can be detected (of the analogue
record in Figure (6:7). There is not much difference
in local times between the ground station and the
satellite position. [The local time at Oulu is \( \sim 2 \) Hrs
ahead of UT].
The continuation of this events (14.00 - 24.00 UT) is shown in Figure (6:2). The average position of the satellite is now at about 08.00 local morning. The satellite pulsations 'switch-on' for two hours at about 17.15 UT with a frequency of about 25 mHz. The activity is either off or weakly irregular until about 21.50 UT when there is evidence of another 'switch-on'. Frequencies in the early patch are 15 - 40 mHz and in the later patch 20 - 50 mHz. The ground records show series of relatively short duration broad band bursts of pulsations followed by Pc 4 pulsations (10 - 20 mHz) from 16.00 UT until 18.30 UT. During the time of the second patch of enhanced pulsations in space a sequence of Pi 2s (~ 10 mHz) occurs in the ground record. These Pi 2s are indicated by arrows in Figure (6:2). There is no indication in the satellite records of any pulsations or of possible trigger which might be related to the Pi 2s seen on the ground (see analogue record in Figure (6:8)). The position of the ISEE-2 spacecraft labelled (2) in Figure (5:8) is ideal for relating to Pc 3 in the morning sector. It is reasonably well placed to detect any obvious IMF effect which might influence the flanks of the magnetosphere to trigger any likely Pi 2 generation mechanism there, (see Stuart and Macintosh, 1974).

Figure (6:3) shows both satellite and ground spectra for the time interval of 04.00 - 11.00 UT, on day 325. As before there is a complete disparity in spectra at the ISEE-2 spacecraft and on the ground station. In the interplanetary medium the pulsations activity is very sporadic with broad band high frequency oscillations. This is a good example of quasi-periodic oscillations in the space. On the ground the continuity
FIGURE 6:3

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mHz

OULU  D

UT
of pulsations activity is high, in a broad band frequency ranging from 10 mHz to 30 mHz.

In the time interval 12.00 - 19.00 UT on day 325 shown in Figure (6:4) the situation is slightly different. There is an outstanding 'switch off' of pulsations activity in the interplanetary medium, at just before 13.00 UT. Before the 'switch off' the activity is continuous with a narrow band of frequencies centered around 40 mHz. The spacecraft position labelled (1) in Figure (5:8) is at a radial distance ~ 22.6 RE; the local time of the spacecraft is about 08.30 morning. The IMF magnitude at this time interval is, on the average, 4.0 nT giving a predicted frequency (25 mHz) different from the centre of the band of frequency of the pulsations activity observed in space. Approximately 10 - 16 minutes after the 'switch off' at the satellite there is a distinct 'switch off' on the ground. The frequency of pulsations on the ground before the 'switch off' is about 25 mHz which is exactly the same as the predicted frequency. The analogue records and the variation of cone angle associated with the strong 'switch off' both on the ground and in space are discussed later with reference to Figure (6:9). The Pc activity a few hours after the 'switch off' is scanty both in space and on the ground. The satellite has wave packets just before 15.00 UT and around 16.00 UT which are not recorded clearly on the ground. Also while the signal at the satellite disappears at about 16.30 UT the ground station records a train of clear Pi 2s indicated by arrows between 18.00 UT and 19.00 UT.

The satellite and ground spectra for day 304 (10.00 - 19.00 UT) shown in Figure (6:5) is a further evidence of lack of correlation between the pulsations
FIGURE 6:5
activity in the two media. The satellite has no pulsation activity between 10.00 UT and 11.40 UT after which there is a 'switch on' of the activity with broad band pulsations in the frequency range 15 - 50 mHz. There is a 'switch off' at 14.00 UT followed by a sharp 'switch on' of activity with frequency of about 20 mHz at 14.45 UT. There is another 'switch off' at 16.30 UT and 'switch on' at 18.00 UT. The dominant frequency for the pulsations activity throughout the interval (10.00 - 19.00 UT) is in the range of 20 - 50 mHz. The IMF magnitude during the interval is in the range of 4 - 9 nT giving a range of predicted frequency comparable to that of the measured frequency of the pulsations activity in space. The ground station has strong Pc 4 (10 - 16 mHz) before and after the first 'switch on' on the spacecraft. The frequency of the activity on the ground is much lower than the predicted one and that of the pulsations in space. The activity shows no correspondence at all, both in frequency and onset, to the pulsations in the interplanetary medium. In addition the ground station recorded a train of Pi 2s (marked with arrows on the spectrum) starting at 17.20 UT which bears no relationship to the interplanetary pulsations. Note that for this interval the average position labelled 3 in Figure (5:8) of the ISEE-2 satellite was around the subsolar point, a position from where it is suitable for Greenstadt's quasi-parallel shock structures to reach the magnetosphere.

A more precise comparison was made directly between the instantaneous wave forms in the two media (ie in space and on the ground) using only 2 hour intervals. Figure (6:6) shows records for day 308 (10.00 - 12.00 UT).
with ISEE-2 data plotted in the top four traces and the H, D and Z components of the magnetic pulsations from the ground station in the bottom three. The ground magnetic field data were treated by removing a 62.5 sec (25 point) running average to attenuate long period magnetic fluctuations leaving a frequency range suitable for Pc 3, 4 fluctuations to compare with the observed bandwidth of the upstream field oscillations. The frequency response of the 62.5 running average is given in Appendix (A1). In Figure (6:6) no pulsations are seen on the spacecraft, whereas on the ground (in the bottom three traces) fairly coherent monochromatic Pc 3, 4 with amplitude reaching about 3 nT are recorded. The IMF magnitude is generally constant, and although there is a distinct change of direction of the IMF at 10.57 UT there is no evidence of any effect on the generation of pulsations either in the interplanetary medium or on the ground.

On day 337 (07.00 - 09.00 UT) shown in Figure (6:7) pulsations are present on the spacecraft until 07.40 UT, there is a 'switch off' at approximately this time followed by a typical example of the 'switch on' of regular and monochromatic oscillations (~ 30 mHz) at 08.10 UT. These Pc-like waves continue beyond the end of the section of the record shown. On the ground there is a well developed Pc 4 activity (~ 10 mHz) continuously throughout the entire interval, with no obvious relation to the IMF or its pulsations. An interesting point is exhibited on the satellite record: the By and Bz components are virtually zero and the pulsations amplitude range is about 2 - 3 nT, the average IMF magnitude is approximately 5 nT. So the pulsations themselves cause a considerable variation of the cone
angle. Events with this characteristic are fairly common and further examination particularly of wave polarization is desirable to discover whether a resonant situation involving cone angle fluctuation is being set up.

On day 304 (17.00 - 19.00 UT) Figure (6:8) there is a very distinct 'switch on' of pulsations at the ISEE-2 about two minutes before 18.00 UT. The pulsations are irregular in wave form and show a decrease in frequency from 30 mHz to 20 mHz at 18.30 UT. There is no obvious change in the magnitude of the IMF at the time. One the ground there is low-level irregular magnetic activity with a train of three classical Pi 2s marked by arrows on the diagram. Again there does not seem to be any connection between ground and satellite activity. Also the satellite activity shows no signature associated with the Pi 2s.

Figure (6:9) shows records for day 325 (12.00 - 14.00 UT) together with the corresponding value of the cone angle. The spectrum of this event is discussed earlier in this section. In contrast to the previous examples this interval exhibits activity in the two media which is similar in form. There is monochromatic Pc-type activity on the spacecraft which 'switches off' at 12.55 UT. From the beginning of the record until this time the cone angle is relatively constant at about 30°. At 12.55 UT the cone angle increases abruptly and thereafter is large and variable. On the ground there is extremely coherent monochromatic Pc 3 activity which 'switches off' approximately at 13.11 UT. As noted before, the frequencies of the waves in the two media are different; the waves in the interplanetary medium have the frequency of about 40 mHz, whereas the Pc 3 activity on the ground has the frequency of approximately
25 mHz. The 10 - 16 minutes delay between the 'switch off' at the satellite and ground is in good agreement with the time lag reported by Webb and Orr (1976), between IMF signature and the consequent Pc activity on the ground. The delay time also agrees with Plyasova-Bakunina et al. (1978) result, and it may be interpreted as the travel time of waves from the interplanetary medium to the magnetosphere and along field lines to the ground.

Figures (6:1 - 6.9) are representative of 200 hours of data for which ISEE-2 and Oulu recordings were examined together. The effects which are highlighted are generally characteristic of most events which were scrutinised. The satellite records had many clear 'switches on' and 'off' with no correspondence at all with the switches on the ground except for one case shown in Figure (6:9). In this case there is a clear association of a 'switch off' at the satellite and on the ground. It is the only one case of similarity of the activity in the two media (for which data were available) that occurred among the total number of 'switch on' and 'off' which were observed; perhaps the similarity is coincidental unless proved otherwise.

6:2-2 Midlatitude station

The procedure used in section 6:2-1 was applied to the comparison of the ground magnetic data from Cambridge (L = 2.4) and the ISEE-2 satellite data. Some examples are described below. [It has to be remembered that the time intervals chosen in the first three examples are the same as those used in section 6:2-1 for high latitude station. The rest of the examples have time intervals which are only part of the previously used intervals at the high latitude station because of
there being data gaps in the magnetic records at the midlatitude station.

In Figure (6:10) the top panel is the dynamic spectrum for the ISEE-2 and the bottom panel is the ground spectrum for day 337 covering the time interval 04.00 - 14.00 UT. The spacecraft has good Pc events with the frequency of about 30 mHz at 04.00 - 07.30 UT. There is a distinct 'switch off' at 07.30 followed by a 'switch on' at higher frequency ~ 45 mHz, at 08.10 UT. The frequency returns to its earlier value at 09.20 UT and then the pulsation activity gradually diminishes from about 10.30 UT. There is no change in the IMF magnitude corresponding to the changes in frequency of the pulsation activity mentioned above. The ground spectrum shows no correlation with that of the waves on board the satellite. The Pc activity starts weakly (with the spectrum mainly of the Pc 4 pulsations) at about 05.00 UT and gradually broadens its spectrum but continues to remain weak until about 10.00 UT. After this time there is well developed Pc 3, 4 activity with frequency between 10 mHz and 30 mHz; the activity continues throughout. Although the ground spectral band covers that of the waves on board the satellite and is quite different from that at the high latitude station there is no correspondence at all between the onset of pulsations activity on the ground and that in the interplanetary medium.

Figure (6:11) shows the dynamic spectrum for day 337 covering the time interval 14.00 - 24.00 UT, which is a continuation of the event described above. The satellite pulsations 'switch on' for two hours at about 17.15 UT. The activity is either off or weakly irregular until about 21.50 UT when there is evidence of another
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FIGURE 6.12

UT
FIGURE 6:11
'switch on'. There is an increase in frequency from 15 - 40 mHz in the early patch to 20 - 50 mHz in the later section. Once again the ground pulsations show no obvious relation to the waves in the interplanetary medium. The ground data show well developed Pc 3, 4 activity (10 - 30 mHz) from the beginning of the interval (at 14.00 UT). The activity develops into a series of 30 minutes broad band wave bursts from about 16.30 UT to approximately 18.20, and finally ends with a Pi 2 indicated by arrow at about 18.30 UT. Thereafter it remains weak throughout the rest of the interval, except at about 22.40 UT and 23.10 when Pi 2s (marked by arrows) emerge. There is no indication in the satellite records of any pulsations or of possible triggers which might be related to the Pi 2s seen on the ground. As already mentioned in section 6:2-1 the position of the ISEE-2 spacecraft is ideal for relating to the Pc 3 in the morning sector.

The satellite and ground spectra for day 325 (04.00 - 11.00 UT) shown in Figure (6:12) also show lack of correspondence of the Pc activity in space and on the ground. There is a complete disparity in spectra at the satellite and on the ground during this interval. The activity on board the satellite is sporadic with broad band high frequency (20 - 60 mHz) oscillations which spread throughout the interval. There is no activity (or the activity is very low) on the ground for nearly 5 hours after which there is a break of two hours activity (15 - 30 mHz), mainly Pc 3 pulsations from 09.00 UT to 11.00 UT. Again the ground pulsations have lower frequencies than those observed at the ISEE-2 satellite, but the frequencies are higher than those observed at the high latitude stations.
FIGURE 6:12
Figure (6:13) showing the spectra on day 325 (12.00 - 14.00 UT) presents a different picture from the previous ones. There is a convincing correspondence between the 'switch off' of activity in the interplanetary medium and on the ground. The frequencies of the activity in the two media are different, the spacecraft has Pc activity of about 30 - 40 mHz while the ground has Pc 3 activity with frequency of about 25 mHz. There is a very distinct 'switch off' of the wave activity at the satellite just before 13.00 UT. A 'switch off' on the ground is also clearly visible at about 13.10 UT. The time lag between the switches is the same as that mentioned in section (6:2-1) for the higher latitude station. We shall return to this event later in this section when it will be discussed using analogue records with reference to Figure (6:19).

It is noted that at this interval (12.00 - 14.00) there is a very convincing evidence of similarity between the spectra at Cambridge (in the midlatitude) and at Oulu (at the high latitude). For detailed examination of this event, the spectra at the two ground stations were determined by the conventional method of spectral analysis, as described in Chapter 4, section 4:2-1.

At Cambridge the spectral peak and the corresponding frequency is 47.6 nT²/Hz and 26.3 mHz respectively; at Oulu the peak and the frequency is 57.6 nT²/Hz and 25.0 mHz respectively. Note that both frequencies are lower than the frequency at the satellite (~ 35 mHz).

Figure (6:14) shows both satellite and ground spectra for the time interval of 10.00 - 14.00 UT on day 304. This interval gives further evidence of lack
of correlation between the pulsations in the inter-
planetary medium and those on the ground. The satellite
has very weak and patchy activity between 10.00 UT and
11.40 UT, thereafter enhanced broad band activity
begins and continues till about 14.00 UT. The frequency
of the activity at the satellite is 20 - 50 mHz. The
pulsation activity on the ground starts from the
beginning of the interval and continues until the end
of the interval; the frequency of the ground activity
is 10 - 30 mHz, generally lower than that of activity at
the satellite.

Continuation of the event described above is shown
in Figure (6:15) and covers the time interval 15.00 -
19.00 UT. Once again the spacecraft has broad band
activity with the frequency of about 20 - 50 mHz from
the beginning of the interval until about 16.00 UT when
the activity 'switches off' briefly. A few minutes
later appears a wave burst lasting for roughly 20 minutes
then another wave burst ~5 min duration at around 17.00
UT; thereafter the activity dies away completely (or
remains very low) until about 18.00 UT when there is a
'switch on' of another patch of activity for an hour;
this patch has much broader band of frequency (~ 10 - 60
mHz) than the first section. The ground station has
well developed Pc 4 activity (10 - 30 mHz) between
16.00 UT and 17.00 UT after which the activity breaks
into isolated Pi 2s (marked by arrows) for the rest of
the time interval. The ground activity has no relation
at all to the activity at the satellite: the frequencies
at the satellite and on the ground are very different;
no correspondence exists between the 'switches' of
activity both on board the spacecraft and on the ground,
in particular there is no signature in the satellite
data corresponding to the Pi 2s on the ground. As noted previously the satellite position is near the subsolar point, the local time of the spacecraft is nearly 11.00 in the morning sector - one hour away from the noon meridian. At this location the spacecraft could see waves which, according to Greenstadt (1972) are suitably positioned to be transferred to the magnetosphere.

The following is the description of a different version of comparison between the instantaneous wave form in the two media (the interplanetary medium and the ground) using 2-hour intervals. As in section 6:2-1 the upper four traces are the satellite records and the lower three traces are the ground records.

On day 308 (10.00 - 12.00 UT) shown in Figure (6:16) there is no pulsation activity at the satellite throughout the interval. On the ground there are signs of Pc 3, 4 activity spread throughout the interval. [The spikes on the records are due to interference at the site]. The pulsation signals are clearer on H-component than on D-component, there is virtually no Pc signal for Z-component. The IMF magnitude (B) is essentially constant and, although there is a change of direction of the IMF field at 10.57 UT, there is no effect on the generation of pulsations both in space and on the ground.

The satellite and ground records on day 337 are shown in Figure (6:17) for the time interval 07.00 - 09.00 UT. Mixed-frequency pulsations activity is present on board the spacecraft from the beginning of the interval to about 07.40 when the activity 'switches off'. Later at about 08.10 UT there is a distinct 'switch on'
of typically regular and monochromatic oscillations ($\sim 30$ mHz) of the Pc 3 type. These Pc-like waves continue beyond the end of the interval. The ground station has a well developed Pc 4 activity with frequency ($\sim 17$ mHz) slightly higher than that at the high latitude station. The activity begins at the beginning of the interval and continues throughout the whole interval with no apparent relation to the IMF or its pulsations.

The satellite and ground records for day 304 (17.00 - 19.00 UT) shown in Figure (6:18) is a further evidence in the midlatitude, of lack of correspondence between the pulsations activity in space and on the ground. The pulsations on board the satellite are irregular in wave form (designated in this work as quasi-periodic oscillations) with a distinct 'switch on' roughly two minutes before 18.00 UT. There is a general decrease in frequency from $\sim 35$ mHz to $\sim 25$ mHz at about 18.30 UT, which has no apparent connection to the mean IMF value. On the ground there is very low-level irregular magnetic activity with two isolated Pi 2 events (marked by arrows).

Figure (6:19) shows the records on day 325 (12.00 - 14.00) when the spacecraft and the ground station have Pc activity that looks similar. The event is the same as that already described in section 6:2.1 for the high latitude stations see Figure (6:9). [Z-component is missing at Cambridge because of an instrument malfunction].

In the series of intervals in which we have highlighted the effects characteristic of most events scrutinized both in the high and middle latitudes,
there is no correspondence between all events in space and on the ground except one. The exceptional event is illustrated in Figure (6:4) and Figure (6:9) for the high latitude station and in Figure (6:13) and Figure (6:19) for the mid-latitude station. One important result connected with the event is that the IMF cone angle is well correlated to the ground pulsations both at the high latitude and mid-latitude stations whereas the frequency of the IMF pulsations is higher than that of the ground pulsations at both high and mid latitudes. This event showing the similarity in the Pc activity in the two media, is the only one in the whole period studied in this work; perhaps the similarity is a coincidence. Generally the frequency of the low frequency waves in the solar wind is found to be higher than the frequency of Pc 3, 4 activity on the ground. The 'switches' in the interplanetary medium and on the ground are found to occur at different times, and the wave forms in the two media are essentially different too. In particular there is no signature in the interplanetary data which corresponds with the Pi 2s observed on the ground. There is no systematic change in the Pc 3, 4 character on the ground (or of its non-relationship to that in the satellite) as the ground stations traverse from AM hours (while the local time of the spacecraft remains virtually unchanged) to PM hours and night where a direct relationship would not be expected, if one existed.

The results mentioned above suggest that direct transmission of waves from the interplanetary medium to the magnetosphere and be observed on the ground as Pc 3, 4 is difficult. There does not seem to be any direct
link between the waves in space and the Pc 3, 4 activity observed on the ground. The Pc activity observed on the ground are essentially different from the wave activity seen on board the satellite. This implies that the Pc activity on the ground are likely to be generated in the magnetosphere and not the interplanetary medium. However it may be possible that some waves in the solar wind would be seen on the ground with frequencies selected by the magnetosphere, perhaps the magnetosphere acts as a selective filter for the broad-band primary spectrum of the magnetic signal coming from space to the ground. The subject on the interplanetary origin of the Pc 3, 4 pulsations will be discussed in the next chapter (Chapter 7).

6:3 Statistical comparison

Ground data for the statistical analysis were provided from Nagycenk Observatory in Hungary; the geomagnetic coordinates of the observatory are 47.2°N latitude and 98.3° longitude (L =1.8). The Nagycenk data are obtained from Earth current measurements which are characterized in 12-period bands. Details of the methods of characterization of the micropulsations measurements at Nagycenk are given by Hollo et al. (1972). The data is the form of hand-scaled hourly and daily mean amplitude, and a catalogue of the period bands (lower and upper limits) of the pulsations occurring in each quarter hour and half hour interval. For each interval the pulsation type and amplitude is given. Data used in this analysis were obtained from the catalogue containing indices for the micropulsation activity in 30 min intervals. The
catalogue is based on the telluric records made at a chart speed of 6mm/min. From each 30 min interval a characteristic shorter interval is chosen which is considered typical for the whole interval. In this shorter interval the period and amplitude of pulsation is hand scaled. The periods and amplitudes are distributed among 12 period bands which give a detailed description for the Pc 3, 4 type pulsations.

Linear regression analysis was used to examine the relationship between the period (T\text{sat}) measured on board ISEE-2 satellite and the period T\text{gr} recorded on the ground at Nagycenk station. The following adjustments were made to the ground records before the analysis.

(a) The center of each period band was used to represent the ground period (T\text{gr}) for each time interval corresponding to a satellite record.

(b) Period bands within the range of Pc 3/4 only were used.

(c) Only continuous types of pulsations were considered.

First, the scatter plot shown in Figure (6:20) was made. The high degree of scatter suggests that any relationship between the periods in the two media is weak or non existant. Nonetheless we derived least square regression lines defined by

T\text{sat} = (32.10 \pm 1.9) + (0.22 \pm 0.05) T\text{gr}
T\text{gr} = (21.37 \pm 3.1) + (0.32 \pm 0.07) T\text{sat}

They are shown on the scatter diagram as full and dashed lines respectively. They intersect each other at a large angle (60°), implying that the correlation is poor. More to the point, the coefficient of linear correlation is small, R = 0.26, though it is significant.
\[ T_{\text{sat}} = (32.10 \pm 1.9) + (0.22 \pm 0.05) T_{\text{gr}} \]

\[ T_{\text{gr}} = (21.37 \pm 3.1) + (0.32 \pm 0.07) T_{\text{sat}} \]
at the 99.9% confidence level because of the large number of degrees of freedom (243). The upper and lower 95% confidence limits of the linear correlation coefficient is 0.31 and 0.21 respectively. The standard errors of the estimate of the regression line, $T_{\text{sat}} \text{ vs } T_{\text{gr}}$ and $T_{\text{gr}} \text{ vs } T_{\text{sat}}$ are 11.2 sec and 13.5 sec respectively, both indicating large scatter. The mean period ($\bar{T}_{\text{gr}} = 34.01 \pm 0.89$ sec) of the ground pulsations is quite different from the mean period ($\bar{T}_{\text{sat}} = 39.54 \pm 0.74$ sec) of the satellite.

That the mean period measured on the ground at Nagycenk is less than the mean period on the ISEE-2 satellite is inconsistent with the result obtained using the IGS magnetometer stations. Recall that (a) in section 4:3-6 the derived F-B relation for Pc 3, 4 band predicted that $T_{\text{gr}} > T_{\text{sat}}$ for the same set of B values, and (b) in sections 6:2-1 and 6:2-2 it was found that $T_{\text{gr}} > T_{\text{sat}}$ all the time. The difference between the Nagycenk data and the IGS data is perhaps due to the different response characteristics of the instruments and different methods of selecting the Pc events. At Nagycenk the Earth current recording system had a frequency response that extends to higher frequencies than the IGS rubidium magnetometer, making it suitable for Pc 3 and higher frequency events. The Pc 3, 4 events at Nagycenk were (by practice) handscaled. The handscaling method is subjective and can be open to errors and bias in that the eye is always certainly drawn to the clearest most sinusoidal events. At the IGS, the rubidium vapour magnetometer had a flat frequency response from DC to $\sim 100$ mHz which makes it ideal for identifying Pc 4 and the
larger Pc 3 pulsations, but not suitable for the higher frequency pulsations which are typically an order of magnitude lower in amplitude. The Pc 3, 4 events were clearly identified both by visual inspection and computation of power spectra, so errors were minimized in the IGS data.
CHAPTER 7

SUMMARY, DISCUSSIONS, INTERPRETATIONS AND CONCLUSIONS

7:1 Scatter in the $E-V_{SW}$ relation

The major results in connection with the solar wind velocity and the ground Pc 3, 4 activity are as follows:

a) The control of pulsation activity by the solar wind velocity works in different ways at different local times. High solar wind velocities ($400 - 500$ km/sec) tend to produce more pulsations in the earlier morning local time than low ($250 - 400$ km/sec).

b) The $E-V_{SW}$ relation is positive; the magnetic energy increases with the increase in solar wind velocity.

c) There is no frequency dependence for the $E-V_{SW}$ relation. Both Pc 3 and Pc 4 bands are affected by the solar wind velocity. The use of five stations has revealed a latitudinal effect in the $E-V_{SW}$ relation.

These results are in general agreement with previous results obtained from different data sets. Some previous works linking the solar wind velocity with the Pc activity both on the ground and at the geostationary satellite have been outlined in Chapter 3, section 3:1. It is recalled that on the ground Singer et al. (1977), Vero and Hollo (1978), Greenstadt et al. (1979) and Wolfe et al. (1980) have obtained a positive correlation between solar wind velocity and the level of Pc activity. Similar results have been reported by Takahashi et al. (1981) using geostationary satellite data.

It has been noted earlier that there is a large scatter in the $E-V_{SW}$ relation and that many factors may contribute to the large scatter. A few of these factors are discussed in the following paragraphs.
It is thought that the large scatter may be caused by the way the solar wind itself is working differently at different local times, as stated in (a) above. The data used in each of the scatter diagrams Figures (4:12 to 4:16) were taken from all local times in the dayside magnetosphere. Although the general diurnal pattern of the Pc 3, 4 activity has a peak just before noon (see Figure (4:9)) there is a substantial number of events observed in the evening sector, whose relation to the solar wind velocity is not clear, (section 4:3-4), and these evening events could contribute significantly to the scatter. The peaks of the spectra which have been used as a basis of the ground events also vary with the local time, with a maximum just before noon, see Mier-Jedrzejowicz and Southwood (1981). In this case the spectra with low energy in the early mornings and evenings could imput misleading energy values in the E-V\textsubscript{sw} relation.

Another factor contributing to the large scatter is that there are many solar wind parameters responsible for the control and generation of the Pc activity at any one time. One of these parameters is the cone angle. There are clearly exceptions to the general trends of pulsation energy on the solar wind velocity, as stated in (b) above. At times of high solar wind velocity (> 500 km/sec) the expected high magnetic energy is not always observed. Other exceptions to the general trend of dependence on the solar wind velocity occurred during times of small solar wind velocities (< 300 km/sec) when high magnetic energy was observed. A few pulsation events with high energy that occurred at the low velocities were examined to see if they might be occurring at times of small
cone angles (< 45°). It was found that the high energy magnetic events were not well ordered by the small cone angle, although the majority of the events examined had relatively small cone angle, θXB = 30° - 50°. Small θXB should be associated with high energy pulsation events according to Greenstadt (1972). Similarly a few events with low energy that occurred at high solar wind velocities were examined to see if they might be occurring at times of large cone angles (>60°). It was found that the events had consistently large cone angle. Therefore the cone angle may account for some of the scatter in the E-V_{sw} relation.

Other possible explanations of the scatter are listed below.

Field line resonance: Pulsations with sufficient energy may not have been observed if the conditions for resonance in the magnetosphere were not attained at these times, or if the ground stations were not sufficiently near the resonance region. Three of the stations Faroe, Oulu and St Anthony, are at plasmapause latitudes where relatively small changes in magnetospheric geometry could have removed the stations from the best signal path. An expanded data set may resolve this issue.

Variable Sources: There may be other mechanisms for generation of Pc 3, 4 activity as many workers believe. Some of these generation mechanisms are outlined in Chapter 2, section 2:2-4. So it may have been that only a portion of enhanced energies were attributable to the process involving the solar wind velocity; the rest of the observed events might have been caused by other sources.
Variable time lag: A factor that might influence either a physical correlation of the magnetic energy with the solar wind velocity or the ability to demonstrate such correlation is the inevitable time delay between a change in \( V_{sw} \) and consequent pulsation activity on the surface of the Earth. The delay time depends on the solar wind condition and on the location of the interplanetary observation point, (in this case the ISEE-2 spacecraft) and is longest when the spacecraft is farthest away from the magnetopause. Variable transport times of changes in \( V_{sw} \) from the upstream observation point to the magnetopause could complicate any effort to correlate the solar wind velocity with the magnetic activity. The difficulty would increase with the satellite distance away from the magnetopause. Indeed the positions of the ISEE-2 spacecraft in the interplanetary medium vary considerably; at times the spacecraft is \( \sim 10 \) RE away from the magnetopause (see Figure (5:9a)).

Oscillations of the magnetosphere: The magnetosphere is known to be capable of 'ringing' (Greenstadt and Olson, 1976 and Russell, personal communication). This means persistence of oscillations in the magnetosphere for some time after the initial excitation at the magnetopause. The ringing could have produced some of the scatter by falsely introducing high energy magnetic activity at low values of the solar wind velocity.

Limitation of the use of the cone angle

The following is the summary of the experimental results on the dependence of the Pc 3, 4 activity on
the IMF cone angle ($\theta_{XB}$).

There is a frequency dependence in the effect of the cone angle on the pulsations activity. The Pc 3 band has a stronger correlation with the cone angle than the Pc 4 band. The amplitudes of Pc 3 pulsations are strongly modulated by the changes in the cone angle; the Pc 3 activity switches on and off correspondingly with the fall and rise in the cone angle. The changes in the cone have no obvious effects on the Pc 4 amplitude.

The Pc 3 pulsations were observed preferably when the cone angle was less than $50^\circ - 60^\circ$, with a probable cut off at $60^\circ$, but a data set containing many more events when $\theta_{XB} > 60^\circ$ will be necessary to sustain such an inference. Most Pc 4 pulsations were seen when the cone angle was less than $30 - 35^\circ$.

The general trend of $E-O_{XB}$ relation for both Pc 3 and Pc 4 is negative, ie the energy decreases with rise in the cone angle and vice versa.

The results summarized above are in general agreement with the previous results obtained on the ground and in the magnetosphere that the Pc 3, 4 activity is correlated with the IMF orientation. The major studies on the ground linking the Pc 3, 4 activity with the IMF orientation are the works of Bol'shakova and Troitskaya (1968), Greenstadt and Olson (1976), Webb and Orr (1976), Vero and Hollo (1978) Greenstadt et al. (1979) and Wolfe et al. (1980); those in the magnetosphere are Arthur and McPherron (1977) and Takatashi et al (1981). In particular the result that the effect of the cone angle on the Pc activity depends on the frequency of the pulsation is in accord with Wolfe et al. result.

Although there is a general agreement that the IMF direction controls the Pc 3 activity the studies which
have used the angle $\Theta$ and $\varphi$ (the ecliptic latitude and longitude respectively) of the IMF have reported different values of $\varphi$ favourable for the Pc 3 activity ($\varphi$ is a measure of deviation of IMF direction from the Earth-Sun line). For example, Bol'shakova and Troitskaya (1968) found the occurrence maximum at $\varphi = 140^\circ - 160^\circ$. The preliminary results of a study, now in progress, by Stuart and Plyasova-Bakounina (personal communication) indicate that ground pulsation activity does not appear to depend upon $\varphi$. Whenever pulsations are present or not the $\varphi$ distribution is centered around Parker's spiral angle. However it is demonstrated that the peak of the Pc 3, 4 activity is at $\Theta_{XB} \sim 15^\circ - 45^\circ$ for all the five ground stations used, see Figure (4:17). This may reflect the fact that there exists a most favourable direction slightly away from the Sun-Earth line.

Different determinations of $\Theta_{XB}$ by different workers also add some difficulties and ambiguities to the comparison between results presented in this work and the previous ones. To represent $\Theta_{XB}$ in the time interval of one hour three different methods have been adopted. Greenstadt and Olson (1976, 1977) used hourly minimum values of the cone angle ($\Theta_{XB \min}$) to compare with hourly maximum amplitude of pulsations. There is a considerable drawback in this method, because the cone angle may be minimum very briefly during the hour interval. One would not necessarily expect to see large amplitude activity for hours during which $\Theta_{XB \min}$ was small for short intervals. Other workers (Vero and Hollo, 1978, 1980; Wolfe et al., 1980) used $\Theta_{XB}$ calculated from hourly averages of $B_x$ and $B$. Greenstadt et al. (1979) used hourly distribution of the cone angle, $\Theta_{XB}$. It
is difficult to resolve the changes in the cone angle within one hour by using hourly mean values. The definition of the 30 min $\Theta_x B$ offered in this work allows the changes in the cone angle to be better resolved. The improved resolution has produced a convincing picture of the relationship between the cone angle and the Pc 3 activity, for example see Figures 4:23a and 4:26.

Low frequency waves in the solar wind: summary and discussions

The following are the main points which this study has revealed.

1) Low frequency waves in the interplanetary medium vary considerably in their wave form. Variations in wave type as designated here occur within a short time (< 1 hour) and occurs at all local time in the morning sector, see Figures (5:9a) and (5:9b). The waves are dominantly transverse, with enhanced $B_y$ and $B_z$ components, but compressional oscillations are also quite common. The transverse character of the IMF waves is illustrated in Figure (7:1). The figure shows the dynamic spectrum of six hour field record of $B_y$ and $B_z$ components. The spectral content in both components is very nearly the same.

The waves are most unlikely to be generated at the bowshock. Fairfield (1969) showed that the low frequency waves (such as the ones described here) generated at or near to the bowshock could not propagate upstream against the solar wind and be observed deep in the interplanetary medium. The waves have Alfvén velocities that are approximately 50 km/sec,
FIGURE 7:1

Y-Component

Z-Component

F, mHz

05 07 09 11

05 07 09 11

12-15 dB 15-18 dB 18-21 dB

- Z-Component
so they are swept back by the solar wind which has a velocity several times greater than Alfvén velocities in the interplanetary medium. The solar wind velocities during the period covered by this study were between 250 km/sec and 600 km/sec and some of the waves were observed at a radial distance 8 RE from the average position of the bowshock.

There are two possible causes of the presence of the low frequency waves (10 - 100 mHz) in the interplanetary medium:

a) Propagation of whistlers into the upstream region. The whistlers are high frequency and structured wave modes (the amplitude grows rapidly in time then decays more slowly lasting typically for several cycles) which often have velocities greater than that of the solar wind. Their frequency may be Doppler shifted to the Pc 3, 4 range in the Earth's reference frame, so they can be observed upstream of the bowshock as long period waves. [It is to be remembered that the velocity of the satellite relative to the Earth is only approximately 1 km/sec at distances within the interplanetary medium, so the spacecraft frame of reference is nearly the same as the reference frame of the Earth].

b) Local generation of waves through cyclotron resonant interaction with energetic protons moving upstream from the bowshock (Barnes, 1970; Fredricks, 1975 and Kovner et al.1976). Fairfield (1969) argued that propagation of whistlers is not sufficient to explain the presence of low-frequency waves in the fore-shock region. Whistlers can be identified as the low-frequency waves only if they can be sufficiently Doppler shifted to a frequency in the low-frequency range (10 - 70 mHz) observed here. The frequently changing
conditions (density and velocity) of the solar wind would make it unlikely that whistler waves velocities in the solar wind frame of reference would continually be just sufficiently greater than the solar wind velocity to result in Doppler shift of the waves into the low-frequency range and to produce the stable wave forms which are observed. [Varying IMF conditions with the solar wind direction would give rise to different Doppler effects that would tend to remove the frequency out of the normal range where it is generally observed]. Even if the waves tend to propagate upstream from the bowshock, they are of relatively short wave-length, and would be considerably damped a very short distance (< 1 RE) away from the bowshock; this would make it almost impossible to observe the low-frequency waves in the interplanetary medium. That no evidence of structured low-frequency waves in the interplanetary medium has been seen in this work and that the IMF waves were actually observed several RE away from the bowshock add more credence to Fairfield's view that whistlers cannot sufficiently explain the presence of the low-frequency waves which are observed. Moreover the intrinsic characters of the whistler mode reported recently in the foreshock region by Hoppe and Russell (1980) require a local source within the solar wind. Local generation is apparently the sole reason for the presence of low-frequency waves in the foreshock region where they may be associated with the different types of ion distribution function noted by Gosling et al. (1978).

Using four events from the ISEE-1, 2 spacecraft observed at the same time interval covered by this study, Paschmann et al. (1979) indicated that the presence of the low-frequency waves such as the ones
described as the quasi-periodic oscillations was coincident with fluxes of diffuse ions. Later Hoppe et al. (1981) described the same four events as strongly compressional waves and also associated them with the diffuse ion population. Hoppe et al. also suggested that the transverse waves such as the ones represented by almost monochromatic oscillations (which are described here as Pc-type waves) are associated with intermediate ions.

Without a statistical mass of ion data it is not possible to draw any further conclusion in this work. In particular it is not clear which type of ion-distribution is responsible for the wave 'bundles' (discrete low-frequency wave packets). Although the bundles contain mixed-period waves they resemble short bursts of monochromatic waves and therefore they should correlate with intermediate ions, (Greenstadt, personal communication), but for the few examples which could be tested the IMF field geometry in relation to the shock and satellite position is that for diffuse ions. For example the wave bundle on day 306, see Figure (5:7b) occurs when intermediate ions are present at the spacecraft; but the bundle on day 328 (Figure 5:7a) occurs at position where diffuse ions should be. No diffuse ions were present nor were there any quasi-periodic waves. It will be necessary to make specific studies of the relations of ions with the low-frequency waves and then assess the IMF geometry in terms of an angle parameter connected with Sonnerup's (1969) acceleration picture, such an angle has been used by Bonifazi and Moreno (1981) to study backstreaming ions.
2) Most of the low-frequency waves were observed when the cone angle ($\Theta_{XB}$) was $15^\circ - 45^\circ$, as shown in Figure (5:13). The amplitudes of the waves are modulated by the changes in the cone angle, the amplitude being stable and enhanced when the cone angle is small (generally below $45^\circ$); the amplitude is low and sometimes 'switches off' (cuts off) completely when the cone angle is large (above $60^\circ$) and variable.

This result may not suggest that the small cone angles cause the generation of upstream waves. Greenstadt (personal communication) argued that the upstream waves are presented better in terms of a local shock geometry than the IMF cone angle because the range of the $\Theta_{XB}$ over which the upstream waves may occur is a wide one and depends on the location of spacecraft away from the subsolar point. Greenstadt suggested that when dealing with shock physics, of which upstream waves are one expression, the appropriate geometrical quantity is the angle ($\Theta_Bn$) between the IMF and the local shock normal.

Strictly speaking $\Theta_{XB} \approx \Theta_{Bn}$ only at the subsolar point. To correlate upstream waves with the cone angle ($\Theta_{XB}$) is to correlate against $\Theta_{Bn}$ at the subsolar point. As long as the observation point (in this case the spacecraft position) is not far away from the subsolar point of the shock, the correlation may appear the same because of the wide range of $\Theta_{XB}$ over which the upstream waves may occur. In practice the spacecraft is not always near to the subsolar point of the shock. The upstream waves reported here were observed when the position of the ISEE-2 satellite
was spread throughout the foreshock region, a situation likely to make the cone angle unsuitable means for the investigation of occurrence and/or amplitude of the upstream waves.

According to Greenstadt the upstream waves are best studied in the framework of the local shock geometry defined by angle $\theta_{BnDc}$ which is the angle between the IMF and the normal to the curve of intersection of the B-V plane with the bowshock (B is the IMF and V is the solar wind velocity) at a point where diffuse ions of average velocity would have left the shock to reach the spacecraft. The details of the geometry described above may be obtained from Greenstadt et al. (1980). The value of $\theta_{BnDc}$ is independent on the position of satellite with respect to the subsolar point of the shock. The upstream waves seem to occur over a narrower range of lower values of $\theta_{BnDc}$ than that of $\theta_{xB}$. To confirm this Greenstadt's programme (personal communication) was used to compute the values of the angle $\theta_{BnDc}$ at the times when the 'switches on-off' and the Pc-type wave events were observed, then these values were compared with the corresponding cone angles.

Figure (7:2) illustrates the comparison between $\theta_{BnDc}$ and $\theta_{xB}$ for the two data sets. The first one is a scatter plot for the 'switch on/off' of upstream waves irrespective of type; the second plot shows data from several observations of the Pc-type waves. Examination of the two scatter diagrams indicates that the range of $\theta_{BnDc}$ angles is less than the range of cone angles, $\theta_{xB}$, and that the $\theta_{BnDc}$ include more lower values than the $\theta_{xB}$. For the
FIGURE 7:2
'switch on/off' events the range of $\theta_{ByDC}$ is $0 - 40^\circ$ and includes an angle which is below $10^\circ$. The range of $\theta_{XB}$ is $0 - 55^\circ$ and includes no angle below $10^\circ$. For the Pc-type wave events the range of $\theta_{ByDC}$ is once again $0 - 40^\circ$ and includes many angles below $10^\circ$; whereas the range for $\theta_{XB}$ is $0 - 50^\circ$ and as before includes no angle that is less than $10^\circ$. Figures 7:2a and 7:2b support Greenstadt's suggestion that the upstream waves are more precisely studied in the framework of local bowshock geometry than the IMF cone angle. 3) For the first time using a large data set (286 events) a functional relationship between the frequency of the waves in the solar wind and the magnitude of IMF has been examined. The result suggests that a linear relationship of the form $F = C_0 + C_1B$ is a better fit to the data in space than the relation $F = CB$. Regression analysis assuming the frequency of the waves in the solar wind to be dependent on the IMF magnitude gives $F = (12.25 \pm 0.98) + (2.73 \pm 0.17)B$ as shown in Figure (7:3) by the thick solid line; there is a positive high correlation coefficient of 0.7 establishing the best fit line to be significant at the 99.9% confidence level. Russell and Hoppe (private communication) UCLA data (85 events) gives $F = (19.18 \pm 1.78) + (2.23 \pm 0.32)B$. [A part of the UCLA data has been used in the work by Russell and Hoppe (1981) mentioned below]. Although better statistical relation can be achieved by using the large data set it is important also to consider the quality of parameters involved, in this case the accuracy of determining the period of
the waves in the interplanetary medium. When only
the Pc type of the wave events (group A and B) whose
period were determined with minimum errors were
analysed the quantities shown in the Table (5:2)
were obtained. The slopes and the intercepts are
not significantly different, (even from the UCLA
data), implying that our data and the UCLA data are
from the same population.

Making the assumption that regression line passes
through origin the relation $F = 4.77 \pm 0.21B$ is found
using 286 events (thin solid line), Figure (7:3).
Russell and Hoppe (1981) using 63 wave events thought
to be related to intermediate upstream ion distribution
(ie Pc type waves) from ISEE-2, 1978 data set found the
relation $F = 5.81B$ (dashed line) making the same
assumption. [Using an enlarged data set (85 values)
provided by C T Russell and referred to here as UCLA
data, the relation $F = 5.33 \pm 0.49B$ is found]. The
regression lines for the data subset (group A) is
also shown in the figure by the dotted line. The line
representing the empirical relation $T = 160/B$ or $F =
6.25B$ is shown in the figure by dot-dashed line.

Examination of Figure (7:3) indicates that the
regression line of the form $F = C_0 + C_1B$ gives
generally higher field values than all the lines (including
the 160/B) which are forced through origin, ie the
lines of the form $F = CB$. In particular none of the
derived relationships expressed in terms of slope
and intercept is comparable to the empirical relation
$T = 160/B$ even with the monochromatic Pc-type waves.
It has been indicated that the derived relationship of the form \( F = C_0 + C_1B \) in space (also on the ground) are statistically better fit to the data than the form \( F = CB \).

One implication is that the relation \( T = \frac{160}{B} \) does not represent the spectrum of the waves in the solar wind, suggesting that any true physical relationship between the frequency of waves in the interplanetary space and the IMF magnitude is distorted by forcing the line through origin. This suggestion is supported by Green et al., 1982 (in press) who have also shown that if the F-B data in space and on the ground are to be fitted with a linear relationship, the form \( F = C_0 + C_1B \) is always a statistically better fit than \( F = CB \). Green et al. have indicated that the value of the intercept \( (C_0) \) is always statistically significant. The implication mentioned above is in agreement with Vero (1979) who cautioned that the empirical relation is a very rough one with \( T \) really representing the spectral peak of a band of excited pulsations, although Gul'elmi and his co-workers believe that the relation \( T = \frac{160}{B} \) fits their data quite well.

Gul'elmi et al., (1973) claimed that the relationship was \( T(\text{sec}) = \frac{160}{B(\text{nT})} \) (ie \( F = 6.25B \)) and Gul'elmi (1974) found \( F = 5.5B \). In both cases Green et al. (1982) has shown that there is no apparent statistical justification (from the data) for a relation of this form \( (F = CB) \). Green has noted that if the intention is to test the best fit of the data to some theoretical relationship, \( F = CB \) may be chosen if this appears appropriate to the
theory. However, it must be considered whether this form is valid for the data range under consideration, otherwise results will be distorted.

An approximation of the theory of the generation of magnetosonic waves in the solar wind has been used to justify the fitting of IMF and ground data to the relation $F = CB$. The theoretical dependence of frequency of pulsations on the IMF magnitude can be examined using the formulations of Hoppe and Russell (1982) based on a combined effect of ion resonance and Doppler shifting and on the assumption that the low-frequency waves are magnetosonic waves. The waves have been shown to have the rest frame frequencies ($F_o$) of the order of 0.1 the local proton gyrofrequency ($F_{ci}$), which are then Doppler shifted and their frequency ($F$), in the spacecraft frame (observed frequency) given by

$$F = F_o + \frac{\vec{V}_{sw} \cdot \vec{k}}{\lambda}$$

(7:1)

where $\vec{V}_{sw}$ is the solar wind velocity, $\lambda$ is the wavelength and $\vec{k}$ is the propagation direction. The equation (7:1) simplifies and reduces to measurable parameters ($F$, $V_{sw}$, $k$, $B$ and $n$) if $F_o < 0.1 F_{ci}$ is assumed. [F is the measured frequency, $V_{sw}$ is the solar wind velocity, $k$ is the propagation constant, $B$ is the IMF magnitude and $n$ is number density]. With this assumption the Alfven speed ($V_A$) can be used as the phase velocity of the waves and then substitute $\lambda = V_A/F_o$ into the equation (7:1), to get

$$F = F_o \left(1 + \frac{\vec{V}_{sw} \cdot \vec{k}}{V_A}\right)$$
\[ \psi = F_0 \left( 1 + \frac{V_{sw} \cos \theta_{kx}}{V_A} \right) \quad (7:2) \]

where \( \theta_{kx} \) is the angle between \( \vec{V}_{sw} \) and \( \vec{k} \). The resonant velocity (\( V_r \)) of proton interacting with a magneto-sonic mode wave has been given by Kennel and Petschek (1966) as

\[ \frac{V_r}{V_A} = \left( \frac{1 + \frac{F_0}{F_{ci}}}{{F_0/F_{ci}}} \right)^{1/2} \quad (7:3) \]

Since \( V_A = B/(\mu_0 m_p)^{1/2} \) and \( F_{ci} = \epsilon B/2\pi m_p \), where \( n \) is the number density of proton and \( m_p \) is mass of proton, it is therefore possible, in principle, to substitute these into equations (7:2) and (7:3), combine them and determine the relationship between the frequency and IMF magnitude.

In practice, some approximations have to be made. Hoppe and Russell suggested the value \( V_r = 2V_{sw} \) and \( \cos \theta_{kx} = -0.8 \). The remaining unknowns are \( n \) and \( V_{sw} \), which appear in the form of \( V_{sw}/n \). Equations (7:2) and (7:3) have been solved numerically for \( F \) as a function of \( B \) for chosen values of the product \( V_{sw}/n \) by Green et al. (1982). Green expanded equation (7:2) to first and second order and noted that there was not a large difference between the results. Figure (7:4) (after Green et al. 1982) shows the results from the second order approximation. The upper dashed limit of the shaded area is the line for the \( V_{sw}/n = 2000 \) (\( n \) in \( cm^3 \), \( V_{sw} \) in \( km/sec \)) and the lower limit is the line for \( V_{sw}/n = 1000 \). This range was considered reasonable for the majority of cases in the solar data, 1974. The solid line represents the relationship \( F = 6.1B \), which agrees with the approximation \( F = 6B \) given by Hoppe and Russell (1982) and
FIGURE 7:4
corresponds to the higher number limit, of the product $V_{sw}/\eta$.

The calculations of Green et al. indicate that the relationship between frequency ($F$) and the IMF magnitude ($B$) is not linear. For a limited range of $B$ it can be approximated as a straight line. The straight line, in most cases, does not pass through origin. It is found (for the period covered by this study) that about 80% of the total (1053) hourly average values of $B$ lie between 3 nT and 9 nT. A statistical best-fit straight line to the data over this range would produce a finite intercept ($C_0$) on the $F$ axis.

The value of $\cos \theta_{kx}$ in equation (7:2) is also important; when a value of -0.7 is used, the limiting straight line becomes $F = 5.3B$, and the curvature of the shaded area in Figure (7:4) becomes more apparent producing even a bigger value of the intercept for a limited range of $B$.

In summary the theory, which has been proposed to justify the relation $F = CB$, and the experimental results on F-B data presented in this work do not agree well.

7:4

Derived relations, F-B in space and on the ground

The main result of the statistical analysis performed for the relationship between the frequency and IMF magnitude indicates that for both satellite and ground pulsations the relationship of the form $F = C_0 + C_1B$ is a better fit to the data than the form $F = CB$.

If the values of the slopes and intercepts are compared for space and ground data, it is found that
the values of intercepts are generally comparable but the values of slopes for space are significantly lower than those for the ground. Thus on the basis of F-B relation alone the suggestion that the Pc 3, 4 pulsations seen on the ground have interplanetary source cannot be supported.

The case for the F-B relationship being the same in space and on the ground is not easy to prove because the theory outlined in the previous section proposes a complex relationship (with many variables) that is difficult to verify by experiments. Special simplifying assumptions have been made, in practice, to reduce the theoretical relationship to a form that can be compared with experimental results. It is possible that the assumptions have been too simple and are the cause of difficulty in comparing the theory with experimental results. The difficulty is increased by the fact that there is a wide range of measured F for any given value of B (or vice versa). Another complicating factor would seem to be that the parameters of any derived F-B relationship are affected considerably by distribution of frequencies and magnitude of IMF in the data set.

For the ground data alone a significantly better linear relationship was obtained between F and B using the simultaneous events from a pair of stations than that from individual events at a single station. The better relationship offered by the use of station pairs is indicative of a proper direction towards improving the predictive capability of ground pulsations using a chain of many stations.
Interplanetary origin of Pc 3, 4 pulsations

The mutual agreement of early researchers of the F-B relationship and the success of the recalibrated Borok-B index imply that some Pc 3, 4 pulsations may be of interplanetary origin. In the work of Green et al. (1982) and Stuart et al. (in progress) it has been shown that a similar F-B relationship holds broadly for Pc 3, 4 at mid-latitudes, (L = 2.5) particularly when the same period is observable over a large range of longitude (~ 45°), see Figure (7:5), (after Stuart et al. personal communication). Greenstadt (1972) showed that for small cone angles the large amplitude oscillations of the shock origin now called the quasi-parallel shock structure, are likely to be swept through the bowshock and magnetosheath to the magnetopause where the oscillations may be amplified by the Kelvin-Helmholtz instability and coupled into the magnetosphere through the field line resonance. Vinogradov and Parkhamov (1974) suggested that magnetohydrodynamic waves arriving from the interplanetary medium can be the source of Pc 3, 4 pulsations observed on the surface of the Earth. The theoretical considerations by Gul'elmi (1974), which were later developed by Kovner et al. (1976) showed that the Pc 3, 4 pulsations could originate from the low frequency waves generated locally in the solar wind or interplanetary medium, and suggested that the periods of the waves in the interplanetary medium would be similar to those of the Pc 3, 4 pulsations on the ground. The view that the periods of Pc 3, 4 on the ground may be similar to the periods of the low frequency waves in the solar wind has been also expressed by Plyasova - Bakounina (1972), Plyasova Bakounina et al. (1978) and
FIGURE 7:5
Golikov et al. (1980). Vero (1980) reported two classes of Pc pulsations, one of which is in the short period range, 12 - 30 sec; these short period pulsations have been supposed to have interplanetary origin. That some low frequency waves in the period range of Pc 3, 4 band were actually seen in the interplanetary medium (Russell and Hoppe, 1981) encouraged the view that some Pc 3, 4 on the ground may originate in the interplanetary medium.

All the derived relationships presented in this work offer no encouragement to the thought that some Pc 3, 4 activity on the ground result from waves that have been originally generated in the interplanetary medium and transmitted to the magnetosphere.

The relationship between the frequency of pulsations and the IMF magnitude (F-B relation) both for space and ground data was found to be presented best in the form of the linear function with significant intercept and slope (ie \( F = C_0 + C_1B \)). The F-B relation for the satellite (IMF) and ground data can be specified by the following equations, respectively

\[
F_1 = C_{01} + C_{11}B
\]

\[
F_2 = C_{02} + C_{12}B
\]

the index 1 and 2 corresponds to IMF and ground data respectively. Both intercepts and slopes obtained from the IMF data are not equal to those obtained from the ground data, ie \( C_{01} \neq C_{02} \) and \( C_{11} \neq C_{12} \).

The F-B relation has been the strongest reason for believing that some Pc 3, 4 are externally generated. But, the two equations above may be separate effects
of B on the waves in the solar wind and the pulsations in the magnetosphere. The waves in the solar wind are now recognized to be caused by ion-cyclotron resonant wave-particle interaction, so the waves have gyro-frequency that is proportional to the IMF magnitude (B). The frequency of Po-pulsations on the ground may be influenced by the IMF magnitude in a different way. The resonant frequency of the pulsations at a given place is a function of the dimension of the magnetosphere. It is possible that the IMF magnitude influence the dimension of the magnetosphere as suggested by Vero (1980). In view of the separate effects of B on the IMF and ground pulsations, any similarity in the F-B relation for the pulsations in the two media may be considered coincidental. This implies that it is not sufficient to assign the Pc 3, 4 on the ground to external origin on the basis of F-B relation alone.

The direct comparison between the waves in the solar wind and Pc 3, 4 recorded at the two ground stations (Oulu and Cambridge) illustrates that there is very rarely any correspondence. Whenever there appears to be some correspondence in the activity, the periods of the waves in the two media are very different. The 'switches on/off' have been observed both in space and on the ground, although the 'switches' in space were more distinct than those on the ground because the signal to noise ratio at the satellite is higher than that on the ground. The 'switches' in the two media are caused perhaps by different processes. The 'switches' at the satellite may be due to the following reasons:

a) The movement of the satellite about the IMF
connecting it to the bowshock.

b) The abrupt changes in the IMF orientation with respect to the bowshock, which occur in conjunction with the foreshock modification by solar wind discontinuities, see Greenstadt et al. (1981).

c) The changes in upstream ion populations (Paschmann et al. 1979).

The 'switches' on the ground would be perhaps due to (a) the changes in the solar wind parameters that influence the generation of pulsations (b) the response characteristics of the magnetosphere, in particular the resonance shells and (c) changes in the condition of plasma instabilities in the magnetosphere. The difference in the causes of the 'switches' at the satellite and on the ground makes it difficult for any correspondence in the onset and/or disappearance of Pc activity in the two media to occur; if there is such a correspondence it may be a coincidental one.

The results presented are supported by Green et al. (1982) who have shown that on the basis of the F-B relation alone the question of interplanetary origin of the Pc 3, 4 pulsations observed on the ground cannot be supported. These results suggest (in agreement with Greenstadt 1980 and Southwood 1981 (personal communication)) that there may be no direct connection in terms of the propagation of waves from the solar wind or even the magnetosheath, straight through to the ground and that any similarity should be regarded as coincidental.

It has been argued that there is no direct connection between the low frequency waves in the solar wind and the Pc 3, 4 activity on the ground and demonstrated
that where direct comparison of simultaneous wave events has been made such a connection has not been revealed. With the rather generalized theoretical assumptions which are difficult to prove, it is hard to believe that waves in the interplanetary medium would be transmitted to the magnetosphere to be observed as Pc 3, 4 on the ground. In assessing the results in the general context of current research the factors listed below have to be considered. [The list is not in order of importance].

1. Some earlier work used small numbers of events or hourly mean values of the solar wind parameters.

2. The satellite being only a single point in space may not be in a position to observe the waves in the interplanetary medium which relate directly to any event in the magnetosphere.

3. Transient changes in the solar wind alter the geometry of the bowshock and thus affect the generation condition of waves in the foreshock in ways which cannot be taken account of here for lack of data (see Greenstadt, 1981).

4. The delay time between the onset of upstream processes and the consequent magnetic activity in the magnetosphere is unknown. The time lag depends on solar wind conditions and position of spacecraft in the interplanetary medium from the magnetopause.

5. It may be that the wave energy from the interplanetary medium penetrates the magnetosphere at the wrong period to excite resonance at the field lines through Oulu and Cambridge. It may be that the primary spectrum of the externally generated waves only affects limited areas of the magnetosphere.
6. It seems that a considerable proportion of the ground pulsations used in this work may be generated by different mechanisms from that of the waves in the solar wind. Certainly at $L = 4.3$ it must be true that a large fraction of Pc 3, 4 observed at Oulu is generated in the magnetosphere. Oulu is often at or near to the plasmapause, and wave particle instabilities are considered to be a common source of pulsations at this latitude. The effect of the plasmapause may work in a different way: Relatively small changes in the geometry of the magnetosphere can remove the ground station from the best signal path.

7. Persistence of oscillations (known as 'ringing') in the magnetosphere after the initial excitation of the magnetopause by an external signal can cause disparity in the correspondence between waves in space and those ones in the magnetosphere.

8. Inospheric effect: One of the important problems in connection with the satellite-ground correlation of the Pc 3, 4 activity is concerned with damping effects of the ionosphere. It has been mentioned in Chapter 2, section 2:2-9 that signals with horizontal scale length shorter than ~120 km are attenuated between the ionosphere and the ground. The reduction in ground amplitude relative to the magnetospheric amplitude increases as the horizontal scale length is decreased. This effect implies that localized structure in space may be totally shielded off from the ground making the satellite-ground correlations of waves difficult.
In this section the overall results of this work are discussed in the context of the two models of generation of the solar wind controlled Pc 3, 4 pulsations. The two models have already been outlined in Chapter 3, section 3:1-4. It is attempted to find out if the data presented in this work fit the two models working separately or jointly.

The overall result is that the Pc 3, 4 activity on the ground has been found to correlate well with the solar wind parameters, and that the low frequency waves in space have some properties similar to those of the ground Pc 3, 4 pulsations. Nevertheless, no direct link has been found between the ground pulsations and the low frequency waves in the interplanetary medium.

**Surface wave generation alone:** The surface wave generation involves the Kelvin-Helmholtz (K-H) mechanism. The K-H mechanism would be driven by any initial perturbation at the magnetopause, e.g. density, velocity and pressure fluctuations. The initial perturbation would not necessarily have to be a wave. In addition, no concept has been advanced, at the moment, that explains the cone angle as a factor contributing to the surface wave generation. It is possible that ground pulsations may be generated by the K-H instability alone without the need for interplanetary waves.

It is recalled that most of the Pc 3, 4 pulsations were observed when the cone angle was small and that the pulsations are a day time activity with an occurrence peak before noon. The frequency of these pulsations depend on the IMF magnitude.
With these results there are several difficulties in assigning the Pc pulsation activity observed on the ground to surface wave generation alone. The critical condition for the K-H instability contains the factor $B_1^2 \cos^2 \psi_i$, where $B_1$ is the magnetosheath field strength at the magnetopause boundary, and $\psi_i$ is the angle between the field and the solar wind flow (Boller and Stolov, 1973). This factor is unfavourable to the K-H instability when the flow and the field are nearly aligned; they would be nearly aligned when the cone angle is small. Another difficulty is that the K-H instability has not provided any hint so far to the relationship between the frequency of waves and IMF magnitude.

On the basis of the results presented here, there is a more serious difficulty for the K-H mechanism acting alone, namely the strong bias of the pulsation activity towards the morning sector, whereas the surface waves driven by solar wind velocity should be essentially symmetric on east and west sides of the magnetosphere. In the context of the two generation models which are being discussed, the local time pattern of the pulsations observed in this work may be associated with subsolar section of the magnetosphere. This is compatible with 'signal' model.

'Signal' excitation alone: The cone angle is the primary effect in this model. Greenstadt (1972) has postulated that waves of large amplitude formed in the subsolar bowshock when the cone angle is less than $50^\circ$ and $70^\circ$ are propagated and convected to the daytime magnetopause where they transfer to the magnetosphere and through the magnetosphere to the ground. Greenstadt et al.
(1980) have worked out a guide to indicate that waves reaching the magnetopause must originate in the shock no more than about 45° or so in the plane of the ecliptic from the subsolar point when the IMF is at Parker's spiral angle (≈ 45°). According to this picture, the bulk of wave excitation is supposed to occur (on average) as a result of large amplitude quasi-parallel structure in the prenoon sector, west of the subsolar point itself. This is compatible with the experimental results presented in this work. Recall that most of the Pc 3, 4 pulsations on the ground were observed when the cone angle was small < 50° - 60°. The small cone angle would cause the quasi-parallel shock structure to prevail in the subsolar region.

The influence of low cone angle in producing pulsations in the Pc 3 and lower half of the Pc 4 period bands is consistent with the way such periods would vary with the IMF magnitude (B), if the pulsations resulted from waves with the cyclotron period near the subsolar magnetopause (Greenstadt et al. 1980). At the subsolar point the waves of the shock origin (which may form significant part of the low frequency waves described in this work) are assumed to have proton cyclotron period \( T \approx 1/B \). Recall that the best correlation of the Pc 3, 4 activity on the ground with \( \theta_{xB} \) has been found for short periods, mainly the Pc 3 band, and that the inverse relations \( T \approx \frac{1}{B} \) has involved just these shorter periods.

The velocity effect can only be justified as a secondary effect in the 'signal' model in any of the two ways. First a high velocity would suggest that more energy in the quasi-parallel structure would be blown downstream into the magnetosheath adding its
measure to energy already available for excitation of the magnetopause. Second, the high solar wind speed is associated with a disturbed magnetosphere in which a flux tube may readjust its position so as to bring enlarged amplitudes of the waves of the shock origin to a limited latitude of ground station where pulsations may be observed with enhanced energy. Any of above effects or combination of them could produce an increase in pulsation energy with velocity without invoking surface wave amplification by the K-H mechanism. However the data presented in this work show strong dependence of energy occurrence on the solar wind velocity and it is unlikely that the solar wind velocity effect would be treated as secondary. Hence it is not probable that the 'signal' model alone can fit the data.

Joint action: The pulsations observed at the five ground stations appear to be influenced strongly by three solar wind parameters, the IMF direction \( \theta_{xB} \), the IMF magnitude \( B \) and the solar wind velocity. On the basis of these results, the effects of these parameters appear to be explained better by joint actions of both 'signal' and 'surface wave' models.

The control by three parameters can be understood in a framework in which disturbances in the magnetosheath are amplified at the magnetopause by K-H instability. The larger the solar wind velocity the more likely is wave growth at the magnetopause. The source of the magnetosheath disturbances that are amplified by this instability may be quasi-parallel shock oscillations described by Greenstadt (1972) or any other sources of upstream waves such as the ones
described by Barnes (1970) and Kovner et al. (1976). The framework implies a joint action of wave excitation and wave transfer. The K-H instability would simply act to amplify waves which have reached the magnetopause from upstream regions.

With the joint action of the signal and surface wave one would expect to see good correspondence between waves in space and the Pc 3, 4 pulsations on the ground, at least for the majority of events. The frequency of the waves in the two media also would be comparable. It has been demonstrated that very little correspondence exists between the occurrence of waves in space and the Pc 3, 4 pulsations on the ground. Even on very rare occasions when there appear to be such correspondence the frequencies in the two media are very different. Thus the data presented in this work may not be fitted easily to the joint-action model.

There is no feature in the data that disqualifies the two models of generation or a combination of them. However, there is no direct evidence that either of the models has been validated. Much complication is introduced by the fact that no unequivocal correspondence has been found between waves in space and the Pc 3, 4 pulsations on the ground. The disparity between the waves in the two media limit the scope of the signal model in the data rather severely. In this situation the data could be explained better in the framework in which the waves in space and the Pc 3, 4 pulsations on the ground are generated by two separate mechanisms. The low frequency waves observed upstream would be generated by ion-cyclotron-resonant wave particle instability, described (as has been outlined) by Barnes (1970) and Kovner et al. (1976). The Pc 3, 4
pulsations on the ground would be generated by excitation of surface waves at the magnetopause by the K-H instability as described by Southwood (1968), Boller and Stolov (1973) and modified by Golikov et al. (1980). It is important (on the basis of the data presented in this study) that the two mechanisms work independently in such a manner that any similarity between the waves in the two media could be regarded as coincidental.

It is to be noted that the scope for the K-H mechanism theory has been limited to the pulsations with longer periods than the P_c 3, 4 pulsations. The theory predicts the diurnal variation in the E-W phase motion. Olson and Rostoker (1978) and Hughes et al. (1978) found the diurnal variation in their data consisting mainly of the P_c 5 pulsation activity. The K-H theory has had no encouraging experimental results in connection with the P_c 3, 4 pulsations. Green (1976), Mier Jedrzejowicz and Southerwood (1979, 1981) have detected no diurnal variation in the E-W phase motion as predicted by theory. In fact, Mier Jedrzejowicz and Southwood (1981) concluded that it is unlikely that K-H mechanism is the major source of the solar wind controlled P_c 3, 4 pulsations observed in the midlatitudes.

However, the lack of experimental support reported is not sufficient to discredit the K-H mechanisms. In the absence of an alternative theory of generation of the solar wind controlled P_c 3, 4 activity the K-H mechanism is a good candidate for the explanation of the P_c 3, 4 pulsations reported in this work. Perhaps the scope of the theory would be widened when it is modified successfully in the way such as that suggested by Golikov et al. (1980).
Summary and conclusions

1) An array of five ground stations in the IGS chain of magnetometers was used for statistical study of the dependence of Pc 3, 4 pulsation activity on three major parameters of the solar wind ($V_{SW}$, $\Theta_{xB}$ and B).

2) Regression and correlation analysis was performed to investigate the relation between the Pc 3, 4 activity on the ground and the half-hourly values of the solar wind parameters measured on board the ISEE-2 spacecraft. [The number of half-hourly data points used in the analysis are summarized in table (7:1) and the correlated parameters are listed in table (7:2)].

3) The results of the analysis indicated that, although the degree of correlation between the ground Pc 3, 4 activity and the solar wind parameters differed from station to station, generally there was a good correlation between the ground activity and parameters of the solar wind. Important results revealed by the study are prefaced in the sections 7:1 and 7:2, two of those results are emphasised:

(a) The control of the cone angle on the Pc 3, 4 pulsation activity was found to depend on the frequency of pulsations; the cone angle was related to the Pc 3 pulsations better than the Pc 4 pulsations. No such frequency dependence on the effect of solar wind velocity on the ground Pc 3, 4 activity was detected.

(b) If the F-B relation was to be fitted to the data, the relationship of the form $F = C_0 + C_1 B$ was found to be statistically better fit than $F = CB$. 
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Number of points</th>
<th>Reference figures</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) 30-minute spectra of ground pulsations</td>
<td>1514</td>
<td>4:10, 4:17, 4:34 - 4:38</td>
</tr>
<tr>
<td>(b) 30-minutes solar wind velocity: ISEE 2</td>
<td>1402 1616</td>
<td>4:8a</td>
</tr>
<tr>
<td>IMP 7, 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(c) 30-minutes IMF magnitude</td>
<td>1053</td>
<td>4:8b</td>
</tr>
<tr>
<td>(d) 30-minutes cone angles ($\Theta_{XB}$)</td>
<td>1053</td>
<td>4:8c</td>
</tr>
<tr>
<td>(e) (c) and (d)</td>
<td>713</td>
<td>4:7c</td>
</tr>
<tr>
<td>(f) (c) and (b)</td>
<td>713</td>
<td>4:7a</td>
</tr>
<tr>
<td>(g) (b) and (d)</td>
<td>713</td>
<td>4:7b</td>
</tr>
<tr>
<td>(h) (a) and (b)</td>
<td>788</td>
<td>4:10</td>
</tr>
<tr>
<td>(i) (a) and (c)</td>
<td>788</td>
<td>4:34 - 4:38</td>
</tr>
<tr>
<td>(j) (a) and (d)</td>
<td>788</td>
<td>4:17</td>
</tr>
</tbody>
</table>
TABLE (7:2) Observational relations between solar wind parameters and Pc3, 4 pulsations on the ground

<table>
<thead>
<tr>
<th>Correlated Parameters</th>
<th>Solar Wind Parameters</th>
<th>General Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occurrence and/or amplitude</td>
<td>Vsw</td>
<td>Positive correlation</td>
</tr>
<tr>
<td></td>
<td>θ_{XB} (IMF rad)</td>
<td>Negative correlation</td>
</tr>
<tr>
<td>Frequency</td>
<td>B</td>
<td>Positive correlation</td>
</tr>
</tbody>
</table>
The F-B relation improved considerably when the same frequency of pulsations was recorded simultaneously over a large area on the surface of the Earth.

4) High time resolution magnetic data measured on board the ISEE-2 satellite were used to study the morphological characteristics of low-frequency (10 - 80 mHz) upstream waves.

5) The results of the investigation of the upstream waves indicated that the waves vary in their wave forms in such a manner that they were divided into three main classes, the Pc-like waves, the quasi-periodic oscillations, and the discrete wave 'bundles'.

   The Pc-like waves were the continuous pulsations similar in type to Pc whose dominant period was in the range of 30 - 45 sec. The quasi-periodic oscillations were the incoherent waves distinguished by mixed-period fluctuations which often lasted for several hours. The 'bundles' were the relatively isolated discrete wave packets with the dominant period range of 25 - 35 sec. All classes had an average amplitude of 4 - 5 nT. The waves were dominantly transverse with enhanced By and Bz components, but compressional oscillations were also quite common.

6) The occurrence and/or amplitudes of the upstream waves were found to depend on the IMF orientation expressed best in terms of local shock geometry.

7) The dependence of the frequency of the upstream waves on the IMF magnitude was tested and the functional relationship between their frequency and the IMF magnitude was found to be best expressed in the form of

\[ F = C_0 + C_1 B. \]
Comparison between the waves on board the ISEE-2 satellite and the Pc 3, 4 recorded simultaneously at high latitude \( (L = 4.3) \) and low latitude \( (L = 2.4) \) ground stations showed that similarity of spectra of the waves in the solar wind and the ground was very rare and correspondence between events was extremely low.

The overall results both of the ground and satellite data were discussed in the context of 'signal' and 'surface wave' models of generation of the solar wind controlled pulsations. Although there was no evidence in the data that disqualifies any of the models, it was difficult for the two models to operate separately or jointly.

It was concluded that:

(a) The ground pulsations are influenced by three major solar wind parameters, \( V_{SW} \), \( \theta_{XB} \) and B.

(b) The waves in the solar wind depend on the IMF orientation and the IMF magnitude.

(c) There is no direct link between the waves in the solar wind and the Pc 3, 4 pulsations on the ground.

Suggestions for further work

Further study is necessary to relate the Pc 3, 4 pulsations on the ground and low frequency waves in the interplanetary medium.

1) A considerable amount of solar wind plasma and magnetic field data is now available from the ISEE-2 satellites. The data should be subjected to a much fuller analysis in an attempt to bring out more detailed knowledge of the solar wind parameters and to continue empirical studies which will build up a valid picture
of morphology of the pulsations in the inter-
planetary medium in all local time sectors of the
dayside hemisphere.

Attempts to correlate the level of Pc 3, 4
activity with the solar wind velocity should focus
on the pre-noon events.

2) An extended latitudinal and longitudinal profiles
of ground stations such as the ones provided by the
IGS array of magnetometers should be used to bring
out cases where direct link between pulsations in the
solar wind and on the ground exists. Particular
attention should be focussed on individual special
events, both in space and on the ground, which are
apparently similar, in order to confirm or deny the
speculation that similarity of wave activity in space
and on the ground is a matter of coincidence.

3) Fine structure analysis should be applied partic-
icularly to the coherent and monochromatic upstream
waves (designated in this work as the Pc-like waves)
in an attempt to investigate their polarization and
propagation characteristics. Such a study will be
helpful to find out whether the upstream waves are
essentially propagating away or towards the Earth.

The three tasks itemed above are suitable for
individual initiative; the item below is of a cooperative
nature, indeed of international participation. It
is to be noted that if the three tasks above are
carried out with positive results, the item below
would be expensive and unnecessary.

4) Three or more spacecraft should be positioned in
the morning and afternoon sectors of the interplanetary
medium to monitor simultaneous upstream wave events which can be compared with the Po 3, 4 activity on the ground. Alternatively the spacecraft should be placed in three regions in the dayside hemisphere along the subsolar point, one in the interplanetary medium, another at the magnetopause and the other in the magnetosphere at a geostationary orbit linked to a ground station by flux tube. The array of three or more spacecraft and ground stations would make it possible to track down waves coming directly from the solar wind through the magnetosphere to the ground.
APPENDIX (A1)

The frequency response of the running mean filter used in section 6.2 is given by

\[ H(p) = \frac{\sin N \pi p/2}{N \sin \pi p/2} \quad \text{(A1.1)} \]

where \( p = f/f_Ny \), \( f_Ny \) is the Nyquist frequency.

\[ f/f_Ny = f/2\Delta t \]
\[ = (2\Delta t)/T \]

\( \Delta t \) is sampling interval, \( T \) is period. Substituting \( p \) in equation (A1.1) and taking \( \Delta t = 2.5 \) sec (the sampling interval of IGS digital magnetic field data) and \( N = 25 \), equation (A1.2) is obtained

\[ H(T) = \frac{\sin 62.5\pi/T}{25 \sin 2.5\pi/T}, \quad T \to \infty \quad \text{(A1.2)} \]

If the running mean is removed from the data, the data is effectively high pass filtered with a response function given by

\[ G(T) = 1 - H(T) \]
\[ = 1 - \frac{\sin 62.5\pi/T}{25 \sin 2.5\pi/T} \quad \text{(A1.3)} \]
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