Polarised radio emission from pulsars and the influence of the magnetosphere

Author: Cristina D. ILIE
Supervisor: Dr. Patrick WELTEVREDE

A thesis submitted to the University of Manchester for the degree of Doctor of Philosophy in the School of Physics and Astronomy Faculty of Science and Engineering

2019
# Contents

Contents .......................... 2  
List of Figures ...................... 10  
List of Tables ....................... 11  
Abbreviations ....................... 12  
Abstract .......................... 13  
Declaration of Authorship .......... 14  
Copyright Statement ............... 15  
Acknowledgements .................. 17  
Dedication ........................ 20  
The Author ........................ 21  
Publications ....................... 22  

## 1 Introduction .......................... 23  
1.1 General properties of a pulsar .................................. 24  
  1.1.1 Pulsar spin-down ........................................ 24  
  1.1.2 Characteristic age ...................................... 25  
  1.1.3 Surface magnetic field strength .......................... 26  
  1.1.4 The pulsar population .................................. 27  
1.2 Basic pulsar analysis techniques .............................. 29  
  1.2.1 Polarisation properties of radio pulses ................. 29  
  1.2.2 Interstellar medium effects ............................. 32  
    Dispersion ............................................... 32  
    Interstellar scattering ................................. 33
1.2.3 Polarisation calibration ........................................ 35
1.2.4 Creating pulse-stacks from time series ....................... 37
1.3 Individual pulses and drifting subpulses ....................... 39
1.4 Pulsar magnetospheres ......................................... 40
1.5 Polarised integrated pulse profiles .............................. 44
1.6 The Rotating Vector Model ..................................... 46
1.7 Orthogonal Polarisation Modes .................................. 48
1.8 The outline of the thesis ........................................ 51

2 Modulation of polarisation and drifting subpulses for PSR B0031–07 52
2.1 Introduction ...................................................... 53
2.2 Observations ..................................................... 55
2.3 Analysis .......................................................... 56
  2.3.1 Drift modes .................................................. 57
    The modulation index ........................................... 58
    LRFS ............................................................ 59
    2DFS ............................................................ 63
  2.3.2 Mode analysis: Polarisation properties ..................... 64
  2.3.3 Mode analysis: P3-folding ................................ 69
2.4 Discussion ....................................................... 73
2.5 Summary and Conclusions ...................................... 77

3 Survey for modulated radio polarisation and drifting subpulses 79
3.1 Introduction ...................................................... 80
3.2 Observations ..................................................... 81
3.3 Analysis techniques .............................................. 82
3.4 Results and discussion of individual pulsars ................... 84
  3.4.1 Pulsars with synchronous modulated OPMs and drifting sub-
    pulses .......................................................... 84
    PSR J0820–1350/B0818–13 .................................. 84
    PSR J1048–5832/B1046–58 ................................... 90
    PSR J1110–5637/B1107–56 ................................... 92
    PSR J1453–6413/B1449–64 ................................... 97
    PSR J1645–0317/B1642–03 ................................ 101
    PSR J1720–2933/B1717–29 ................................ 103
    PSR J1921+2153/B1919+21 ................................ 108
    PSR J2046–0421/B2043–04 ................................ 111
3.4.2 Pulsars with non-synchronous modulated OPMs and drifting subpulses ........................................ 113
PSR J1932+1059/B1929+10 .................................. 113
PSR J2048–1616/B2045–16 .................................. 119

3.4.3 Pulsars with mixture of OPMs and non-random modulated intensity .................................................. 123
PSR J0738–4042/B0736–40 .................................. 123
PSR J1456–6843/B1451–68 .................................. 127

3.4.4 Pulsars with periodic modulation, and no OPM mixture ................................................................. 134
PSR J0630–2834/B0628–28 .................................. 134
PSR J1057–5226/B1055–52 .................................. 134
PSR J1539–5626/B1535–56 .................................. 135
PSR J1603–2531 .................................................. 138
PSR J1605–5257/B1601–52 .................................. 139
PSR J1651–5222/B1647–52 .................................. 140
PSR J1722–3207/B1718–32 .................................. 141
PSR J1733–2228/B1730–22 .................................. 142
PSR J1741–0840/B1738–08 .................................. 143
PSR J1745–3040/B1742–30 .................................. 145
PSR J1757–2421/B1754–24 .................................. 146
PSR J1817–3618/B1813–36 .................................. 146
PSR J1825–0935/B1822–09 .................................. 149
PSR J1847–0402/B1844–04 .................................. 151
PSR J1900–2600/B1857–26 .................................. 152
PSR J1946+1805/B1944+17 .................................. 153
PSR J2346–0609 .................................................. 155

3.4.5 Pulsars with OPM mixture, and no periodic modulation ................................................................. 155
PSR J1136+1551/B1133+16 .................................. 155
PSR J1731–4744/B1727–47 .................................. 157

3.5 Discussion and Conclusions ........................................... 159

4 Evidence for magnetospheric effects on the radiation of pulsars 165
4.1 Introduction ................................................... 165
4.2 Observations .................................................. 167
4.3 Method ....................................................... 168
4.3.1 Systematic uncertainties ................................. 171
4.4 Results ....................................................... 176
4.4.1 Pulsars with significant RM variations ................. 177
## Polarisation properties of new GHRSS discoveries

### 5

<table>
<thead>
<tr>
<th>Subsection</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 Introduction</td>
<td>211</td>
</tr>
<tr>
<td>5.2 The geometry of radio beams</td>
<td>214</td>
</tr>
<tr>
<td>5.3 Observations</td>
<td>217</td>
</tr>
<tr>
<td>5.4 Analysis and discussion of individual pulsars</td>
<td>218</td>
</tr>
<tr>
<td>5.4.1 PSR J0418–4154</td>
<td>218</td>
</tr>
<tr>
<td>5.4.2 PSR J0514–4407</td>
<td>218</td>
</tr>
<tr>
<td>5.4.3 PSR J2144–5237</td>
<td>223</td>
</tr>
<tr>
<td>5.5 Summary and Conclusions</td>
<td>225</td>
</tr>
</tbody>
</table>

## Conclusions

### 6

<table>
<thead>
<tr>
<th>Subsection</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Phase-resolved RM Plots</td>
<td>233</td>
</tr>
</tbody>
</table>

Word count: 55,705
List of Figures

1.1 Schematic diagram of the geometry of a radio pulsar .......................... 25
1.2 Period and period derivative diagram ................................................ 28
1.4 Small section of the pulse-stack of PSR J0820–1350 .......................... 39
1.5 Simulation of drifting subpulses patterns based on different line of sights intersecting a carousel beam ......................................................... 41
1.6 Examples of various integrated polarisation profiles ........................... 45
1.7 Projected magnetic field lines on a plane orthogonal to the line of sight of the observer ............................................................... 47
1.8 Schematic diagram of a cross-sectional top-down view the emission beam with two offset circulating carousel systems ......................... 50
2.1 Section of PSR B0031–07 pulse-stacks showing both mode A and mode B of drifting at 1369 MHz and 310 MHz ............................... 59
2.2 Distribution of the duration of stretches of data in a certain mode of drifting .................................................................................... 60
2.3 Fluctuation analysis of PSR B0031–07 for the combined and mode separated data ............................................................................. 61
2.4 Polarisation properties of PSR B0031–07 for the combined and mode separated dataset ............................................................... 65
2.5 Distribution of polarisation orientations for all pulse longitudes of PSR B0031–07, on Poincarè spheres for the combined and mode separated data-set ........................................................................ 68
2.6 $P_3$-folds of mode A and mode B of drifting for PSR B0031–07 .... 71
3.1 Polarisation properties of PSR J0820–1350 ...................................... 85
3.2 Poincarè spheres of PSR J0820–1350 .............................................. 87
3.3 Fluctuation analysis and pulse-stack of PSR J0820–1350 .................. 88
3.4 $P_3$-folds of PSR J0820–1350 .......................................................... 90
3.5 Polarisation properties of PSR J1048–5832 ........................................ 91
3.6 Poincarè sphere of PSR J1048–5832 ................................................. 92
3.7 Fluctuation analysis of PSR J1048–5832 ...................................... 93
3.8 $P_3$-folds of PSR J1048–5832 ............................................. 93
3.9 Polarisation properties of PSR J1110–5637 ............................. 94
3.10 Poincarè sphere of PSR J1110–5637 ................................ 95
3.11 Fluctuation analysis of PSR J1110–5637 ............................ 96
3.12 $P_3$-folds of PSR J1110–5637 ............................................. 97
3.13 Polarisation properties of PSR J1453–6413 .......................... 98
3.14 Fluctuation analysis of PSR J1453–6413 ............................ 99
3.15 $P_3$-folds of PSR J1453–6413 ............................................. 100
3.16 Polarisation properties of PSR J1645–0317 .......................... 101
3.17 Poincarè spheres of PSR J1645–0317 .............................. 102
3.18 Fluctuation analysis and pulse-stack of PSR J1645–0317 ........ 104
3.19 $P_3$-folds of PSR J1645–0317 ............................................. 104
3.20 Polarisation properties of PSR J1720–2933 .......................... 105
3.21 Poincarè sphere of PSR J1720–2933 .............................. 106
3.22 Fluctuation analysis of PSR J1720–2933 ............................ 107
3.23 $P_3$-folds of PSR J1720–2933 ............................................. 107
3.24 Polarisation properties of PSR J1921+2153 ......................... 108
3.25 Fluctuation analysis of PSR J1921+2153 ............................ 109
3.26 $P_3$-folds of PSR J1921+2153 ............................................. 110
3.27 Polarisation properties of PSR J2046–0421 .......................... 111
3.28 Fluctuation analysis of PSR J2046–0421 ............................ 112
3.29 $P_3$-folds of PSR J2046–0421 ............................................. 113
3.30 Polarisation properties of PSR J1932+1059 .......................... 114
3.31 Poincarè sphere of PSR J1932+1059 ................................ 115
3.32 Fluctuation analysis of PSR J1932+1059 ............................ 116
3.33 $P_3$-folds of PSR J1932+1059 ............................................. 117
3.34 $P_3$-folds of PSR J1932+1059 ............................................. 117
3.35 $P_3$-folds of PSR J1932+1059 using IP phases ....................... 118
3.36 Polarisation properties of PSR J2048–1616 ........................ 120
3.37 Poincarè sphere of PSR J2048–1616 .............................. 121
3.38 Fluctuation analysis of PSR J2048–1616 ............................ 122
3.39 $P_3$-folds of PSR J2048–1616 ............................................. 123
3.40 Polarisation properties of PSR J0738–4042 ........................ 124
3.41 Poincarè sphere of PSR J0738–4042 ................................ 125
3.42 Fluctuation analysis of PSR J0738–4042 ............................ 126
3.43 Pulse energy analysis for PSR J0738–4042 ........................ 128
3.44 Polarisation properties of PSR J1456–6843 ........................ 129
3.45 Poincarè sphere of PSR J1456–6843 ........................................ 130
3.46 Fluctuation analysis of PSR J1456–6843 .......................... 131
3.47 Pulse energy analysis for PSR J1456–6843 ...................... 132
3.48 Polarisation and fluctuation analysis of PSR J0630–2834 ....... 133
3.49 Fluctuation analysis of PSR J1057–5226 ......................... 135
3.50 Polarisation properties of PSR J1057–5226 ..................... 136
3.51 Polarisation and fluctuation analysis of PSR J1539–5626 ....... 137
3.52 Polarisation and fluctuation analysis of PSR J1603–2531 ...... 138
3.53 Polarisation and fluctuation analysis of PSR J1605–5257 ...... 139
3.54 Polarisation and fluctuation analysis of PSR J1651–5222 ....... 140
3.55 Polarisation and fluctuation analysis of PSR J1722–3207 ...... 141
3.56 Polarisation and fluctuation analysis of PSR J1733–2228 ...... 142
3.57 Polarisation and fluctuation analysis of PSR J1741–0840 ...... 144
3.58 Polarisation properties of PSR J1745–3040 ..................... 145
3.59 Polarisation and fluctuation analysis of PSR J1757–2421 ...... 147
3.60 Polarisation and fluctuation analysis of PSR J1817–3618 ...... 148
3.61 Polarisation properties of PSR J1825–0935 ..................... 149
3.62 Fluctuation analysis of PSR J1825–0935 ........................ 150
3.63 Polarisation properties of PSR J1847–0402 ..................... 151
3.64 Polarisation and fluctuation analysis of PSR J1900–2600 ...... 152
3.65 Polarisation and fluctuation analysis of PSR J1946+1805 ...... 153
3.66 Polarisation and fluctuation analysis of PSR J2346-0609 ...... 154
3.67 Polarisation properties of PSR J1136+1551 ..................... 156
3.68 Fluctuation analysis of PSR J1136+1551 ....................... 157
3.69 Polarisation properties of PSR J1731–4744 ..................... 158
3.70 Fluctuation analysis of PSR J1731–4744 ....................... 159
3.71 Period and period derivative diagram ............................ 160

4.1 Phase-resolved RM plot for PSR J1703–3241 .................... 172
4.2 Simulations demonstrating the effect of scattering with a timescale
of 4 and 8 ms, for a pulse period of 1 sec. ......................... 173
4.3 Simulating the effect of adding misaligned observations with vary-
ing RM of the ionosphere RM_{iono} for PSR J0835–4510 ....... 175
4.4 DM distributions for pulsars with or without RM variations .... 202
4.5 The amplitude of phase-resolved apparent RM variations, ΔRM, as
a function of their DM. .................................. 204
4.6 Measured scattering timescales, τ_s, scaled to 1.4 GHz, as a function
of DM. .................................. 205
4.7 A histogram of the number of profile components for pulsars with and without apparent RM variations 206
4.8 A histogram of the number of profile components for pulsars with a shallow or a steep PA swing 206
4.9 PA residuals after removing a $\lambda^2$ dependence for pulse longitude $150^\circ$ and scattering timescale of 8 ms in the simulations displayed in Fig. 4.2 207

5.1 Schematic diagram showing where $\gamma$-rays originate in the pulsar magnetosphere in the outer gap model and the two pole caustic model 212
5.2 Pulse profiles for PSR J0418–4154, J0514–4408 and J2144–5237 213
5.3 Schematic diagrams showing the geometry of the radio beam of a pulsar 215
5.4 Polarimetry profiles for PSRs J0418–4154, J0514–4407 and J2144–5237 219
5.5 Intensity profiles of PSR J0514–4407 at 322, 650 and 1369 MHz 221
5.6 Intensity profiles of PSR J2144–5237 at 322, 650 and 1369 MHz 225

A.5 Phase-resolved RM plots for PSR J0837–4135, PSR J0907–5157, PSR J0908–4913 (MP) and PSR J0908–4913 (IP) 238
A.7 Phase-resolved RM plots for PSR J1048–5832, PSR J1056–6258, PSR J1057–5226 (MP) and PSR J1057–5226 (IP) 240
A.11 Phase-resolved RM plots for PSR J1401–6357, PSR J1428–5530, 
PSR J1430–6623 and PSR J1453–6413. For more details on what 
is displayed in the individual panels, see Fig. 4.1. . . . . . . . . . 244
A.12 Phase-resolved RM plots for PSR J1456–6843, PSR J1512–5759, 
PSR J1522–5829 and PSR J1534–5334 . . . . . . . . . . . . . . . . . . 245
A.13 Phase-resolved RM plots for PSR J1539–5626, PSR J1544–5308, 
PSR J1555–3134 and PSR J1557–4258 . . . . . . . . . . . . . . . . . . 246
A.14 Phase-resolved RM plots for PSR J1559–4438, PSR J1602–5100, 
PSR J1604–4909 and PSR J1605–5257 . . . . . . . . . . . . . . . . . . 247
A.15 Phase-resolved RM plots for PSR J1633–4453, PSR J1633–5015, 
PSR J1644–4559 and PSR J1646–6831 . . . . . . . . . . . . . . . . . . 248
A.16 Phase-resolved RM plots for PSR J1651–4246, PSR J1651–5222, 
PSR J1653–3838 and PSR J1701–3726 . . . . . . . . . . . . . . . . . . 249
A.17 Phase-resolved RM plots for PSR J1703–3241, PSR J1705–1906 
(MP), PSR J1705–1906 (IP) and PSR J1705–3423 . . . . . . . . . . 250
A.18 Phase-resolved RM plots for PSR J1709–1640, PSR J1709–4429, 
PSR J1717–3425 and PSR J1721–3532 . . . . . . . . . . . . . . . . . . 251
A.19 Phase-resolved RM plots for PSR J1722–3207, PSR J1722–3712 
(MP), PSR J1722–3712 (IP) and PSR J1731–4744 . . . . . . . . . . 252
A.20 Phase-resolved RM plots for PSR J1739–2903 (MP), PSR J1739–2903 
(IP), PSR J1740–3015 and PSR J1741–3927 . . . . . . . . . . . . . . 253
A.21 Phase-resolved RM plots for PSR J1745–3040, PSR J1751–4657, 
PSR J1752–2806, and PSR J1807–0847. For more details on 
what is displayed in the individual panels, see Fig. 4.1. . . . . . . . . 254
A.22 Phase-resolved RM plots for PSR J1817–3618, PSR J1820–0427, 
PSR J1822–2256 and PSR J1823–3106 . . . . . . . . . . . . . . . . . . 255
A.23 Phase-resolved RM plots for PSR J1824–1945, PSR J1825–0935 
(MP), PSR J1825–0935 (IP) and PSR J1829–1751 . . . . . . . . . . 256
A.24 Phase-resolved RM plots for PSR J1830–1059, PSR J1832–0827, 
PSR J1845–0743 and PSR J1847–0402 . . . . . . . . . . . . . . . . . . 257
A.25 Phase-resolved RM plots for PSR J1848–0123, PSR J1852–0635, 
PSR J1900–2600 and PSR J1913–0440 . . . . . . . . . . . . . . . . . . 258
A.26 Phase-resolved RM plots for PSR J1941–2602, PSR J2048–1616, 
PSR J2330–2005 and PSR J2346–0609 . . . . . . . . . . . . . . . . . . 259
List of Tables

3.1 Table showing details of the pulsars observed as part of the survey investigating whether the modulation of the polarisation properties with drifting subpulses is common .......................... 83

4.1 Results from the phase-resolved Faraday rotation analysis of 98 pulsars ............................................................. 181

4.2 Pulsars which show no significant phase-resolved rotation measure variations ..................................................... 195

4.3 Table summarising the observational results from investigating the phase-resolved rotation measure variations, such as the classification of whether a pulsar showed significant variations or not; or whether the observed variations can be explained by scattering alone, or magnetospheric effects play an important role . . . . . 197

4.4 A list of pulsars for which we discovered magnetospheric effects caused phase-resolved RM variations .......................... 200

5.1 Table summarising the parameters of three newly discovered pulsars from GHRSS ................................................. 214
List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATNF</td>
<td>Australia Telescope National Facility</td>
</tr>
<tr>
<td>DFT</td>
<td>Discrete Fourier Transform</td>
</tr>
<tr>
<td>DM</td>
<td>Dispersion Measure</td>
</tr>
<tr>
<td>GHRSS</td>
<td>GMRT High Resolution Southern Sky</td>
</tr>
<tr>
<td>GMRT</td>
<td>Giant Metrewave Radio Telescope</td>
</tr>
<tr>
<td>ISM</td>
<td>Inter-Stellar Medium</td>
</tr>
<tr>
<td>LRFS</td>
<td>Longitude Resolved Fluctuation Analysis</td>
</tr>
<tr>
<td>MSP</td>
<td>Milli-Second Pulsar</td>
</tr>
<tr>
<td>OPM</td>
<td>Orthogonal Polarization Mode</td>
</tr>
<tr>
<td>PA</td>
<td>Polarization Angle</td>
</tr>
<tr>
<td>PSR</td>
<td>Pulsating Source of Radio</td>
</tr>
<tr>
<td>RFI</td>
<td>Radio Frequency Interference</td>
</tr>
<tr>
<td>RFM</td>
<td>Radio to Frequency Mapping</td>
</tr>
<tr>
<td>RM</td>
<td>Rotation Measure</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>RMST</td>
<td>Rotation Measure Synthesis Technique</td>
</tr>
<tr>
<td>RVM</td>
<td>Rotating Vector Model</td>
</tr>
<tr>
<td>S/N</td>
<td>Signal-to-Noise ratio</td>
</tr>
<tr>
<td>ToA</td>
<td>Time of Arrival</td>
</tr>
<tr>
<td>WRST</td>
<td>Westerbork Synthesis Radio Telescope</td>
</tr>
</tbody>
</table>
Abstract

Since the discovery of pulsars 50 years ago, a lot of progress has been made in understanding how the radio emission mechanism of pulsars works. Nevertheless, explaining the wealth of observational phenomenology has proven difficult. In this thesis, we investigated the radio polarisation properties of pulsars. It has become clear that the propagation of radio emission in the pulsar magnetosphere plays a major role in shaping the observed radiation, especially where polarisation is considered.

We started by studying the time-dependence of radio polarisation by observing the polarisation properties of individual pulses of PSR B0031–07, a pulsar with multiple stable drift modes. Furthermore, using a larger sample of 31 pulsars, we aimed to explore if it is common for switches between orthogonal polarisation modes (OPMs) to be linked to periodic intensity variability. Eleven pulsars in the sample showed both a mixture of OPMs and drifting subpulses. Out of these, nine showed synchronous switching of OPMs with the drifting subpulses and for the remaining two pulsars we showed that the drifting might well be too complex to reveal the link between polarisation and the periodic intensity variations. So if the pulsar has OPM switches, it is most likely linked to drifting subpulses if present. This is argued to be a consequence of propagation effects in the pulsar magnetosphere. Even if no periodic intensity variations are observed, it was established that changes in polarisation are coupled to variability in intensity.

The frequency dependence of radio polarisation was studied by conducting the largest investigation to date into the origin of phase resolved apparent rotation measure (RM) variations in the polarised signals of 98 radio pulsars. A total of 42 pulsars showed significant phase resolved apparent RM variations. Our results are inconsistent with all variations being caused by interstellar scattering. Instead, magnetospheric propagation is argued to be important, and thus leaving a frequency dependent imprint in the observed polarised radiation.

Lastly, we investigated the polarisation properties of three newly discovered pulsars from the GMRT High Resolution Southern Sky Survey to get geometrical information about the pulsar and its emission beams. We conclude that the magnetic axis of PSR J0514–4407 is highly inclined with respect to the rotation axis. This is consistent with what we would expect given that is it a gamma-ray emitting pulsar.
Declaration of Authorship

I, Cristina D. Ilie, declare that this thesis titled, “Polarised radio emission from pulsars and the influence of the magnetosphere” and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.

- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.

- Where I have consulted the published work of others, this is always clearly attributed.

- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.

- I have acknowledged all main sources of help.

- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.
Copyright Statement

(i) The author of this thesis (including any appendices and/or schedules to this thesis) owns certain copyright or related rights in it (the “Copyright”) and s/he has given The University of Manchester certain rights to use such Copyright, including for administrative purposes.

(ii) Copies of this thesis, either in full or in extracts and whether in hard or electronic copy, may be made only in accordance with the Copyright, Designs and Patents Act 1988 (as amended) and regulations issued under it or, where appropriate, in accordance with licensing agreements which the University has from time to time. This page must form part of any such copies made.

(iii) The ownership of certain Copyright, patents, designs, trademarks and other intellectual property (the “Intellectual Property”) and any reproductions of copyright works in the thesis, for example graphs and tables (“Reproductions”), which may be described in this thesis, may not be owned by the author and may be owned by third parties. Such Intellectual Property and Reproductions cannot and must not be made available for use without the prior written permission of the owner(s) of the relevant Intellectual Property and/or Reproductions.

(iv) Further information on the conditions under which disclosure, publication and commercialisation of this thesis, the Copyright and any Intellectual Property and/or Reproductions described in it may take place is available in the University IP Policy¹, in any relevant Thesis restriction declarations deposited in the University Library, The University Library’s regulations² and in The University’s policy on Presentation of Theses.

¹See documents.manchester.ac.uk
²See www.library.manchester.ac.uk/about/regulations/
“The time you enjoy wasting is not wasted time.”

Bertrand Russell
Acknowledgements

There are a number of people I would like to thank for the support, guidance and friendship, without whom this thesis would not have been possible. I know I am not very good at expressing my feelings in words, however here I gave it my best try and I hope I was able to express my gratitude to you all. First and foremost, I would like to thank my supervisor Dr. Patrick Weltevrede. Words cannot even begin to describe how grateful I am for all the times you spent helping and guiding me towards being a good researcher. You have been patient, even when you needed to explain a concept to me a couple of times, because I did not understand it the first time. You have always given me great ideas and supported me throughout my whole PhD.

I would like to thank Dr. Simon Johnston, who has taken the role of my second supervisor for all the projects I have worked on. You have been very helpful and have guided me into becoming a better researcher which writes more concisely (a lot more concisely!). Thanks to you I had the wonderful opportunity to leave Europe for the first time and come to Sydney, Australia and work with you for a month. You were very welcoming and helped me accommodate to my new environment.

I would also like to thank Prof. Benjamin Stappers, Dr. Michael Keith, Dr. Ben Perrera and Dr. Lina Levin-Preston for all their helpful advice throughout the duration of my PhD. Regardless of your busy schedules, you have always been happy to help me with all my problems, big and small.

Dr. Benjamin Shaw. You have helped me numerous times by answering all my random scripting or programming questions and so many more other random ones (also my gossip buddy). I feel that you were more than just my colleague, you became my friend, even if I annoyed you at times. The office was for sure a happier place when you were there. We shared shared many great times, laughs, snacks and trips to get bubble tea (I mean lunch)! And I hope that in many years time I will have the honour to be Prof. Ben Shaw’s friend, because are made to become a researcher and you deserve it.

Chia Min and Elliott. We have started our PhD journey together in 2015, and here we are three and a half years later all finishing together. You guys have been my companions, my office and snack buddies and I will miss you very much. I was very lucky to share an office with such great people from which I had lots to learn from.
I would also like to thank all my other pulsar friends: James McKee, Simon Rookyard, Sally Cooper, Thomas Scragg, Crispin Agar, Lin Wang and Mitch Mickaliger for making my PhD experience more enjoyable. It has been wonderful to meet you all and I will miss you very much.

I would like to thank Laura Driessen for firstly, creating this awesome thesis template and saving me a lot of time and of course for becoming my good friend in such a short amount of time. Before your arrival to Manchester, I lost hope that I could make any good friends at this age. For sure I had more fun in the last year and a half than I had in the rest of my PhD. Of course I will be forever grateful to you for introducing me to pole fitness, which has helped me get into the best form of my life, as well as meet a wonderful group of girls.

I would also like to thank the wonderful people from the “Brunch group”: Manisha Caleb, Charles Walker, Chia Min, Tana Dale Joseph, Kaustubh Rajwade, Rohini Joshi, Tiaan Bezuidenhout, Alex Clarke, Josh Hayes, Mark Kennedy and Therese Cantwell who made the last year and a half of my PhD the most memorable. We did much more than to go for brunch at the weekends, cinema, parties, Eurovision parties, picnics and many more.

Outside of my JBCA community, there are several people I would like to thank. Of course, Chris I would firstly like to thank you. Without you, for sure the PhD would not have been as fun as it was. We have worked together, travelled to spectacular destinations, cooked many feasts, baked a lot of cakes, played a lot of games, and laughed so much on this journey. I would like to thank you for your help, patience and support that you have given me. I hope our next adventure will be even more fun!

Simona and Alexandra. You are my oldest and dearest friends, and even if there have been more than 2200 km between us for the past seven years, that did not stop our friendship. You have been there for me since we were in highschool and I know I can always count on your help and support in dark times. Every time we saw each other, it was like nothing has changed between us, and our Christmas times spent together have helped me re-charge my batteries and be ready to go back to work more determined than ever. One tradition which has stayed with us and hope will continue until we are really old, must be our silly reunion photo sessions.

My mother and grandparents. Without your constant love, support, including financial support, and self-sacrifice I would not even be in Manchester. I do not even know how to thank you mum, for the immense effort you made when in 2011 you decided to make my dream come true and help me go to Manchester
so I could study Astrophysics. And of course, you supported me for every international exam I thought I needed, in order to become a better student. And to think this started one day when I was 13 years old and I came to you and said ‘Mum, I want to go and study science abroad!’. You did not even believe me at first. Our calls every day have certainly brighten my days and reminded me that my family is always there to support me.

My brother Dan. Although we have not known each other our whole lives, I feel we have become good friends. I would like to thank you for the support you have given me to become a British citizen and for all the wonderful times we spent in Bucharest every time I visited home.

Dad, it has been more than 12 years since cancer took you away from us. The day I am writing this would have in fact been your 61st birthday. Although you were not there to send me to university, or even there when I decided that I would like to follow in your footsteps as a researcher, you WERE the one which inspired my love of physics and mathematics. Since I could walk, you started teaching me about science and engineering, how to take things apart and put them back together etc. Now that we are both Doctors of Science (almost!), I cannot help but wonder: How would a conversation between us go today?
Dedicated to my mum and grandparents

Dedicat mamei și bunicilor mei
The Author

Cristina-Diana Ilie was born on the 23rd of August 1991 in Constanța, Romania, which is where she grew up. She attended the “OVIDIUS” Theoretical High-school, following a bilingual Mathematics-Computer Science curriculum. She graduated from highschool in 2010 with a Primus inter Pares award. She successfully completed a year of Aerospace Engineering at the POLITEHNICA University of Bucharest with an excellence award, before realising she is more interested in research and physics, rather than engineering. Hence, in the search of a challenge, she started an MPhys Physics and Astronomy degree at The University of Manchester in 2011, which she completed with a First Class in 2015. In September 2015, she started her PhD in the Pulsars and Time Domain Astrophysics group at the Jodrell Bank Centre for Astrophysics, at The University of Manchester.
Publications


Chapter 1

Introduction

Pulsars are fast (periods between 1.3 ms and 23.5 sec) rotating neutron stars which have strong magnetic fields (of order $10^{12}$ Gauss), and were discovered by Jocelyn Bell-Burnell and Anthony Hewish in 1967 (Hewish et al., 1968). Neutron stars are compact objects, supported by neutron degeneracy pressure, with radii of about $\sim 10$ km and densities of around $10^{14}$ g cm$^{-3}$. The existence of neutron stars as the final stage of evolution of a high-mass star (between $8 M_\odot$ and $40 M_\odot$) after the supernovae explosion was initially postulated by Baade & Zwicky (1934), however at the time astronomers did not expect neutron stars to be observable after predicting their small sizes and without an especially effective emission mechanism expected (Oppenheimer & Volkoff, 1939).

Once pulsars were identified as neutron stars, their radio pulses were explained as beams of radiation coming from the magnetic poles, somewhere close to the surface of the star. Since the magnetic axis is in general misaligned with the rotation axis, the radiation is observed when the beam passes by Earth, in a similar manner to a lighthouse. Pacini (1968) was the first one to suggest that this misalignment would result in dipole radiation, hence the period of the neutron star will increase over time, i.e. the rotation will slow down. This was first confirmed by observing the pulsar in the Crab Nebula (Richards & Comella, 1969).

Pacini (1968) also suggested that the strong rotating magnetic field will result in a co-rotating magnetosphere surrounding the pulsar, an idea further theoretically developed by Goldreich & Julian (1969). The rotating magnetic field will induce an electric field which will rip charges from the surface of the neutron star. These charges will flow along the magnetic field lines. Hence, the pulsar will be surrounded by a co-rotating magnetosphere of relativistic plasma. The observed radiation is thought to be beamed coherent radio emission which originates in the magnetosphere at a certain height above the magnetic pole.
Chapter 1. Introduction

The structure of this Chapter is as follows. In Section 1.1, we present some of the important parameters used when describing a pulsar, including parameters describing the geometry, as well as an overview of different classes of pulsars. In Section 1.2, the basic techniques used to record and process radio signals of pulsars are described, including how to calibrate and process polarisation information. Section 1.3 presents some of the observed properties of individual pulses, while Section 1.4 summarises how and where the radio emission of pulsars originates. In Section 1.5 we discuss some properties of integrated pulse profiles obtained after averaging over many rotations of the neutron star. Section 1.6 describes a geometrical model aimed to explain the orientation of the observed linear polarisation of pulsars and Section 1.7 describes orthogonal polarisation modes and various models postulated to explain their origin.

1.1 General properties of a pulsar

Some important parameters are introduced here, which are used when defining the geometry of a pulsar. A schematic diagram of a pulsar is presented in Fig. 1.1. The vertical axis in the diagram represents the rotation axis of the neutron star, with $\Omega$ as the rotational angular velocity. The magnetic axis, represented in red in Fig. 1.1, is generally misaligned from the rotation axis with an angle $\alpha$, in order for pulsed emission to be observed. The angle between the magnetic axis and the line of sight of the observer at closest approach, is usually referred to as the impact angle, $\beta$.

1.1.1 Pulsar spin-down

A pulsar is generally considered as a solid sphere which rotates with period $P$ and angular velocity $\Omega = 2\pi/P$. It slows down over time and the period increases with the rate $\dot{P} \equiv dP/dt$, where $t$ represents time.

The rotational energy, which is the rotational kinetic energy, is

$$E_{\text{rot}} = \frac{I\Omega^2}{2},$$  \hspace{1cm} (1.1)

where $I$ is the moment of inertia. The moment of inertia depends on how the mass of the object which rotates is distributed. For a neutron star with uniform density, a radius of 10 km, and a mass of $1.4M_\odot$, $I = 10^{45}$ g cm$^2$. An accurate determination of $I$ requires knowledge of the relationship between the mass and the radius of the neutron star i.e. the equation of state of the star. A lot of
1.1. General properties of a pulsar

Figure 1.1: A schematic diagram of the geometry of a rotating neutron star. Image adapted from Lorimer & Kramer (2005).

Theoretical work has been done in trying to determine this equation (e.g. Steiner et al. 2010; Steiner & Gandolfi 2012; Steiner et al. 2013; Näätänen et al. 2016) but the physics is uncertain. Observationally there are large uncertainties on the measurements of mass and radius, hence it is hard to distinguish between different models.

The rate at which a rotating object will lose rotational energy is

\[
\dot{E} = -dE_{\text{rot}}/dt = -I\Omega (d\Omega /dt) \equiv -I\Omega \dot{\Omega} = 4\pi^2 I\dot{P}/P^3, \tag{1.2}
\]

where \( \dot{E} \) is generally referred to as the \textit{spin-down luminosity} (e.g. Lorimer & Kramer 2005).

1.1.2 Characteristic age

The magnetic field of pulsars is considered to be mainly dipolar (Pacini, 1968). In vacuum, a rotating magnetic dipole loses energy at a rate of

\[
\dot{E}_{\text{dipole}} = \frac{2|m|^2 \Omega^4 \sin^2 \alpha}{3c^3}, \tag{1.3}
\]
where \( \mathbf{m} \) is the magnetic moment, \( c \) is the speed of light and \( \alpha \) is the angle between the rotation axis and the magnetic axis (see Fig. 1.1) (e.g. Jackson 1962). Equation is in cgs units. If the rotational energy loss of a neutron star occurs through magnetic dipole radiation (referred to as magnetic braking), then we can equate equation (1.2) and equation (1.3), in order to obtain

\[
\dot{\Omega} = -\left( \frac{2|\mathbf{m}|^2 \sin^2 \alpha}{3Ic^3} \right) \Omega^3.
\]

(1.4)

We can re-express equation (1.4) in a more general way, in terms of \( \Omega \) or in terms of the period \( P \), as

\[
\dot{\Omega} = -K\Omega^n, \quad \dot{P} = -KP^{2-n},
\]

(1.5)

(1.6)

where \( K \) is a constant and \( n \), the magnetic braking index, is 3 only for pure magnetic braking energy loss. The braking index has been measured for several pulsars (e.g. Kaspi & Helfand 2002; Hobbs et al. 2004, 2010) and many deviations are seen from \( n = 3 \), pointing towards additional physics which causes the spin-down of the pulsar.

If we integrate equation (1.6) and substitute \( K = \dot{P}/P^{2-n} \), then

\[
\tau = t - t_0 = \int_{P_0}^{P} \frac{1}{KP^{2-n}} dP = \frac{P}{\dot{P}(n-1)} \left[ 1 - \left( \frac{P_0}{P} \right)^{n-1} \right],
\]

(1.7)

where \( t_0 \) is the time at the birth of the pulsar, \( P_0 \) is the initial period of the pulsar at \( t_0 \), and \( \tau \) is referred to as the characteristic age. If one considers that the period today is much larger than the initial period of the pulsar \( (P \gg P_0) \) and that \( n = 3 \), then equation (1.7) takes a simpler form,

\[
\tau = \frac{P}{2\dot{P}}.
\]

(1.8)

Although \( \tau \) is a good approximation, it does not necessarily reflect the true age of a pulsar, as several assumptions were made when deriving this equation.

1.1.3 Surface magnetic field strength

In equation (1.4) the magnetic moment can be written in terms of the magnetic field strength and the radius of the neutron star, \( \mathbf{m} = B R^3 \) (Jackson, 1962). If \( \alpha \) is taken to be \( 90^\circ \), \( I = 10^{45} \) g cm\(^{-2} \) (as discussed in Section 1.1.1) an expression
for the **surface magnetic field** is obtained

\[
B_s = 3.2 \times 10^{19} \sqrt{\dot{P} P} \text{ Gauss.} \tag{1.9}
\]

As for the characteristic age of a pulsar (Section 1.1.2), several assumptions were made when deriving \( B_s \), hence equation (1.9) only provides a rough estimation of the magnetic field strength on the surface of a neutron star.

### 1.1.4 The pulsar population

A very useful way to visualise all the previously derived parameters for pulsars \((P, \dot{P}, \tau \text{ and } B_s)\) is via the \( P-\dot{P} \) diagram. An example of a \( P-\dot{P} \) diagram is shown in Fig. 1.2. In the diagram, lines of constant \( \tau \) and \( B_s \) are shown. As one can see, there is a large range of observed pulsar periods, with the slowest known pulsar having a period of \( P = 23.5 \text{ s} \) (PSR J0250 + 5854; Tan et al. 2018) and the fastest pulsar having \( P = 1.4 \text{ ms} \) (PSR J1748–2446ad; Hessels et al. 2006).

From Fig. 1.2, few categories of pulsars can be defined. Firstly, the main island of pulsars visible on the top right-hand side of the plot contains what pulsar astronomers refer to as the **normal pulsars**. Generally, these are pulsars with periods of more than 50 ms and surface magnetic field strengths ranging from \( 10^{11} \) Gauss to \( 10^{13} \) Gauss. Most of the pulsars described in this thesis fall under this category. In the top-left corner of this island, young pulsars are situated. As indicated in the \( P-\dot{P} \) diagram, most of these pulsars are still associated with a supernova remnant. The life of a pulsar is believed to start in this region of the diagram, as the end-point of a supernova explosion, and to evolve along a track downwards until it reaches a region past the **death line** (the yellow shaded region). There is a debate in the literature whether all pulsars are born with similar small periods (Gonthier et al., 2002) of the order of 20 ms (like the Crab pulsar, one of the youngest pulsars), or whether they are born with a wide range of periods (Vivekanand & Narayan, 1981). Past the death line, the pulsars are believed to become **radio quiet**, because they are no longer able to produce radio emission.

Several authors have attempted to replicate how pulsars evolve with time in the \( P-\dot{P} \) diagram (e.g. Ridley & Lorimer 2010; Bates et al. 2014; Gullón et al. 2014). Nevertheless, to this day this is still a highly debated topic. For example, some of these simulations do not include a change of \( \alpha \) over time. There is both observational and theoretical evidence that the magnetic axis and rotation axis become more aligned as the pulsars age (Tauris & Manchester, 1998; Weltevrede & Johnston, 2008; Philippov et al., 2014). Recently, Johnston & Karastergiou
Figure 1.2: $P$-$\dot{P}$ diagram. The pulsars marked with a red star are associated with a supernova remnant (SNR), and the pulsars marked with a blue dot are in a binary system. The information required to produce this plot was obtained from the ATNF pulsar database (Manchester et al., 2005), accessed February 2019, and the tool used to produce it was the Python module PSRQPY, published by Pitkin (2018).
(2017) considered the effect of the decay $\alpha$, as well as its effects on the braking index $n$ in their simulation of pulsar evolution on the $P$-$\dot{P}$ diagram.

Another clearly separated region in the $P$-$\dot{P}$ diagram is in the bottom left corner. These pulsars are known as millisecond pulsars (MSP), as most of them have periods lower than 30 ms. MSPs have lower surface magnetic fields strengths compared to the normal pulsars (under $10^{10}$ Gauss) and are older. As indicated in Fig. 1.2, most MSPs are in a binary system with another stellar object. The MSP are recycled neutron stars which became spin-up through accretion from their companion (Alpar et al., 1982; Radhakrishnan & Srinivasan, 1982). Recently, Manchester (2017) compiled a review of the MSP research done over the past 37 years since the discovery of the first MSP, PSR B1937+21 (Backer et al., 1982).

Another smaller class of neutron stars are magnetars (containing only known 29 objects) (Kaspi & Beloborodov, 2017). These can be found in the top right-hand corner of the $P$-$\dot{P}$ diagram. They have the highest surface magnetic field strengths of the entire pulsar population ($10^{12}$ Gauss to over $10^{14}$ Gauss) and relatively slow periods (between 2 s and 8 s). The magnetars emit most of their radiation in X-rays and in $\gamma$-rays. A catalogue containing a list of the known magnetars and their properties was compiled by Olausen & Kaspi (2014)\(^1\).

### 1.2 Basic pulsar analysis techniques

In this Section, basic techniques of processing radio signals recorded for pulsars are discussed.

#### 1.2.1 Polarisation properties of radio pulses

Soon after the discovery of pulsars (Hewish et al., 1968), it was observed that their radio signals are highly linearly polarised (Lyne & Smith, 1968). It is well known (e.g. Kliger et al. 1990) that electromagnetic radiation can be treated as a transverse wave. Such a wave consists of two oscillating fields, one being the electric field and the other the magnetic field. In vacuum, the direction of both these fields and the direction of propagation are mutually orthogonal. The time-dependent orientation of the fields can be quantified as the state of polarisation. The convention is that the direction of the electric field is described by the polarisation state.

\(^1\)www.physics.mcgill.ca/~pulsar/magnetar/main.html
One way of describing the polarisation properties of light is by using the Stokes parameters $I$, $Q$, $U$ and $V$. $I$ represents the total intensity, $Q$ and $U$ are the orthogonal components used to describe linear polarisation with intensity $L = \sqrt{Q^2 + U^2}$ and $V$ is the circular polarisation. The term orthogonal used in the context of linearly polarised light indicates two independent polarisation directions. For circularly polarised light, this refers to left and right circularly polarised light.

The electric field vector $E$ is considered the vector sum of two orthogonal components $E_x$ and $E_y$, where $x$ and $y$ are Cartesian orthogonal basis. The Stokes parameters from two orthogonal linear receivers can be written in terms of the time averaged components of the electric field $\langle E_x \rangle$ and $\langle E_y \rangle$, as follows

\begin{align*}
    I &= \langle E_x^2 \rangle + \langle E_y^2 \rangle \quad (1.10) \\
    Q &= \langle E_x^2 \rangle - \langle E_y^2 \rangle \quad (1.11) \\
    U &= 2\langle E_x^2 \rangle \langle E_y^2 \rangle \cos \phi \quad (1.12) \\
    V &= 2\langle E_x^2 \rangle \langle E_y^2 \rangle \sin \phi, \quad (1.13)
\end{align*}

where $\phi$ represents the phase difference between the two orthogonal components of the electric field (Lorimer & Kramer, 2005). For a fully polarised wave the Stokes parameters are related by

\begin{equation}
    I^2 = Q^2 + U^2 + V^2. \quad (1.14)
\end{equation}

However, light does not necessarily need to be 100% polarised. It can have a certain degree of polarisation given by $|\mathbf{p}|/I$, where $\mathbf{p}$ is the polarisation vector and its magnitude is given by $|\mathbf{p}| = \sqrt{Q^2 + U^2 + V^2}$ (e.g. Burke & Smith 2002).

A good way to visualise polarised light is by using a Poincaré sphere, as shown in Fig. 1.3. A polarisation state can be represented as a certain orientation of the polarisation vector $\mathbf{p}$ in a Cartesian $QUV$ space. In spherical polar coordinates, $\mathbf{p}$ can be represented using the magnitude of vector $\mathbf{p}$ and two angles: the ellipticity angle $\chi$, and the position angle (PA) of linear polarisation. If a polarisation state is fully polarised, the polarisation vector $\mathbf{p}$ will extend up to the radius of the Poincaré sphere. In the case of purely linear polarised light, the vector $\mathbf{p}$ would lie in the $QU$ plane (equatorial plane of the sphere) and the orientation of linear polarisation is given by

\begin{equation}
    \text{PA} = \frac{1}{2} \arctan \frac{U}{Q}, \quad (1.15)
\end{equation}
1.2. Basic pulsar analysis techniques

The polarised state is given by the orientation of the polarisation vector \( \mathbf{p} \), which in spherical polar coordinates is characterised by two angles: the orientation of linear polarisation \( \text{PA} \) and ellipticity angle \( \chi \). Note that the angles represented on the sphere are \( 2\text{PA} \) and \( 2\chi \).

The PA is therefore defined between \( 0^\circ \) and \( 180^\circ \) (or \( -90^\circ \) and \( 90^\circ \)).

If the ellipticity angle is not zero, then there is a circular component to the polarised state. The ellipticity angle \( \chi \) is given by

\[
\chi = \frac{1}{2} \arctan \frac{V}{\sqrt{Q^2 + U^2}} = \frac{1}{2} \arctan \frac{V}{L},
\]

(1.16)

where \( \chi \) is defined between \( -45^\circ \) and \( 45^\circ \). If the angle of the polarisation state is situated at the North or South pole of the Poincaré sphere then this represents pure right and left handed circular polarisation respectively. For any other value of the ellipticity angle, the polarised state is called elliptical.

When recording the incoming electric field vector components \( E_x \) and \( E_y \), their uncertainties are described by a Gaussian distribution. The uncertainties on the Stokes parameters can be obtained by propagating the errors of \( E_x \) and \( E_y \) in equations (1.10), (1.11), (1.12) and (1.13). The Stokes parameters uncertainties are thus described by a chi-squared distribution, however as the Stokes parameters are obtained after averaging over many instances, the central limit theorem means that their error distribution tends towards a normal distribution. Therefore, the uncertainties of the Stokes parameters are generally considered to be described by a Gaussian distribution with a standard deviation that is equal for each of parameter

\[
\sigma_I = \sigma_Q = \sigma_U = \sigma_V,
\]

(1.17)
(Everett & Weisberg, 2001). In order to obtain uncertainties on the PA, the uncertainties from the Stokes parameters can be propagated using Gaussian error propagation formulae, resulting in

$$\sigma_{PA} = \frac{\sqrt{U^2 \sigma_Q^2 + Q^2 \sigma_U^2}}{2(Q^2 + U^2)} = \frac{\sigma_I}{2L},$$  \hspace{1cm} (1.18)$$

where in the last step of equation (1.18) \( L = \sqrt{Q^2 + U^2} \) has been used. A similar calculation can be performed for \( \chi \), resulting in

$$\sigma_{\chi} = \frac{\sigma_I}{2\sqrt{Q^2 + U^2 + V^2}},$$  \hspace{1cm} (1.19)$$

where \( \sqrt{Q^2 + U^2 + V^2} \) represents the total polarisation. It is important to note that the uncertainties on PA and \( \chi \) do not follow a Gaussian distribution (e.g. Naghizadeh-Khouei & Clarke 1993). Deviations become important when the significance of \( L \) or the total polarisation is lower. In the analysis presented in this thesis the PA and \( \chi \) were computed when the significance of \( L \) or total polarisation exceeded 2\( \sigma \), where \( \sigma \) is the standard deviation computed from the off-pulse region, i.e of the noise.

### 1.2.2 Interstellar medium effects

As the radio signal of a pulsar propagates through the cold ionised interstellar medium (ISM), it can experience effects such as dispersion or interstellar scattering. If the radio pulse is polarised, then in addition it will experience Faraday rotation.

**Dispersion**

The radio emission from pulsars experiences a frequency dependent time delay as it propagates through the ISM, due to the frequency dependence of the refractive index of the magnetised plasma. The relative time delay experienced by two radio waves at two different frequencies is given by

$$\Delta t \simeq 4.15 \times 10^6 \times \text{DM} \times (\nu_1^{-2} - \nu_2^{-2}) \text{ ms},$$  \hspace{1cm} (1.20)$$
where the two frequencies $\nu_1$ and $\nu_2$ are expressed in MHz and DM, conventionally expressed in pc cm$^{-3}$, is the dispersion measure. The DM is given by

$$\text{DM} = \int n_e dl. \quad (1.21)$$

where $n_e$ is the free electron density and $dl$ is distance element along the line of sight (e.g. Lorimer & Kramer, 2005). The dispersive delay depends on the plasma frequency. As the plasma frequency is inversely proportional to the mass of the charged particles in the ISM, free electrons are mainly responsible for dispersion.

A pulsar is always observed over a certain frequency bandwidth, i.e over a range of frequencies. As the dispersive delay quadratically depends on frequency (equation (1.20)), higher frequency signals will arrive earlier compared to lower frequency signals. This will cause ‘smearing’ of the recorded pulses, if uncorrected for.

The removing of the dispersive delay is referred to as de-dispersion. There are two main methods to achieve this. The first method is known as incoherent de-dispersion (Large & Vaughan, 1971) (which is used in this thesis), and is based on splitting the observing bandwidth into narrow frequency channels and shifting them relative to each other in time, using the expected delay for a given DM of the pulsar. A drawback of this method is that due to the fact that the frequency channels have a finite bandwidth, a small residual delay will occur across each channel, which is uncorrected. Nevertheless, with a sufficiently large number of channels this effect is small. There is however a maximum limit on how narrow the channels can be, which is inversely proportional to the sampling time of the observation (Nyquist sampling theorem).

A newer method, referred to as coherent de-dispersion, does not suffer from such drawbacks, however it is more computationally demanding. The method was developed by Hankins & Rickett (1975), and consists of performing a convolution of the radio signal received by a telescope with an inverse transfer function for the ISM.

**Interstellar scattering**

The ISM is not a homogeneous medium, as it has regions of low electron density and regions of higher electron density (such as HII regions). Radio signals propagating through the ISM will experience an effect called scintillation, which causes frequency dependent intensity variations over time. Furthermore, interstellar scattering will cause a broadening of the pulse profile in the shape of a scattering tail. In this Section, we will focus on the scattering effect. Interstellar
scattering is thought to occur due to the multi-path propagation in the inhomogeneous ISM which causes radiation to arrive with a certain delay. An observed pulse shape affected by scattering can be described as a convolution between the intrinsic pulse shape and a broadening function which can be taken to be a one-sided exponential in the form of \( \exp\left(-t/t_s\right) \). Here \( t \) represents time and \( t_s \) is the scatter broadening timescale (Scheuer, 1968).

The scatter broadening timescale depends on observing frequency such that \( t_s \propto \nu^{-\alpha} \). The value of \( \alpha \) depends on how the inhomogeneities of the ISM are modelled. A widely used model is the thin screen model, where all scattering is considered to occur halfway between the pulsar and the Earth (e.g. Scheuer 1968; Williamson 1972). This yields \( \alpha = 4.4 \) (Rickett, 1977). Other models (e.g. Cronyn 1970) suggest \( \alpha = 4 \). Multi-frequency observations (e.g. Löhmer et al. 2004; Lewandowski et al. 2013, 2015a; Geyer et al. 2017) reveal a range of different \( \alpha \) values for different pulsars, ranging between 1.3 and 5.6. To complicate things further, Geyer et al. (2017) found evidence that there might be a frequency evolution of \( \alpha \). From these observations one can make the general statement that pulse profiles observed at higher frequencies will be

Bhat et al. (2004) and Geyer et al. (2017) showed that there is a parabolic correlation between \( t_s \) and the DM of pulsars. This implies that, generally, pulsars which are further away, and hence have typically a higher DM, also tend to be more more affected by scattering.

**Faraday rotation**

As polarised light passes through a magnetised plasma, i.e the ISM, it will experience Faraday rotation. In a cold magnetised plasma like the ISM, linearly polarised light can be considered as the superposition of right and left-handed circular polarisation. As light propagates through this medium, electrons will start gyrating due to the Lorentz force. The circular component of the electric field which rotates in the same direction as the gyrating electrons will couple more strongly to the plasma than the other orthogonal component, thus it will propagate slower. The relative delay between the two circular modes results in a rotation of the orientation of linear polarisation (\( \Delta \text{PA} \)), as a function of observing wavelength (\( \lambda \)) given by

\[
\Delta \text{PA} = \text{RM} \lambda^2.
\]  

(1.22)
1.2. Basic pulsar analysis techniques

Here the constant of proportionality is known as the rotation measure (RM) which has units of rad m$^{-2}$, and is related to the properties of the ISM via

\[ RM = \frac{e^2}{2 \pi m_e c^4} \int_0^L n_e B_{\|} dl, \]  

(1.23)

where \( e \) and \( m_e \) are the charge and mass of the electron, \( c \) is the speed of light in vacuum, \( n_e \) is the electron density, \( B_{\|} \) is the component of the magnetic field parallel to the line of sight, \( L \) is the distance to the pulsar and \( dl \) is distance element along the line of sight (e.g. Lorimer & Kramer, 2005). All the discussed quantities are in SI units.

Smith (1968) was the first author to measure the RM of a pulsar. Currently, we know the RM of 1133 sources (e.g. Hamilton & Lyne 1987; Han et al. 1999, 2006; Noutsos et al. 2008, 2015; Force et al. 2015; Young et al. 2015; Han et al. 2018; Sobey et al. 2019). This information can be retrieved from the Australia Telescope National Facility (ATNF) pulsar catalogue\(^2\) (Manchester et al., 2005).

A detailed description of two main methods, and their shortcomings, used to measure the RM of pulsars will be discussed in more detail in Chapter 4. If one sums the frequency channels of an observation together, then the effect of Faraday rotation should be removed from each channel first, in a process called de-Faraday rotation. If this is not done properly, the observed degree of linear polarisation will be underestimated and sensitivity in measuring the PA is reduced. The method involves computing the \( \Delta \)PA for each frequency channel, using the determined RM of the pulsar, and then applying the offset to the Stokes \( Q \) and \( U \).

1.2.3 Polarisation calibration

In order to study polarisation properties, it is important to perform polarisation calibration first. The recorded Stokes parameters are in general affected by the imperfections of the receiver and signal chain, hence this needs to then be corrected for, to obtain what is referred to as the intrinsic Stokes parameters. The type of receiver used for the observations performed in this thesis is linear and it consists of two perpendicular dipoles which record the orthogonal components of the incoming electric field (\( E_x \) and \( E_y \)). These quantities are correlated to produce the four Stokes parameters, as described in Section 1.2.1 (equations (1.10), (1.11), (1.12) and (1.13)).

The transformation from un-calibrated Stokes parameters to intrinsic Stokes parameters is performed using a Mueller matrix (e.g. Mueller 1948; Heiles et al.\(^2\)http://www.atnf.csiro.au/research/pulsar/psrcat/
2001). When applying this transformation, the system is assumed to be linear. The Mueller matrix is a real-valued $4 \times 4$ matrix. Out of its sixteen parameters, only seven are independent from each other. Since these parameters depend on the observing frequency, they need to be applied to each frequency channel separately. One of these seven parameters is the overall gain and is not useful for the scope of this thesis, as it is an overall scaling parameter which affects all Stokes parameters equally. This parameter can be determined with flux calibration.

Out of the six parameters left, four of them are referred to as the leakage parameters. These correct for the effect where the signal recorded for one orthogonal direction is detecting some signal from the other orthogonal direction. These four parameters should be approximately constant in time given a certain receiver and signal chain, thus they do not need to be determined separately for each observation. For example, they were determined for the Parkes radio telescope during the Parkes Pulsar Timing Array project (e.g. Manchester et al. 2013). This was done by observing a pulsar as it crosses the entire sky. As the polarised signal from the pulsar should intrinsically remain unchanged, the the orientation of the electric field components of the source will change with respect to the receiver. Alternatively, the feed of the telescope can be rotated during the observation to produce a similar effect. The method allows the leakage parameters to be determined. This is generally applied to altitude-azimuth mounted antennas, such as the Parkes Telescope, and does not work for telescope with an equatorial mount.

The remaining two parameters are called differential gain and differential phase. Differential gain refers to the fact that the two dipoles orthogonal polarisations are recorded with different sensitivities. Differential phase refers to the artificial phase difference between the two polarisations induced as a result of different propagation times of the signals before they are correlated. This could be, for example, due to cables of different length transmitting the signals from the dipoles.

For the Parkes data the differential phase and gain are obtained using a polarisation calibration observation recorded shortly before or after the pulsar is observed. The principle of it is that you make a short observation, generally around 120 seconds, which is pointing slightly offset from the source right before the actual observation. The purpose of the offset is to make sure that the background observed is similar to the one when the source is observed, but without the pulsar signal. The background can contain other radio sources, such as the Sun, nearby planets, radio galaxies or diffuse synchrotron radio emission. During the polarisation calibration observation a noise diode signal is recorded. This is a known
polarised signal injected in the signal path, which in the case of Parkes turns on and off with a frequency of 11.123 Hz and is 100% linearly polarised. The signal is orientated at an angle of 45° between the two dipoles. This implies that only a Stokes $U$ component is expected. Deviations from this expectation allow the differential gain and phase to be determined.

As the calibration signal is periodic it can be averaged using a folding procedure similar to what can be done for pulsars (see Section 1.2.4). A tool called PAC, which is part of the PSRCHIVE software package (van Straten et al., 2012), can be used to solve for the frequency dependent differential gain and phase from the calibration signal. These parameters, together with the leakage parameters taken from a so-called “receiver solution” specific to the receiver and backend, can then be applied to the pulsar signal resulting in polarisation calibrated data.

### 1.2.4 Creating pulse-stacks from time series

For single-pulse studies of pulsars, the incoming radio waves recorded with a radio telescope are generally stored as a time series with frequency resolution. The data needs to then be processed, in order to obtain a product which can be further analysed, as described in the following Chapters. The data firstly needs to be folded. Folding refers to the process of synchronously averaging the data using the pulse period $P$ (e.g. Lorimer & Kramer 2005). This means that a transformation between time and rotational pulse phase is performed. One rotation of the star spans a rotational phase between 0° and 360°. When averaged over the full observation duration, an integrated pulse profile is formed. When averaged over smaller intervals, one creates what is referred to as “subintegrations”. Single pulses can be separated from the data by not averaging at all during the folding process. In this Section, we will discuss the processing of single pulses as performed as part of this thesis.

When folding the raw data, an ephemeris is used. This contains information about the pulsar necessary to predict the (time dependent) spin period as would be observed at the centre of mass of the Solar System, also known as the barycentre. This prediction requires at least the period $P$, the period derivative of the star $\dot{P}$ and its position to be known. For some pulsars, especially young ones, higher order derivatives of the period are used when making such predictions. If the pulsar is in a binary system, this needs to be taken into account as well.

The ephemeris also contains information about the position of the pulsar in the sky. This is important for the folding because the orbital motion of the Earth
Chapter 1. Introduction

introduces an annual sinusoidal variation in the perceived spin period at the observatory. The position of the pulsar in the sky might change with time because of a significant proper motion, which should be corrected for when folding the data. The corrections applied to the arrival times of the pulses take into account other effects such as general relativity effects. For example, general relativity predicts a delay in the pulse arrival time as the pulse propagates through the gravitational potential of the Sun (e.g. Lyne & Smith 2004; Lorimer & Kramer 2005).

As described in Section 1.2.2, individual pulses suffer a frequency dependent time delay as they propagate through the ISM. During the folding process, the data were de-dispersed with the known DM. Both folding and de-dispersion (but keeping the full frequency resolution) were achieved using software called DSPSR (van Straten & Bailes, 2011).

After the folding process polarisation calibration was performed (see Section 1.2.3), calibrated single pulses with full frequency resolution are obtained. Next, we will describe the steps required to create a pulse-stack, a plot of a range of consecutive individual pulses placed on top of each other (See Fig. 1.4 for an example). As the emission of pulsars is broadband, the highest sensitivity is reached by averaging over the full bandwidth. Since the effects of the interstellar medium have been corrected for and the frequency-dependent polarisation calibration has been performed, this can now be done in a meaningful way. The averaging over frequency was done using the tool PAM, which is part of the PSRCHIVE software package (van Straten et al., 2012). Frequency channels affected by Radio Frequency Interference (RFI) were not included in this average. In order to identify the badly affected channels, a plot of frequency as a function of pulse number was obtained and visually inspected. Frequency channels in which the pulsar signal was not visible due to very bright RFI were deemed as badly affected. These channels were removed using the tool PAZ. After the folding process, the data are organised in separate files for separate stellar rotations. In order to plot and analyse the pulse-stack it is useful to re-order the data in an array of pulse phase and pulse number stored in a single file. This combining was done using the software tool PSRADD (van Straten et al., 2012). An example of a small section of a pulse-stack is displayed in Fig. 1.4.

The resulting pulse-stack might have an average noise level which is not zero making the off-pulse noise to have a non-zero intensity level. This “baseline” could affect future analysis of the data, especially because it will change throughout the observation. As long as these variations are slow compared to the period of the pulsar, removing the baseline is relatively straightforward. This was
1.3. Individual pulses and drifting subpulses

Individual pulses from pulsars display a complex behaviour. Drake & Craft (1968) showed that individual radio pulses exhibit structure, commonly referred to as \textit{subpulses} and Sutton et al. (1970) observed that in the case of some pulsars the subpulses move systematically in rotational longitude. A way to visualise any systematic shape variations is by plotting a \textit{pulse-stack} as shown in Fig. 1.4. The subpulses form diagonal intensity bands which are commonly referred to as \textit{drift-bands}. This effect is known as \textit{drifting subpulses} and reveals the dynamics within the pulsar magnetosphere. Drifting subpulses appear to be an integral part of the emission mechanism as they were shown to be very common, occurring in at least a third of the pulsar population (Weltevrede et al., 2006, 2007; Basu et al., 2016, 2019).

\textbf{Figure 1.4}: A section of the pulse-stack of PSR J0820–1350, containing 80 consecutive individual pulses. The observed diagonal intensity bands are known as \textit{drifting subpulses}. Achieved using a software tool called PMOD from the PSRSALSA software (Weltevrede, 2016). During this process, an arbitrary selection of the on-pulse region (where the pulsar is on) is made in order to remove the pulsar signal and calculate the mean noise level.
In Fig. 1.4, the separation between two consecutive subpulses within a single pulse is generally referred to as $P_2$. The period with which a certain subpulse returns to the same longitude is called $P_3$ and is usually expressed in units of the period of the pulsar $P$. The slope of a driftband is also referred to as the drift rate and is given by $D = P_2/P_3$.

Various models have been postulated in order to explain drifting subpulses, most notably the carousel model (Ruderman & Sutherland, 1975), which will be described in Section 1.4. In this model, the radio beam consists of localised active emission regions circulating around the magnetic axis due to an $\mathbf{E} \times \mathbf{B}$ drift. The circulation time of the carousel is related to $P_3$ and the number of sub-beams in the carousel configuration. Each subpulse is emitted from a certain sub-beam in the carousel. As the carousel rotates, the sub-beams will gradually pass through the line of sight, hence a systematic shift in time of the subpulse will happen. A simulation of how a pulse-stack will look for different scenarios of where the line of sight intersects the emission beam was done by Weltevrede (2007) and is shown in Fig. 1.5.

For certain pulsars, more than one stable drift mode has been reported. A notable example is PSR B0031$-$07 which has three stable drift modes with $P_3 = 12P$ (mode A), $P_3 = 6P$ (mode B) and $P_3 = 4P$ (mode C) (Huguenin et al., 1970; Vivekanand & Joshi, 1997; Smits et al., 2005, 2007; McSweeney et al., 2017). The average profile, obtained after adding together many individual pulses, is different for each different drift mode. This phenomenon is known as profile mode changing. PSR B0031$-$07 will be discussed in more detail in Chapter 2. Other examples of pulsars with multiple drift modes and mode changing, as well as an overview of mode changing can be found in Rankin (1986).

In some pulsars, an abrupt interruption (within less than a period) of the radio emission is seen to occur. This phenomenon is referred to as nulling, and was first seen in pulsars by Backer (1970b). Since then, nulling has been reported in more than 100 pulsars (e.g. Ritchings 1976; Wang et al. 2007; Gajjar et al. 2012; Basu & Mitra 2018), with durations lasting from a few pulses (PSR B0818$-$13, Janssen & van Leeuwen 2004) to more than 95% of the time (e.g. PSR J1752$+$2359, Gajjar et al. 2014).

### 1.4 Pulsar magnetospheres

Since the discovery of pulsars, a lot of progress has been made in understanding the origin of their radio emission (e.g. Petrova 2013; Jones 2014; Mitra 2017; Philippov & Spitkovsky 2018; Philippov et al. 2019), nevertheless a model which
Figure 1.5: A top view of the carousel of circulating sub-beams. Three cases of a line of sight intersecting the beam are indicated by A, B and C. For each case a pulse-stack was simulated illustrating how the drifting subpulses pattern would be affected (Weltevrede, 2007).
is able to fully explain all the observations does not yet exist. In this Section, an overview of the general properties of the pulsar magnetosphere from which the radio emission originates will be presented.

Goldreich & Julian (1969), building on previous work from Deutsch (1955), showed that a rotating neutron star cannot be surrounded by a vacuum. Instead it will have a co-rotating magnetosphere of relativistic plasma, which has been stripped off the surface of the star. At the light cylinder radius (see Fig. 1.1), defined as $r_{LC} = c/\Omega$, the plasma should rotate with the speed of light to be co-rotating with the star, hence co-rotation is no longer possible beyond the light-cylinder. Furthermore, beyond the light-cylinder the magnetic field lines from one magnetic pole will not be able to connect to the opposite magnetic pole, i.e. they do not close. Hence, two regions can be defined in the pulsar magnetosphere with distinct properties.

The first region is known as the closed field line region. The field lines in this region are closed and contained within this cylinder, as shown in Fig. 1.1. Due to the rotation of the magnetic field, an electric field will be induced in this region. The presence of this field will lead to charges being removed from the surface of the neutron star, which are confined to flow along the field lines of the ultra-strong magnetic field. Since the field lines are closed in this region, the charges cannot escape. The charges will re-distribute themselves until the electric field is screened in this region, so the build up of charges will stop when the so-called “force-free” state is reached. The charge density at which this will happen is referred to as Goldreich & Julian charge density, $\rho_{GJ} = \Omega \cdot B / 2\pi c$, where $B$ is the magnetic field. This region is all also referred to as the dead-zone since no emission is thought to originate from this region.

The second region defined by the light-cylinder is the open field line region. A charge build up will occur in this region as well to the same density $\rho_{GJ}$. The fundamental difference with the closed field line region is that here plasma can escape the pulsar magnetosphere via the open field lines. This outflow requires constant replenishment of magnetospheric charges. These charges are thought to originate from gaps, which will be discussed in a moment.

Goldreich & Julian (1969) considered a rotating neutron star with the magnetic axis aligned with the rotation axis (an aligned rotator with $\alpha = 0^\circ$). This is a big simplification in terms of the physics, however, $\alpha$ has to be non-zero in order for pulsed emission to be observed. Nevertheless Mestel (1971) showed that the magnetosphere derived by Goldreich & Julian (1969) is a good approximation for the case of a misaligned rotator, as well in terms of the basic picture. Detailed force-free simulations of the magnetosphere of an oblique rotator were
performed by, for example, Spitkovsky (2006); Kalapotharakos & Contopoulos (2009); Kalapotharakos et al. (2012); Gourgouliatos & Lynden-Bell (2019). The authors predict the existence of a current sheet region extending past the light-cylinder.

The open field line region connects to the surface of the star via an area referred to as the polar cap. This region is centred on the magnetic axis and its boundaries are determined by the last open magnetic field lines, i.e. those field lines which touch the light cylinder. The radio emission is believed to originate above the polar cap.

In a model developed by Ruderman & Sutherland (1975), the positive charges are bound to the surface of the neutron star in the form of nuclei in a lattice and only the negative charges can be ripped off the surface by the electric field in the magnetosphere. A potential difference of about $10^{12}$ V is created between the surface and the co-rotating magnetosphere in a so-called charge depletion zone, or gap. In the gap, force-free conditions do not hold. The gap created in the polar cap region is referred to as the polar gap, and is further discussed in this Section since it is thought to be responsible for the radio emission. Another gap, known as the outer gap, exists in a region close to the light-cylinder. Higher energy emission, like $\gamma$-ray emission originates in that region. The outer gap is discussed in more detail in Section 5.1.

Electrons moving along the open magnetic field lines in the polar gap region will be accelerated to relativistic velocities, and will produce high energy photons via several suggested mechanisms, such as curvature radiation (e.g. Ruderman & Sutherland 1975) or inverse Compton radiation (e.g. Daugherty & Harding 1986; Bussard et al. 1986). These photons have very high energies, higher than the threshold necessary to produce positron-electron pairs. A cascade of electrons $e^-$ and positrons $e^+$ is produced, since these newly created particles can produce more photons, creating a secondary pair plasma (Sturrock, 1971). The coherent radio emission is believed to originate in this secondary plasma above the polar gap.

The pair cascade might not occur in the entire polar cap region at all times. Ruderman & Sutherland (1975) suggested that the pair production occurs in discrete regions above the magnetic pole and they referred to these regions as 'sparks'. These sparks will rotate around the magnetic pole as a result of the $\mathbf{E} \times \mathbf{B}$ drift experienced in the magnetosphere similar to a carousel, hence this model is often referred to as the carousel model. This model was proposed to explain the periodic variability observed in the shape of individual pulses, as discussed in Section 1.3. An alternative model has been proposed by Spitkovsky & Arons (2002), in which
drifting subpulses are created by a diocotron instability occurring in the magnetosphere (see also Fung et al. 2006). More models are discussed in Chapter 2 (Section 2.1 and Section 2.4).

1.5 Polarised integrated pulse profiles

In Section 1.2.4, it was described how pulsar data recorded with a radio telescope can be folded. By folding over typically hundreds of rotations, an integrated pulse profile is obtained with a higher signal-to-noise ratio (S/N) than of individual pulses. The integrated pulse profile can be visualised as a plot of intensity against pulse longitude. Integrated pulse profiles have generally been observed to be stable over a long period of time (unlike the variable behaviour of individual pulses) and to have a different shape for each pulsar (e.g. Lyne & Smith 2004).

Examples of integrated intensity pulse profiles for several pulsars are shown in Fig. 1.6. The linear ($L = \sqrt{Q^2 + U^2}$) and circular polarisation (Stokes $V$) are also shown as well as the time averaged PA curve. The emission from the pulsars shown in Fig. 1.6 is highly linearly polarised. The geometrical model which describes the pulse longitude dependence of the PA curve will be further discussed in Section 1.6.

Early observations of pulsars revealed that the integrated pulse profile can have a complex shape with one or multiple peaks, referred to as profile components (Lyne et al., 1971; Manchester, 1971; Taylor & Manchester, 1977; Rankin, 1983). This can be seen in Fig. 1.6 as well, as the pulsars have two or three profile components. For some pulsars, another component appears at 180° rotational phase from the main pulse (MP) and this is generally referred to as an interpulse (IP) (Rickett & Lyne, 1968). The most general interpretation is that the IP originates from the other magnetic pole of the pulsar when the magnetic axis is almost orthogonal to the rotation axis ($\alpha \approx 90^\circ$). However, other authors (Manchester & Lyne, 1977) suggested an alternative model in which both the MP and IP originate from the same beam, which is very wide. These two ideas are not mutually exclusive, and for different pulsars a different interpretation is favoured.

The width of the integrated profile can be defined based on a couple of arbitrary intensity points in the integrated profile, such as at 10% of the peak of the intensity curve and this width is labelled $W_{10}$, or at 50% with the labelling $W_{50}$. $W_{10}$ is typically observed to be between 10° and 20°, however a whole range of values have been reported between 1° to 360° at various frequencies (Gil et al., 1993; Kramer et al., 1994; Mitra & Rankin, 2002; Skrzypczak et al., 2018; Johnston & Karastergiou, 2019).
1.5. Polarised integrated pulse profiles

Figure 1.6: Examples of integrated polarisation profiles for different pulsars. In the top panels, the total intensity pulse profile is represented by the black curve, linear polarisation with the red curve, circular polarisation with the green curve. The time averaged PA is shown in the lower panels. The PA points were plotted when the significance of $L$ exceeded $3\sigma$. Image produced with data from Johnston & Kerr (2018).

As discussed in Section 1.3, the integrated pulse profile can change between several stable configurations as a function of time (mode changing). The integrated profile can also show evolution as a function of observing frequency. Soon after the discovery of pulsars it was recognised that the width of the integrated profiles was often larger at lower frequencies compared to higher frequencies. Cordes (1978) proposed a model where lower radio frequencies originate higher up in the magnetosphere. The lower frequency radio emission is beamed along the field lines which diverge with altitude, and is therefore confined to a wider beam. This is known as radius-to-frequency mapping. Some authors (e.g. Chen & Wang 2014) found that for almost 20% of pulsars in their sample, the profile width decreased with lower observing frequencies, opposite to the expectation from radius-to-frequency mapping.

The emission mechanism models presented so far do not account for the behaviour of the circular polarisation. Han et al. (1998) concluded that the presence of circular polarisation is quite common but not many specific trends were observed. The authors noted that the circular polarisation tends to be strongest in the middle of the profile, however this was not always the case, and that sign reversals of circular polarisation occurred most often towards the centre of the
pulse profile. Another interesting trend observed was a correlation between the PA swing direction and the direction of circular polarisation for pulsars with a double component profile connected by a bridge. You & Han (2006) confirmed these findings using a larger data-set. More recently, Johnston & Kerr (2018) investigated the polarisation properties of 600 pulsars and did not report any trends regarding the direction of circular polarisation. The authors also report that pulsars with high $\dot{E}$ have on average higher fractional circular polarisation, compared to low $\dot{E}$ pulsars.

The opinions are divided in the literature about the origin of circular polarisation in pulsars. There are some people who believe the circular polarisation is generated by the emission mechanism itself (e.g. Michel 1987; Radhakrishnan & Rankin 1990; Gangadhara 1997, 2010) or there are some who suggest the occurrence of circular polarisation might be due to propagation effects experienced by the radiation in the magnetosphere (e.g. Cheng & Ruderman 1979; Lyubarskii & Petrova 1998; Melrose 2003; Melrose & Luo 2004). More details will be discussed in Section 1.7.

### 1.6 The Rotating Vector Model

In order to explain the observed orientation of linear polarisation and the S-shaped swing of the PA curve seen in many pulsars, Radhakrishnan & Cooke (1969) proposed a geometrical model later called the Rotating Vector Model (RVM). In this model, a few assumptions are made about the emitting regions of the pulsars. The coherent radio emission is assumed to originate close to the magnetic pole and the magnetic field is considered to be dipolar, hence an observer looking down on the magnetic pole would see the magnetic field lines projected in a radial distribution as in Fig. 1.7. Another assumption made is that the electric field of the radio emission is either polarised in the plane containing a magnetic field line or perpendicular to it. Since the direction of the electric field of the radiation defines the PA, the PA curve is determined by the projection of the magnetic field lines at the emitting region in the plane of the sky.

The exact shape of the PA curve depends on both $\alpha$ and $\beta$ and this was quantified by Komesaroff (1970). The equation describing the change of the position angle as a function of pulse phase is given by

$$PA = PA_0 + \tan^{-1} \frac{\sin(\phi - \phi_0) \sin \alpha}{\sin \zeta \cos \alpha - \cos \zeta \sin \alpha \cos(\phi - \phi_0)}, \tag{1.24}$$
where PA is the position angle of linear polarisation, $\zeta = \alpha + \beta$ and $\phi$ is pulse longitude. The pulse longitude at which the line of sight crosses the field lines in the plane of the magnetic and rotation axes (the *fiducial plane*) is $\phi_0$ and $PA_0$ represents the PA at that point. At $\phi_0$ the steepest part of the PA swing is predicted to occur. The maximum rate of change of the PA curve was derived by Komesaroff (1970)

$$\left(\frac{d\phi}{d\phi}\right)_{\text{MAX}} = \frac{\sin \alpha}{\sin \beta}.$$ (1.25)

This model was successfully used to explain many observed PA swings in pulsars (e.g. Lyne et al. 1971; Manchester 1971; Johnston & Weisberg 2006; Weltevrede & Johnston 2008; Rookyard et al. 2015) including those shown in Fig. 1.6, and these observations suggested that the PA is intrinsically frequency independent up to the point where the radiation starts propagating through the ISM. However, we show in Chapter 4 that magnetospheric effects create an additional frequency dependence of the observed PA (Ilie et al., 2019). The PA is expected to be frequency independent, as it only depends on the projection of the magnetic field lines on a plane perpendicular to the line of sight. Li & Han (2003); Karastergiou (2009) showed that scattering in the ISM may cause a frequency dependence of the PA as well as a distortion of the shape of the curve. In Chapter 4, we show that both interstellar scattering and magnetospheric effects
produce additional frequency dependencies of the PA.

1.7 Orthogonal Polarisation Modes

In Fig. 1.6, PSR J0134–2937 shows two $90^\circ$ transitions in the PA curve around pulse longitudes $248^\circ$ and $250^\circ$. At the longitudes where this happens depolarisation (reduction in $L$) in the integrated profile can be observed. These types of jumps were explained to occur due to the co-existence of two Orthogonal Polarised Modes (OPMs) (Backer et al., 1976; Stinebring et al., 1984; McKinnon & Stinebring, 2000; McKinnon, 2002). These modes are purely linearly polarised and if plotted on a Poincaré sphere, they would lie on opposite sides of the equatorial plane.

The existence of two OPMs is incorporated in the RVM because the radiation was assumed to be polarised either parallel or perpendicular to the plane of a magnetic field line. Thus, if two adjacent field lines are dominated by different OPMs, then a rapid $90^\circ$ change might occur in the PA curve. The OPM that dominates at a certain pulse longitude will determine the shape of the PA. The drop in the average polarisation profile is expected if there is an incoherent mixture of OPMs pointing in opposite directions on the Poincaré sphere resulting in the cancellation of polarisation.

There are in fact two ways one could add together two polarised waves with orthogonal polarisation: coherent addition or an incoherent addition. Two waves are said to be coherent if the phase difference between them remains constant as a function of time, as well as their frequency. The waves are incoherent if the phase difference changes as a function of time (e.g. Kliger et al. 1990). If we consider two 100% linearly polarised OPMs which have a constant phase relation (coherent), the resulting wave sum would be, for example, 100% circularly polarised if the phase difference between the two orthogonal waves were $\pi/2$. If there were zero phase difference between the two OPMs, then the coherent sum would be a wave which is 100% linearly polarised. If the same OPMs, of the form $(I,Q,U,0)$ and $(I,-Q,-U,0)$, would have a phase relationship which is not constant in time (they are incoherent), adding them together will result in un-polarised radiation $(2I,0,0,0)$. This is because of the changing phase relation, which will result in the polarised vector sum pointing in random directions on the Poincaré sphere i.e. there will not be a preferred direction (e.g. Tinbergen 1996).

Similar to circular polarisation the origin of the alternating dominance of OPMs as function of pulse longitude is uncertain as well. The production of two
orthogonal polarised modes could be intrinsic to the radio emission mechanism (e.g. Gangadhara 1997). Other authors (Melrose, 1979; Allen & Melrose, 1982) suggest that due to propagation effects in the magnetosphere the natural modes in a plasma, which are linearly polarised and orthogonal, experience different degrees of refraction resulting in a spatial separation of the modes. A full physical description of this was done by Arons & Barnard (1986). The authors explained how there are three natural modes of propagation in a cold highly-relativistic magnetised plasma, the super-luminous Ordinary mode (O mode) and the eXtraordinary mode (X mode). There is also a sub-luminous ordinary mode, but that mode does not escape the pulsar magnetosphere. Beskin et al. (1993) and Beskin & Malyshkin (1998) suggested that in fact there are four natural modes that can exist in the pulsar magnetosphere, however also this additional mode cannot escape. More recently, Melrose et al. (2018) disproved the existence of the additional fourth plasma mode in the magnetosphere. Lyubarskii (1996) argued that conversion from the sub-luminous O mode into the super-luminous O mode can occur in the magnetosphere making the sub-luminous mode more relevant, as it can escape after conversion. The X mode propagates without being affected by refraction, thus its path is a straight line from the emitting region. The O mode propagates along the field lines before detaching (Barnard & Arons, 1986).

In the initial stages of the propagation, the two modes do not interact with each other. However, the plasma density falls rapidly with height above the neutron star surface. When this density falls considerably, the two modes become coupled and changes to their polarisation state can happen. When the density falls even more, the two waves de-couple again and maintain their polarisation state when leaving the pulsar magnetosphere. The region where the modes are coupled is referred to as the polarisation-limiting region (PLR) (Cheng & Ruderman, 1979; Stinebring, 1982; Lyubarskii & Petrova, 1998; Petrova, 2006). Many authors believe that in this region modes become elliptical. Petrova (2001) suggested that before the modes reach this region significant conversion of the O mode into the X mode occurs.

Since only the O mode is more refracted in the magnetosphere, the O and X modes propagate along different paths. So although they both might originate from the same emission site close to the neutron star surface (polar gap, see Section 1.4) they will not be observed simultaneously. Imagine a carousel of sparks which is responsible for the generation of two OPMs. One could then expect two images of the carousel to be produced, which are magnified differently (since only one mode is refracted) and have orthogonal polarisation. A schematic
FIGURE 1.8: A schematic diagram of a cross-sectional top-down view the emission beam with two offset circulating carousel systems. The carousel system of one of the modes has a larger radius than the other. The dashed circle represents the peak locations of the sub-beams of the outer OPM and the full circle represents those of the inner OPM. The two carousel systems are azimuthally shifted so that sub-beams corresponding to the two OPMs are alternating. Image adapted from Rankin & Ramachandran (2003).
diagram of this is shown in Fig. 1.8, where the propagation is assumed to be in the azimuthal as well as the radial direction. This phenomenon was investigated through the analysis of single pulse polarisation (Rankin & Ramachandran, 2003; Edwards, 2004), and our work in Chapters 2 and 3.

1.8 The outline of the thesis

This thesis, which aims to investigate the polarisation properties of pulsars and their connection to the propagation of radio emission in the pulsar magnetosphere, is organised as follows.

Chapter 2 presents an investigation into the relation of the switches between two orthogonal polarisation modes at a single pulse level and the subpulse drifting seen in total intensity for for PSR B0031–07. A connection between the two is established for both drift modes detectable at the observing frequency of the observations. The results from this Chapter are presented in Ilie & Weltevrede (2018).

Chapter 3 presents an extensive analysis building on the results of Chapter 2, but now for a large sample of pulsars. We investigate whether polarisation modes switches synchronous with drifting subpulses. Before the work in this thesis, only four pulsars were known to show this effect. Together with PSR B0031–07, this number is now twelve. These results show that this is a common phenomenon. Some of these results from this Chapter are presented in Ilie & Weltevrede (2018).

Chapter 4 reports an investigation into the origin of phase resolved apparent rotation measure variations in the polarised signals of radio pulsars. We establish that scattering cannot be the only cause of these variations, and show clear examples where magnetospheric effects are responsible. The work presented in this Chapter has been published as Ilie et al. (2019).

Chapter 5 focuses on the investigation of the time-averaged polarisation properties and pulse profile evolution of three out of the ten pulsar discoveries from the Giant Metrewave Radio Telescope High Resolution Southern Sky Survey. The pulsars studied are PSRs J0418–4154, J0514–4408 and J2144–5237. The work presented in this Chapter will be published as part of Bhattacharyya et al. (2019).

Chapter 6 presents the concluding remarks from this thesis, including some suggested directions for potential future analysis.
Chapter 2

Synchronous modulation of radio polarisation and drifting subpulses for PSR B0031–07

In this Chapter we establish that for PSR B0031–07 the orthogonal polarisation modes switch on a single pulse level synchronously with the periodic drifting subpulses seen in total intensity. There are only four other pulsars known in the literature for which this phenomenon is seen. PSR B0031–07 is unique as it is the only source in this group which has multiple stable drift-modes, and for both drift-modes visible at our observing frequency (mode A and mode B) centred at 1369 MHz, we observe the synchronous modulation of polarisation modes with the drifting subpules. In mode A, a discontinuity in the modulation pattern of polarisation properties is observed halfway through the on-pulse region, coinciding with a slight change in the slope of the intensity driftband. This, plus other differences when comparing the modulated polarisation properties of the drift modes, suggests that a drift-mode change is more than a change in the underlying carousel radius, as previously suggested for this pulsar. It was found that the ellipticity evolves asymmetrically in time during the modulation cycle, which in the framework of a carousel model implies that the sub-beams are asymmetric with respect to the sense of circulation, something which is not seen for the other four pulsars which show synchronous modulation of the polarisation properties and the drifting subpulses. Birefringence in the magnetosphere, resulting in the orthogonal polarisation modes to spatially separate, is not enough to explain these results. Hence more complex magnetospheric processes, possibly allowing conversion between orthogonal polarisation modes, might play a role.
2.1 Introduction

Since the discovery of pulsars, 50 years ago (Hewish et al., 1968), a lot of progress has been made in understanding how the radio emission mechanism of pulsars works. Nevertheless, a theoretical model which is able to explain all the observations has not yet been developed. This work aims to explore the connection between variability in single pulse intensities and periodic switching of the position angle (PA) of the linear polarisation and how this relates to the radio emission mechanism.

Individual pulses display very complex behaviour and for many pulsars are observed to systematically shift in time, forming diagonal intensity bands in the pulse-stack (as seen, for example, in Fig. 2.1), a phenomenon referred to as drifting subpulses (Drake & Craft, 1968). As discussed in more detail in Section 1.3, there are two periodicities to quantify drifting subpulses: $P_2$ (separation between two consecutive subpulses) and $P_3$ (vertical spacing between the diagonal drift bands). $P_3$ is normally defined as a multiple of the pulse period, $P$. Because subpulse drifting is so common in pulsars (Weltevrede et al., 2006, 2007; Basu et al., 2016), it is believed to be an integral part of the emission mechanism. The most notable model aimed at explaining this behaviour is known as the carousel model (Ruderman & Sutherland, 1975) (see Section 1.4). This suggests that the emission beam is made out of sub-beams of emission circulating around the magnetic pole and each subpulse is thought to originate from one of these sub-beams of the carousel. As the carousel rotates, the sub-beams will gradually move across the line of sight, hence a systematic shift in pulse phase will occur in the pulse-stack. Since Ruderman & Sutherland (1975), many authors have either refined the carousel model (e.g. Deshpande & Rankin 1999; Gil & Sendyk 2003; Wright 2003; van Leeuwen & Timokhin 2012; Hassall et al. 2013) or suggested an alternative model to explain drifting subpulses (e.g. Clemens & Rosen 2004; Gogoberidze et al. 2005; Fung et al. 2006).

The PA of some pulsars is observed to trace an S-swing change during a stellar rotation, which is explained by the Rotating Vector Model (RVM) (Radhakrishnan & Cooke, 1969; Komesaroff, 1970) (see Section 1.6) as the change in projection of the dipolar magnetic field lines on the plane of the sky. Discontinuities in the shape of 90° jumps have been seen to occur in the PA swing. This is explained with the co-existence of two Orthogonally Polarised Modes (OPMs) of radiation (Backer et al., 1976). The origin these modes, and why different OPMs can dominate in different parts of a pulse profile, is still uncertain (as discussed in more detail in Section 1.7). In early theoretical work, some authors (e.g. Gangadhara
1997) suggested that the production of two observed OPMs is intrinsic to the radio emission mechanism. Other authors (e.g. Melrose 1979; Allen & Melrose 1982; Arons & Barnard 1986) suggest that the two OPMs are two natural modes of propagation in a highly-relativistic magnetised plasma, the Ordinary mode (O mode) and the eXtraordinary mode (X mode). These are predicted to be linearly polarised and orthogonal.

The phenomena of synchronous modulation of the dominant OPM with the periodicity of drifting subpulses is known for four pulsars. The first authors to observe such a connection were Taylor et al. (1971). The authors looked at the driftbands of PSR B0809+74 at 235 MHz and observed a variation of the PA in the form of a smooth transition across the subpulses. Their results showed that the PA swing was basically the same for all subpulses and that the curve was independent of the rotational phase of their occurrence. This conclusion was inconsistent with the accepted RVM, where the PA was a function of rotational phase only. It was not until 30 years later that Ramachandran et al. (2002) disproved Taylor et al. (1971), and showed that the transitions through subpulses for PSR B0809+74 were not smooth but rather sharp 90° transitions and that the behaviour of individual pulses does not contradict the RVM. The authors revealed that the flips between the two OPMs are synchronous with the drifting subpulses. This finding was soon followed by the discovery of similar behaviour in PSR B1237+25 (Rankin & Ramachandran, 2003), and for PSRs B0320+39 and B0818–13 (Edwards, 2004). It should be noted that for PSR B1237+25 the synchrony of the OPM flips and the drifting subpulses was not established using a technique such as $P_3$-folding (see Section 2.3.3), making it hard to establish if the OPM switching is strictly synchronous with the drifting subpulse, or what the detailed polarised structure of the modulation cycle is.

In order to explain the fact that, for some pulsars, the switches between OPMs are modulated by the periodicity of drifting subpulses, Rankin & Ramachandran (2003) suggested revisiting the carousel model. It was proposed that a single circulating carousel system produces two images of the same system, the radiation of each image being one of the OPMs, with the two images being offset in the azimuthal direction (with respect to the magnetic axis) as well as radially (away from the magnetic axis) magnified by different amounts (see Fig. 1.8). The two images are believed to arise due to birefringence in the pulsar magnetosphere (Rankin et al., 2006) and correspond to the O and X modes in the highly magnetised plasma. These modes are believed to experience different degrees of refraction. The X mode propagates without being affected by refraction, thus its trajectory is a straight line from the emitting region. The O mode propagates on a
2.2. Observations

curved path before escaping the pulsar magnetosphere (e.g. Petrova & Lyubarskii 2000; Petrova 2001; Lyubarsky 2002; Weltevrede et al. 2003). Since only the O mode is refracted in the magnetosphere, the two modes propagate along different paths, although they both originate from the same emission site close to the neutron star surface (see Section 1.4 for the origin of radio emission). Hence, two images of the emission carousel will be produced, which are magnified differently and have orthogonal polarisation.

In this work, we show that synchronous modulation of OPMs with the drifting subpulses exists for PSR B0031—07 (J0034—0721). This is a particularly interesting pulsar as it is known to exhibit drifting subpulses with three different stable drift modes, with \( P_3 = 13P \) (mode A), \( P_3 = 7P \) (mode B) and \( P_3 = 4P \) (mode C) (Huguenin et al., 1970). The occurrence of these modes depends on the observing frequency (e.g. Smits et al., 2005, 2007). For example, at 1.4 GHz only mode A and mode B have been observed to occur (Smits et al., 2007). Manchester (1975) investigated the polarisation properties of this pulsar and reported the presence of two OPMs. Our investigation builds on an initial analysis presented in a Masters thesis by Chen (2015). However, detailed analysis was hampered by strong instrumental variations on a timescale comparable with the rotation period of the neutron star. In this analysis we will describe the observed behaviour in more detail and discuss potential models.

The structure of this Chapter is as follows. In Section 2.2, the observations performed are described. In Section 2.3.1, we confirm the presence of multiple modes of drifting in PSR B0031—07, while in Section 2.3.2 we discuss the polarisation properties of this pulsar in depth. In Section 2.3.3, we show that the PA switches between the two OPM states are synchronous with the drifting subpulses, for both modes A and B. In Section 2.4, the results are discussed, as well as potential models. The conclusions are presented in Section 2.5.

2.2 Observations

Three different observations of PSR B0031—07 were performed using the H-OH receiver of the Parkes telescope at a central frequency of 1369 MHz and with a bandwidth of 256 MHz, split into 512 frequency channels. This was recorded with the backend system known as the Parkes Digital FilterBank PDFB4. The first two observations were made on the 9th of April 2016 and the third one was performed on the 29th of August 2016. In the three observations 13,622, 7,982 and 7,951 individual pulses were recorded.
Data was de-dispersed and folded to create single pulses using DSPSR (van Straten & Bailes, 2011). After processing, the time resolution was 1024 pulse longitude bins. At the start of each observing session, a short pulse calibration observation of two minutes was performed, which was pointed offset from the pulsar, which allows correction for differential gain and phase. These are two of the seven independent parameters of the Mueller matrix (e.g. Mueller, 1948; Heiles et al., 2001), which is used in the process of polarisation calibration. The calibration was performed using the program PAC from the PSRCHIVE\textsuperscript{1} software package, as described in more detail in Section 1.2. The average polarisation properties of the second observation (e.g. PA swing) were very different compared to the other two observations, as well as the those described in the literature (Johnston & Kerr, 2018). This observation is not considered further in this analysis, since more investigation is required.

2.3 Analysis

A data-set obtained after combining the two observations has been used in the analysis to boost the sensitivity. This was achieved using tools from PSRCHIVE\textsuperscript{1}. The observations were aligned according to an ephemeris. This ephemeris was optimised to model the times of arrival (ToAs) by fitting for the period $P$ and period derivative $\dot{P}$, based on observations from the Lovell Telescope. The ToAs spanned a period between January 2009 and November 2017. The timing precision is calculated as the weighted uncertainties of the residuals (residuals are obtained after subtracting the timing model from the ToA). This represents the precision of the alignment and it was determined as 2333.4 $\mu$s, which considering the period of the pulsar it is 0.25\% (2.3 pulse longitude bins). This precision is relatively low due to the fact that the pulsar has different modes of emission which have different profile shapes (e.g. Wright & Fowler 1981). Hence, since different timing observations have a different mixture of the modes, the use of a single template profile shape to measure the ToA will result in a reduction of timing precision. After a mode separation was performed on our observations (see Section 2.3.1), it was checked and confirmed that the individual modes of the two observations were aligned properly, using a tool from the software package PSRSALSA\textsuperscript{2} (Weltevrede, 2016). The analysis presented in this Chapter has been done on the combined observation, however we checked that the results are consistent with those obtained from the two individual observations.

\textsuperscript{1}http://psrchive.sourceforge.net/
\textsuperscript{2}https://github.com/weltevrede/psrsalsa
2.3. Analysis

2.3.1 Drift modes

In this section, we will confirm the presence of the A and B drift modes in our data, as well as confirm that the occurrence of mode C is extremely rare at an observing frequency of \( \sim 1.4 \) GHz, as discussed by Smits et al. (2005, 2007).

A small section of the pulse-stack of PSR B0031–07 containing 100 consecutive pulses is displayed on the left-hand side of Fig. 2.1, showing several mode A drift bands up to pulse number 7,970. After this, two drift bands of the faster drifting mode B can be seen. For comparison, on the right-hand side of Fig. 2.1, an archival observation at 310 MHz from Westerbork Synthesis Radio Telescope (WSRT) is displayed (Weltevrede et al., 2007), showing four mode A drift bands up to pulse number 4,240, followed by four drift bands of mode B. In the right-hand panel, one can also see examples of nulling, which are pulses for which the radio emission mechanism appears to be inactive (e.g. pulses 4,180-4,190). It is obvious from Fig. 2.1 that the appearance of the drift bands is less clear at higher frequencies, as previously reported by, for example, Smits et al. (2005). Nevertheless, the choice was made to observe at this frequency because of the excellent performance of the Parkes telescope in producing polarisation calibrated pulsar data (Weltevrede & Johnston, 2008).

As we are interested in the modulation of the OPMs, the analysis which follows requires to separate the data in the different drift modes, since each drift mode has different polarisation and modulation properties. The methodology of mode separation is as follows. The pulse-stack was visually investigated and, for example, when performing the separation of mode A, all individual pulses that were classified as not to belong to this mode were removed from the sequence. A similar procedure was applied when separating mode B. One occurrence of mode C was seen in the pulse-stack (the length of the whole observation is \( \sim 5 \) hours), as several drift bands following an occurrence of mode B. However, due to the rarity of mode C, we did not attempt to include this mode in any further analysis. This is consistent with the findings of Smits et al. (2007), in which they report a total of four occurrences of mode C in their multi-frequency observations (except at 4.85 GHz) in a time span of 10 hours. Due to the decreasing clarity of the appearance of drift bands at our observing frequency (see Fig. 2.1), the mode separation could not be automated in a reliable way. Each individual pulse in the stack was assigned one of the following categories: mode A, mode B, mode C, or emission which was too weak to be classified (which is often because it is a null). The fourth category was included in order to avoid mis-labelling weak emission. There were no individual pulses where radio frequency interference (RFI) affected the mode identification.
Out of a total of 21,573 individual pulses, the pulsar was in a null state for 8,606 pulses (39.9%). The pulsar was on (in one of the three drift states) for 43.1% of the time (9,294 individual pulses). For the rest of the individual pulses we saw emission (i.e., it was not a null), however the emission was too weak to be classified reliably (17%). During the time the pulsar was on and classifiable, 30.5% of the time it was in mode A (2,838 individual pulses), 69.2% of the time it was in mode B (6,430 individual pulses) and 0.3% of the time it was in mode C (26 individual pulses). At 328 MHz, Smits et al. (2005) reported that PSR B0031–07 was on (in one of the three drift modes) 61.8% of the time (of which 17.8% mode A, 80.1% mode B and 2.1% mode C). These fractions are quite different from our results, where we clearly see a higher occurrence of mode A and a lower occurrence of mode B and C compared to lower frequencies. The null fraction, however, remains the same across different frequencies. The conclusion that mode A is more common at our frequency remains true even if none of the pulses which were marked as too weak to be classified are mode B pulses. In that extreme case still 26.1% of pulses would correspond to mode A, thereby significantly exceeding the 17.8% reported by Smits et al. (2005) at a lower observing frequency.

Distributions of the duration of individual stretches of mode A and B data are shown in Fig. 2.2. From these plots, we can see that mode A emission tends to be longer compared to mode B emission. The mode A stretches of data are between 25 and 200 pulses in duration (between 2 and 15 consecutive driftbands). Mode B stretches of data range between a few pulses up to 100 individual pulses (between 1 and 15 consecutive driftbands).

Mode separation is a somewhat subjective analysis, since it has been done by visually inspecting the pulse-stack and because of variability in the emission unrelated to drifting subpulses. Hence, we verified the mode separation was performed correctly by doing a fluctuation analysis on the mode separated data to see if the expected periodicities dominate. The resulting plots for the fluctuation analysis on the total intensity of the combined data, as well as the mode separated data, are shown in Fig. 2.3 and a detailed explanation of what is displayed in each panel is described in the following subsections.

**The modulation index**

The modulation index gives an indication of how much the intensity varies from pulse to pulse for a certain pulse longitude and is equal to the standard deviation of the intensity divided by its average. Here the modulation index is computed in
2.3. Analysis

Figure 2.1: Small sections of the PSR B0031−07 pulse-stacks showing both mode A and mode B driftbands. **Left:** Observation from the Parkes Telescope at 1369 MHz. **Right:** Archival observation from the WSRT at 310 MHz.

The intensities in a column of the pulse-stack with drift bands will resemble a sinusoidal pattern with periodicity \( P_3 \). The computation of the Longitude Resolved Fluctuation Spectrum (LRFS; Backer 1970a) allows the investigation of this periodicity by performing Discrete Fourier Transforms (DFTs) in the vertical direction on the Stokes I pulse-stack. This is achieved by splitting the stack into blocks of a certain chosen size corresponding to the length of the Fourier transforms, and...
Figure 2.2: Distribution of the duration of stretches of data in a certain mode of drifting. 
Top: Mode A. Bottom: Mode B.
Figure 2.3: Fluctuation analysis of PSR B0031−07. The top panels show the integrated pulse profiles, as well as the modulation index (data points with their associated uncertainties). The middle panel displays the LRFS and the left panel represents the horizontally integrated power. The bottom panels show the 2DFS, with two side panels, which display the horizontally and (between the two dashed lines) vertically integrated power. 

Left: Analysis of the combined data. Middle: Analysis of mode A separated data. Right: Analysis of mode B separated data.
DFTs are computed for every block. The final fluctuation spectrum, displayed in the second panels of Fig. 2.3, is obtained by averaging the power spectra obtained for the individual blocks. The length of a block has to be a power of two. For example, in the case of the combined data, the analysis was done with a block size of 512 pulses, thus only 21,504 out of 21,573 individual pulses were used. The larger the size of the block, the higher the spectral resolution. However, with increasing size of the block, the signal-to-noise (S/N) per spectral bin will decrease. Hence, the used size is a compromise. For more details on the method and implementation, see Weltevrede et al. (2006, 2007); Weltevrede (2016).

For the mode separated data, the choice of block size was made based on the average mode length, as inferred from the distributions displayed in Fig. 2.2. As discussed in Section 2.3.1, the continuous stretches of mode A are often longer than 64 pulses, while for mode B the stretches are generally a bit shorter. Hence, the mode A separated data was organised into sequences of 64 continuous individual pulses and mode B separated data into sequences of 32 individual pulses. These were the respective DFT sizes used to compute the LRFS. Care was taken to only consider blocks in which all pulses were classified to be in the same mode and incomplete blocks were discarded.

The power in the LRFS is horizontally integrated and shown in the panel left of the LRFS (Fig. 2.3). The LRFS is expected to show a peak at the frequency that best describes this pattern. Harmonics may appear if the driftbands are narrower compared to a sinusoidal pattern. If there are multiple modes of drifting with different values of $P_3$ in the pulse-stack, we expect to see power at the corresponding frequencies in the LRFS. In the left-most LRFS in Fig. 2.3, based on the not mode separated data, it can be seen that there are three peaks. The first peak is at zero frequency, pointing towards fluctuations with long timescales possibly because of nulling. The second peak occurs at a fluctuation frequency $P/P_3$ of around 0.07 cycles per period (cpp), indicating $P_3 \sim P/0.07 \sim 14P$. Hence, there are driftbands with a separation of about 14$P$, corresponding to drift mode A. The fact that the peak is resolved in fluctuation frequency indicates that $P_3$ is variable. The power excess ranges from $P_3 \sim 0.06$ cpp to $P_3 \sim 0.08$ cpp, indicating that $P_3$ varies $\sim 2P$ around the central value, which is consistent with what can be seen directly in the pulse-stacks. A weaker peak for a mode B periodicity can be seen in the LRFS, at $P/P_3 \sim 0.16$ cpp, indicating $P_3 \sim P/0.16 \sim 6P$. This spectral response is clearer in the 2DFS and will be further discussed in Section 2.3.1. As a confirmation for the successful mode separation, in the corresponding mode separated analysis for mode A and mode B (middle and right column in Fig. 2.3), only the periodicity of the drift mode of interest remains.
The LRFS is very useful to identify $P_3$ periodicities and to locate at what rotational phases they occur, however it is not sensitive to $P_2$. Periodic fluctuations in the intensity of individual pulses will show a power excess in the LRFS, but that does not necessarily imply that there are subpulses which drift in pulse phase. In order to identify and quantify the drifting phenomena, the 2DFS analysis can be used.

2DFS

For the 2-Dimensional Fluctuation Spectrum (2DFS, Edwards & Stappers (2002)) analysis, additional DFTs are performed in the horizontal direction of the pulse-stack. Both the LRFS and the 2DFS techniques are available to use with the PSRSALSA software package (Weltevrede, 2016). The 2DFS method is sensitive to $P_2$ periodicities as well as $P_3$ periodicities, with the horizontal axis corresponding to the fluctuation frequency $P/P_2$. Directly below the vertically integrated 2DFS is shown. To better illustrate the presence of drifting subpulses, only a limited interval in $P/P_3$ was integrated over to avoid contributions from other types of modulation. This area is indicated in all plots from Fig. 2.3 by the two horizontal dotted lines. A symmetric peak at $P/P_2$ around zero would indicate that there is no preferred direction for subpulses to drift in pulse phase, i.e. no systematic drifting or that both drift directions occur equally. A power excess which is offset horizontally from zero in either direction indicates the presence of drifting subpulses. The direction of drifting is given by the sign of the offset. The horizontal spread of power in the 2DFS power plot can be influenced by several factors, including the shape of the profile (Edwards & Stappers, 2002), as well as the changing slope of the driftband as a function of pulse phase (McSweeney et al., 2017).

In the 2DFS analysis of the not mode-separated pulse-stack (left plots Fig. 2.3) it can be clearly seen that two drift modes exist. There is power at the same $P/P_3$ frequencies as observed in the LRFS, and it is offset to the left. A negative $P_2$ indicates that subpulses drift towards earlier values of pulse longitude, as is obvious from Fig. 2.1 as well. The peaks in the 2DFS occur at a value of $P/P_2$ of around $-15$ cpp, giving $P_2 \sim -360^\circ/15 \sim -24^\circ$. By looking at the fluctuation analysis for the mode A and mode B mode-separated stacks (middle and right panels of Fig. 2.3), the peaks in $P/P_3$ and $P/P_2$ can be confirmed in their respective 2DFS plots. $P_3$ and $P_2$ for the mode separated stack were measured using an interactive tool of PSRSALSA (Weltevrede, 2016), where we calculated the centroid of power in the 2DFS several times for slightly different regions including the feature of interest. The resulting spread corresponds to a systematic uncertainty which
dominates over the statistical uncertainty, as is often the case (Weltevrede et al., 2006). For mode A, the obtained values are $P_3 = (13.0 \pm 0.2)P$ and $P_2 = 30^{+15}_{-10} \degree$. For mode B, the obtained values are $P_3 = (6.9 \pm 0.2)P$ and $P_2 = 20^{+7}_{-5} \degree$. These values are consistent with the measurements from Smits et al. (2007) at 1167 MHz, as well as $P_3$ measurements from Huguenin et al. (1970) and Smits et al. (2005) and consistent with what can be seen by eye in the pulse-stack from the left-hand side of Fig. 2.1. The fluctuation analysis thus, confirms that the two drift modes expected to occur at our observing frequency of 1369 MHz were identified and separated correctly.

2.3.2 Mode analysis: Polarisation properties

In this section, we will investigate the polarisation properties of the mode separated data and establish that the polarisation properties are variable.

Looking at the top panels from Fig. 2.4, it is clear that mode A and mode B have significantly different intensity profiles and average polarisation properties. The intensity profile of mode A peaks at a pulse longitude of $\sim 177 \degree$, while mode B peaks at a later longitude of around $\sim 182 \degree$. Such a shift has been previously reported by Vivekanand & Joshi (1997) at 327 MHz. Wright & Fowler (1981) also found that at a frequency of 1620 MHz, the profile of mode A is narrower compared to the profile of mode B, which in turn is narrower compared to the mode C profile. At 327 MHz, Vivekanand & Joshi (1997) observed a difference in the widths of the mode separated profiles as well. At 1167 MHz, Smits et al. (2007), measured the width at which the total intensity dropped by 90% (10%-width) of the mode A profile to be $(25 \pm 6) \degree$ and of mode B to be $(38 \pm 5) \degree$. In our observation, the widths of mode A and mode B separated data are consistent with these results. The measured 10%-width of mode A is $(27.6 \pm 0.3) \degree$, and for mode B is $(44.1 \pm 0.3) \degree$. The widths were measured by obtaining an analytic description for the profile shape by fitting 3 von Mises functions (the von Mises distribution resembles a Gaussian distribution, but cyclic) and then measuring the separation between the points situated at an intensity of 10% of the peak amplitude, on either side of the peak. The uncertainty was obtained from bootstrapping, i.e. by repeatedly adding Gaussian noise with the standard deviation measured from the off-pulse region of the profile. The analytic function describing the profile shape was then refined and several new measurements of the width were performed. The quoted uncertainty is the standard deviation of these iterations.

The average linear polarisation $L$ and circular polarisation $V$ of the not mode-separated data are low, as seen in the top panels of Fig. 2.4. In comparison,
2.3. Analysis

Figure 2.4: Polarisation properties of PSR B0031−07. In the top panels, the total intensity pulse profile is represented by the black curve, linear polarisation with the red curve, circular polarisation with the green curve and the total polarisation with the dashed blue line. The time averaged PA and ellipticity angle $\chi$ are shown in the second and third row of panels respectively. The bottom two rows of panels display the PA and $\chi$ distribution obtained for individual pulses when the significance of $L$ exceeded 2 sigma, with the grey-scale corresponding to the number of occurrences. Note that the average PA swing is displayed on a scale between 0° and 180°, while the PA distribution is plotted between −90° and 90°. Top: The not mode separated pulse-stack. Bottom left: Mode A separated pulse-stack. Bottom right: Mode B separated pulse-stack.
Chapter 2. Modulation of polarisation and drifting subpulses for PSR B0031–07

$L$ in the mode separated data is stronger, which suggests that different OPMs dominate for different drift modes thereby causing depolarisation. $L$ is the highest for drift mode A separated profile at a pulse longitude $\sim 177^\circ$. Stokes $V$ appears to be moderately high in mode A and relatively low, but significant, for mode B. Looking at the PA swings (obtained from equation (1.15)) of the two drift modes (second row panels of Fig. 2.4), we can see that they are different from each other. The two OPM jumps observed in the PA swing of the not mode-separated pulse-stack (left of Fig. 2.4) can also be seen in the PA swing of the more strongly polarised mode A (middle of Fig. 2.4). An OPM transition does not occur for mode B (right of Fig. 2.4). Smits et al. (2007) analysed the integrated pulse profiles for this pulsar at 0.243, 0.607, 0.840 and 4.850 GHz and found that the behaviour of the polarisation properties depend strongly on the observing frequency. For example, the PA swing of mode B does not show any abrupt OPM transitions at a frequency of 0.607 GHz, however at 0.840 GHz a $90^\circ$ jump can be observed.

The ellipticity angle swing (obtained from equation (1.16)), see third panels of Fig. 2.4, appears to peak where the two OPM transitions occur in the profile of the not mode-separated data and mode A. For mode A, the ellipticity angle swing is non-zero across the whole profile, which is expected given the presence of Stokes $V$. For mode B, the ellipticity angle is small for most pulse longitudes, except around longitude $\sim 189^\circ$ and towards the trailing edge.

The occurrence of OPM jumps in the PA swing of B0031–07 indicates the presence of two OPMs dominating at different pulse longitudes (Manchester, 1975). To further investigate these polarisation modes, the PA distribution of individual pulses for each drift mode, as well as for the not mode-separated data were determined, using PSRSALSA (Weltevrede, 2016). Only points for which the linear polarisation exceeded $2\sigma$ above the noise level were included. A similar analysis was performed to determine the ellipticity angle distribution of individual pulses. The obtained distributions are displayed in Fig. 2.4 in the two bottom panels. It is clear from the PA distribution plots that at most pulse longitudes there is a different mixture of OPMs for both modes A and B.

We define the OPM observed at PA $\sim 65^\circ$ as OPM$_A$, and the OPM at PA $\sim -25^\circ$ as OPM$_B$. The link between the occurrence of OPMs at certain longitudes and the modulation cycle will be discussed in Section 2.3.3. In the case of mode A drifting, OPM$_A$ often dominates over OPM$_B$, hence we observe jumps in the integrated PA swing. For Mode B, OPM$_B$ dominates at all pulse longitudes, hence we do not observe any OPM jumps in the integrated pulse profiles (only a very steep transition in the PA swing at $190^\circ$). Since OPMs point in opposite directions in a Poincarè sphere, mixing them at the same pulse longitude should lead to
depolarisation of the integrated profile. This is consistent with what we see in
Fig. 2.4. The occurrence rate of the two OPMs is comparable for the not mode-
separated dataset, whereas in the case of mode A, OPM\textsubscript{A} dominates often over
the other. It is therefore not surprising that the degree of linear polarisation is
higher for mode A than for the non-mode separated data.

In the mode A separated PA distribution, a structure can be seen flaring off
from OPM\textsubscript{B}, starting with pulse longitude 178°. This extends diagonally upwards
all the way to the other OPM. The structure is not visible in the mode B separated
PA distribution and we currently have no interpretation for what physics might
be responsible.

The ellipticity angle distribution observed for the not mode-separated data
and for the mode A data does not appear to be uni-modal, with one lobe extending
towards significant negative ellipticity, however the distributions are largely
overlapping. The $\chi$ distribution for mode B separated data appears uni-modal as
far as can be assessed given that it is quite broad, extending to high positive and
negative ellipticity. From these distributions one cannot deduce if the two OPMs
are related to the bi-modality of the ellipticity angle distribution.

Correlations between the linear and circular polarisation can be revealed by
considering the distribution of polarisation orientations which can be visualised
in the form of a Poincarè sphere using the Hammer equal area projection (Fig. 1.3).
The data was re-binned to 64 pulse longitude bins, in order to increase the S/N
per sample. Since the PA tracks in the distributions in Fig. 2.4 are relatively flat,
certainly where the polarised emission is strongest, the introduced spread is min-
imal. Poincarè spheres were produced for both the not mode-separated data, as
well as for the mode separated data. In all three panels of Fig. 1.3, the presence
of the two OPMs is clear (offset by $\sim 180^\circ$ in longitude). OPM\textsubscript{A} is clearly ellipti-
cal, since it appears offset from the equator, while OPM\textsubscript{B} appears almost entirely
linearly polarised.

The average position for OPM\textsubscript{A} and OPM\textsubscript{B} in the Poincarè sphere was deter-
mined in the following manner. A symmetrical box of chosen size was centred on
each OPM and the centroid (mean location weighed by the number of samples)
was calculated for that region. The statistical uncertainty on the centroid was
determined by bootstrapping (adding white noise with root-mean-square deter-
mined from the off-pulse region and re-computing the centroid). The dominant
uncertainty, however, was the systematic uncertainty arising from the subject-
ive choice in the size of the box. The procedure was repeated a number of
times while varying the size of the box and the quoted uncertainty is the stan-
dard deviation of these. OPM\textsubscript{B} from the not mode-separated Poincarè spheres
Figure 2.5: Distribution of polarisation orientations for all pulse longitudes, on a Poincaré sphere using the Hammer equal area projection. Only emission with total polarisation exceeded $2\sigma$ were included in the distribution. All on-pulse longitudes are included, but the effect of the shallow PA-swing was compensated for to reduce smearing. The data was re-binned to 64 longitude bins to boost the S/N per sample. The latitudes represent great circles of constant $\chi$. The north pole of the sphere represents pure positive circular polarisation, while the south pole corresponds to $-V$. The equator represents pure linear polarisation. The constant latitude lines are separated by $30^\circ$ in $\chi$. The meridians represent lines of constant PA. These range from $-90^\circ$ (left) to $90^\circ$ (right), in steps of $15^\circ$. The number of samples in each polarisation direction is represented by the colour scale. Top: The not mode-separated data. Bottom left: Mode A separated data. Bottom right: Mode B separated data.
in Fig. 1.3 has a PA = \((-22.10 \pm 0.07)\)° and \(\chi = (-0.46 \pm 0.03)\)°. OPM\(_A\) from the not mode-separated Poincarè spheres in Fig. 1.3 has a PA = \((66.13 \pm 0.09)\)° and \(\chi = (7.28 \pm 0.04)\)°. Both OPMs are elliptical, although one mode is practically linear. It is clear the two modes are not situated on antipodal points on the Poincarè sphere. First of all because only one OPM has appreciable circular polarisation, but furthermore, the OPMs are not exactly orthogonal in PA either. Since samples from all pulse longitudes were considered when producing the Poincarè spheres, a spread will be introduced if the PA or \(\chi\) is significantly evolving as function of pulse longitude. Furthermore, since the strength of OPM\(_A\) and OPM\(_B\) have a different pulse longitude dependence, a relative offset between the two modes can be introduced. To estimate the magnitude of this systematic error, the average shape of the PA swing was subtracted to remove much of the pulse longitude dependence of the PA. This did not include an OPM jump to ensure that the two OPMs remain separated in PA at all pulse longitudes. The PA offset of the centroids of OPM\(_A\) and OPM\(_B\) did not significantly change in this process, confirming that the OPMs of PSR B0031–07 are not orthogonal in both PA and \(\chi\) at our frequency. According to most theories, OPMs are expected to be orthogonal in both PA and ellipticity (e.g. Melrose et al. 2006), however deviations from orthogonality have been previously observed for other pulsars too (e.g. Edwards et al. 2003; Edwards 2004).

### 2.3.3 Mode analysis: \(P_3\)-folding

In order to explore the relation between the two OPMs observed for both modes of drifting and the periodicity of drifting subpulses, we used a technique called \(P_3\)-folding. The principle of the this method is that the data is averaged over the modulation cycle in order to obtain the average shape and properties of a driftband. However, a complication that arises when averaging successive drift bands over large stretches of data is that the value of \(P_3\) is not fixed and varies, as demonstrated in Section 2.3.1, hence if folding is performed without taking into account these variations, issues can arise (e.g. Deshpande & Rankin 2001; van Leeuwen et al. 2002). Hassall et al. (2013) were the first to compensate for these variations using a tool from the PSRSALSA software package, which is used in this analysis as well.

The folding algorithm works as follows. For both drift modes, the \(P_3\) cycle is resolved in \(2P_3/P\) bins. This oversampling by a factor of two implies that subsequent bins are dependent, but this gives a smoother visual result. The effective
resolution was made to match the intrinsic resolution by smoothing the data using a Gaussian smoothing kernel. Before being folded, the mode separated data was split in blocks of $3P_3$ pulses. Care was taken to only use blocks containing continuous stretches of pulses in a given mode, similar to what was done for the fluctuation analysis described in Section 2.3.1. Each block was first folded at a fixed value of $P_3$, taken to be the average value for the given drift mode as determined from the fluctuation analysis described in Section 2.3.1. A larger block size will increase the S/N per block, allowing the variability in $P_3$ to be better determined via the cross-correlation explained below. However, at the same time, a larger block size would cause smearing since the fixed period folding might no longer be accurate enough. The variations in $P_3$ were taken into account by cross-correlating the folded data for each block, resulting in phase offsets, which are used when summing the individually folded data for the separate blocks. This is done in an iterative manner. In the first iteration, the first block of individual pulses is used as the template in the process of cross-correlation when aligning the other blocks. In the next iteration, the result from the previous iteration is used as the template, thus giving a better alignment. The number of iterations was chosen such that further iterations do not lead to significant improvement in the final result.

The calculated offsets from the cross-correlation can be strongly influenced by the presence of randomly occurring bright pulses weakening the correlation of the underlying drifting subpulses pattern. Karuppusamy et al. (2011) showed that for PSR B0031–07 the emission is a combination of drifting subpulses, nulls and sporadic bright pulses. This was confirmed for our data by visually inspecting the pulse-stack. If these bright pulses appear in different parts of the modulation cycle, then the software will try to align them as well as the drifting subpulses, causing inaccurate results. In order to minimise this issue, all samples above a certain selected threshold of intensity were clipped before folding. This means that their intensity was set to the threshold intensity when exceeding the threshold, thereby maximising the power in the drifting subpulses. The offsets determined from folding the clipped data were used to fold the un-clipped pulse-stack. These offsets were also used to fold Stokes $Q$, $U$ and $V$, since the drifting subpulses are clearest in Stokes $I$, and to ensure the folded Stokes parameters are identically aligned. By combining the results for $Q$, $U$ and $V$, using equation (1.15) and equation (1.16), an average driftband was obtained for $L$, PA and $\chi$.

The $P_3$-folds of Stokes $I$, $L/I$, $V/I$, PA and $\chi$ for both drift modes are shown in Fig. 2.6. The average driftbands are shown twice, above each other, in the individual panels for the purpose of continuity.
2.3. Analysis

Figure 2.6: $P_3$-folds of Mode A (left) and Mode B (right) of drifting for PSR B0031$-07$. From top to bottom, Stokes $I$, $L/I$, $V/I$, PA and $\chi$ are displayed. The bottom row shows the ellipticity angle, $\chi$. Each driftband is shown twice for continuity.
Looking at the Stokes $I P_3$-folds, shown in the top row of Fig. 2.6, we can see clear diagonal driftbands indicating that the mode separation was done correctly, and that the $P_3$-fold reflects what is happening in the data. The mode A driftbands (top left panel) appear to be straight diagonal bands which extend between longitude $170^\circ$ to $182^\circ$, however some weak intensity can be seen up to longitude $200^\circ$. The mode B driftbands (top right panel) are longer compared to mode A driftbands, extending between pulse longitude $170^\circ$ up to longitude $210^\circ$.

Comparing the $P_3$-folds of Stokes $I$ and PA for mode A separated data (first and fourth left panels of Fig. 2.6), we note that, between pulse longitudes $170^\circ$ and $182^\circ$, OPM$_A$ (represented in white) coincides with the location of the intensity driftband, and OPM$_B$ (dark orange) occurs in between the intensity driftbands. This implies that throughout the modulation cycle, the dominance of the two OPMs switches periodically with $P_3$, with OPM$_A$ dominating most often where we see the intensity driftband. After pulse longitude $182^\circ$, an inversion occurs in the polarisation and the intensity appears to follow OPM$_B$, while OPM$_A$ occurs in between the intensity driftbands. In this region, periodic switches with $P_3$ still occur between the dominating OPMs in the modulation cycle, however OPM$_B$ now occurs most often where the intensity driftband is seen. At all pulse longitudes where in the PA distribution (Fig. 2.4) the dominance of OPMs alternates, there appears to be a link between the transitions between OPMs and the modulation cycle. If the OPM switching was not linked to drifting subpulses, we would not expect to observe any changes in the vertical direction in the $P_3$-folds. Similarly, in the case of mode B separated data, periodic switches between the two OPMs can be seen in the plot shown on the second row on the right-hand side of Fig. 2.6, after longitude $177^\circ$. At earlier longitudes, OPM$_B$ dominates at all times (see the PA distribution in Fig. 2.4), hence no vertical structure is seen.

In the $P_3$-fold of $L/I$ for mode A, shown in the second left panel of Fig. 2.6, it can be seen that the fractional linear polarisation drops at the edges of the total intensity driftband (shown in the top left panel). This is also where in the PA panel (the fourth left panel) switching between OPMs occurs, hence depolarisation can be expected. A similar behaviour can be seen in the $L/I P_3$-fold of mode B (second right panel), after pulse longitude $170^\circ$, where there is a mixture of OPM present.

In the $P_3$-folds of $V/I$, displayed in the third panels from the top in Fig. 2.6, it can be seen that the circular polarisation is modulated by the periodicity of drifting subpulses. Given that OPM$_A$ is elliptical, we expect Stokes $V$ to be modulated as well. Indeed we see that for mode A (third left panel), between pulse longitudes $170^\circ$ and $182^\circ$, periodic switches occur between a significant circular
polarisation component (coinciding with OPM\textsubscript{A}) and almost no circular polarisation (coinciding with OPM\textsubscript{B}). A similar trend can be seen for mode B after pulse longitude 170°.

In the bottom left panel, where the $P_3$-fold of $\chi$ of mode A is shown, one can see that OPM\textsubscript{A} has significant ellipticity, while OPM\textsubscript{B} is almost not elliptical (see Fig. 2.5). Particularly interesting is an asymmetry in time (pulse number) in the ellipticity for especially mode A. For that mode, between pulse longitude 170° and 180°, the driftband corresponding to OPM\textsubscript{A} starts with a lower ellipticity and it becomes highly elliptical before the OPM flips, as indicated by the change of colour in the plot (i.e. a bright yellow edge on the upper side of OPM\textsubscript{A} in the bottom-left panel of Fig. 2.6). Such an asymmetry can only be seen in the $\chi$ $P_3$-fold. The maximum ellipticity for both drift modes occurs in the transition region where the two OPMs flip in dominance and the fractional linear polarisation is zero. Unlike the ellipticity, the linear polarisation appears to be symmetrical in time i.e. at all the edges of OPM\textsubscript{A} $L/I$ is minimised. For mode A, a similar behaviour can be seen for OPM\textsubscript{A} between pulse longitudes 184° and 194°. However, now OPM\textsubscript{A} starts highly elliptical and becomes linear during the modulation cycle. An asymmetry is also present for mode B (bottom right panel), however the effect is less pronounced as for mode A. Up to pulse longitude 181°, the OPM\textsubscript{A} driftband is symmetrical in pulse number, as the ellipticity is maximised at the both the start and end of the OPM\textsubscript{A} band (bright yellow edge), however after this longitude only the OPM\textsubscript{A} band has a hint of ellipticity.

2.4 Discussion

We have discovered that for PSR B0031$–$07 the switches between the two OPMs are modulated synchronously with the drifting subpulses for both the A and B drift modes. This has only been seen for four other pulsars so far, and none of those pulsars have multiple stable drift modes.

Rankin & Ramachandran (2003) suggested that this behaviour can be accommodated in the carousel model. In this model, drifting subpulses reflect a pattern of sub-beams circulating around the magnetic pole and the origin of this pattern is “sparking” (pair production) near the surface of the star. To explain the observed behaviour two patterns are required, each corresponding to one of the OPMs. Due to different propagation paths in the magnetosphere, i.e birefringence, two ‘images’ of the same pattern are created. To explain the observations these images should be shifted both radially and azimuthally with respect to each other. Thus for PSR B0031−07, this should happen for (at least) both the A and B modes.
Chapter 2. Modulation of polarisation and drifting subpulses for PSR B0031–07

of drifting, although we will point out that this picture must be more complicated for this pulsar.

Smits et al. (2005, 2007) constructed a geometrical model in order to explain the drifting subpulses (in total intensity) of PSR B0031–07. The authors suggested that the emission of this pulsar would come from configurations of the carousel which is believed to expand or contract depending on the drift mode. The widest carousel configuration would correspond to drift mode A. This model can explain the fact that the intensity and occurrence of mode B drift bands decreases with increasing observing frequency, while the occurrence of mode A increases with observing frequency if radius-to-frequency mapping (RFM; Cordes 1978) is assumed. RFM is the effect where higher frequency emission originates from closer to the stellar surface, from magnetic field lines which are further away from the magnetic axis (see Section 1.5). Therefore, at higher observing frequencies we expect to see less of mode B, which is the more contracted carousel configuration.

However, the Smits et al. (2005, 2007) model was not designed to explain the polarisation properties of this pulsar. In the context of a symmetrical circular carousel, such as was applicable to PSR B0809+74 at 328 MHz (Rankin et al., 2006), one would expect to observe a symmetry of the driftbands with respect to the centre of the profile. We do not see such symmetry in the $P_3$-folds of PSR B0031–07, as an inversion occurs in the PA of mode A (see Section 2.3.3) such that the drift band as seen in total intensity is dominated by $\text{OPM}_A$ in one half of the profile, and $\text{OPM}_B$ in the other half. For mode B, in the earlier part of the pulse there is only $\text{OPM}_B$ present, while in the trailing half of the profile we see switches of the OPM synchronised with the drifting subpulses. Therefore two offset images of the same carousel are not enough to explain our observations, and additional effects would be required. These could potentially be asymmetric propagation effects in the pulsar magnetosphere. The same conclusion would apply for PSR B0818–13, which has complicated, and asymmetric, structures in its polarisation, which are synchronous with the drifting subpulses (Edwards 2004, and see Section 3.4.1, where the asymmetry observed at 1369 MHz is discussed). Although Edwards 2004 does not discuss the asymmetry of the driftbands specifically, it was concluded that for B0818–13, which has two non-orthogonal highly elliptical OPMs, a model with two offset OPM ‘images’ of the same carousel is not enough to explain the observed polarisation behaviour.

In the context of a single expanding or contracting carousel, one would expect that all differences between the two drift modes, including those in polarisation, arise because of a changing radius of the carousel. As the carousel contracts, both
images of the carousel corresponding to the two OPMs should contract as well. So one would not expect the relative arrangement of the two images to change appreciably between the drift modes. Therefore, with this scenario alone, it is very hard to explain why, for example, the observed discontinuity in the PA $P_3$-fold only appears in mode A (see Section 2.3.3).

The observed discontinuity in the PA $P_3$-fold of drift mode A at longitude 182° is very puzzling. In the case of PSRs B0320 + 39 and B0818 – 13 (Edwards, 2004), and also PSR B0809 + 74 at both 328 MHz and 1380 MHz (Edwards, 2004; Rankin et al., 2006), the total intensity driftbands are dominated by one OPM, while the other OPM dominates in between driftbands. The same appears to be true for PSR B1237 + 25 (Rankin & Ramachandran, 2003). PSR B0031 – 07 is different, since the total intensity drift band in drift mode A is dominated by different OPMs in the leading and trailing half of the profile.

Looking at the $P_3$-fold of drift mode A in PA (fourth left panel of Fig. 2.6), the pattern traced by a given OPM appears to be split in the middle of the profile with a vertical offset appearing. This at least visually resembles a subpulse phase jump as seen, for example, in the total intensity driftbands of PSR B0320 + 39 (Edwards et al., 2003). For PSR B0031 – 07 the total intensity $P_3$ folds are more continuous, although coincident with the discontinuity as seen in the PA $P_3$-fold of drift mode A, a small change in the slope of the intensity driftband can be seen, such that the driftband becomes shallower after the discontinuity.

Edwards et al. (2003) suggested that a subpulse phase jump is another type of phenomenon which might require superposed ‘images’ of the same carousel system. Here each image should have drifting subpulses which are out of phase because of an azimuthal offset. Hence, what we observe is a sum of the two images, each dominating in different halves of the profile. At the longitude where the phase modulation jump occurs, in the middle of the profile, the two images destructively interfere. Edwards (2004) pointed out that if the two superposed out of phase ‘images’ correspond to the two OPMs, both the subpulse phase step as seen in total intensity and the synchronous switching of the dominant OPM can be explained. Edwards & Stappers (2003) observed the intensity phase modulation of PSR B0320 + 39 at 328 MHz and 1380 MHz and noted that the change in the phase jump with frequency could be explained if the carousel systems had offset beam central coordinates.

Other authors (e.g. Clemens & Rosen 2004, 2008; Rosen & Demorest 2011) suggested that non-radial oscillations of the surface of the neutron star could explain drifting subpulses as well as the subpulse phase steps observed in intensity driftbands. However, it is unclear in this model how the polarisation is expected
to be affected, and why for PSR B0031–07 no subpulse phase step would be observed in total intensity, while there is a discontinuity in the PA of the driftbands in the middle of the profile.

Another puzzling issue is related to the asymmetric behaviour of the ellipticity in time (pulse number) (Fig. 2.6), such that in mode A in the leading half of the profile, the driftband dominated by $\text{OPM}_A$ becomes more elliptical during the modulation cycle. This implies that either the mixture of the two OPMs changes as a function of the modulation cycle ($\text{OPM}_A$ dominates more at the end of the cycle) or that the ellipticity of $\text{OPM}_A$ fluctuates during the modulation cycle. If the mixture of OPMs would change, thus creating this asymmetry in ellipticity, one would expect to observe a similar phenomenon in the $L/I$ $P_3$-fold, which is not seen. Hence, the ellipticity of $\text{OPM}_A$ varies during the modulation cycle. In the carousel model, the pattern of circulating sub-beams is in general taken to be symmetric with respect to the sense of circulation, in the sense that the structure of the sub-beam is similar in its leading and trailing half. Here, some form of symmetry breaking is required by physics which is affected by the sense of the circulation. Similar symmetry breaking has not been seen for the other four pulsars which show OPM switches synchronous with drifting subpulses. Note that the asymmetry can only be seen for $\text{OPM}_A$, while $\text{OPM}_B$ displays symmetrical behaviour in pulse number in the $P_3$-folds. As discussed in Section 2.3.2, $\text{OPM}_B$ is almost entirely linearly polarised, so it might not be too surprising that the time asymmetry in ellipticity is only seen for the more elliptical $\text{OPM}_A$. The origin of this asymmetry is unclear, as it is hard to distinguish whether it was caused by a propagation effect or if it is intrinsic to the emission mechanism itself.

From theory (e.g. Arons & Barnard 1986) one could expect the OPMs to be purely linearly polarised. However, we demonstrated (see Section 2.3.2) this is not the case for PSR B0031–07. In addition, the OPMs are not perfectly orthogonal in PA. Although at 328 MHz Smits et al. (2005) observed the OPMs to be orthogonal, the authors do not quote an associated uncertainty, hence further comparison is impossible. The two OPMs are not antipodal in the Poincarè sphere, with the largest deviation being that only one mode has appreciable ellipticity. This suggests that the mechanism which is responsible for the production of the circular polarisation affects the two OPMs differently. As discussed in Section 1.6, especially the origin of circular polarisation is uncertain. Also PSR B0329+54 has two OPMs with different degrees of ellipticity (Edwards & Stappers, 2004). The authors explained this in term of Generalised Faraday Rotation (GFR, Kennett & Melrose (1998)) and coherent addition of the radiation of the two OPMs. As discussed in Section 4.5, this allows partial conversion of linear into circular
polarisation. For more details on coherent and incoherent OPM addition, refer to Section 1.7. Melrose et al. (2006) offered an alternative explanation for the observed variable polarisation properties of individual pulses of PSR B0329 + 54, by assuming incoherent addition of the radiation of the two OPMs.

As seen for PSR B0329 + 54, in general it is hard to distinguish whether the observed polarised radiation is the incoherent or coherent sum of OPMs, or maybe just a mixture. For PSR B0031 – 07, when the rate of occurrence of both OPMs is comparable in the PA distribution of the not separated dataset, the linear polarisation is generally low, while when the rate of occurrence of one OPM is higher, as seen for the mode A separated dataset, $L$ is also higher (as discussed in Section 2.3.2), which indicates that the observed radiation is an incoherent addition of OPMs.

On the other hand, as pointed out by for example Dyks (2017), a good indicator for the natural polarisation modes being coherently combined would be the presence of a peak of circular polarisation near an OPM transition, while $L/I$ decreases and the total polarisation is not affected (see also Section 1.7). Fig. 2.4 shows that the ellipticity angle peaks where the OPM transitions occur (longitudes $172^\circ$ and $178^\circ$), however the average total polarisation does not remain constant (it decreases however it does not drop completely to zero). This points towards a combination of coherent and incoherent OPM addition (partial coherent addition).

## 2.5 Summary and Conclusions

We established, using the $P_3$-folding technique, that for PSR B0031 – 07 the orthogonal polarisation modes switch synchronously with the drifting subpulses seen in total intensity. This is observed for both drift modes (out of a total of three) which are present at our observing frequency (Smits et al., 2005, 2007). The rate of occurrence of the two observed drift modes (A and B) are consistent with the measurements from Smits et al. (2007). A similar connection between the periodicity seen in polarisation and total intensity has only been reported for four other pulsars (Ramachandran et al., 2002; Rankin & Ramachandran, 2003; Edwards, 2004). PSR B0031 – 07 is the only pulsar in this group of pulsars which shows drift-mode changes, making it a unique source to test emission models.

PSR B0031 – 07 is also different from the other four pulsars, as it was found that the ellipticity evolves asymmetrically with time during the modulation cycle, such that the ellipticity is monotonically changing from pulse to pulse across driftbands. The asymmetry is different for the two drift modes. If the carousel
model is to be applied in this case, some form of symmetry breaking is required by physics which is affected by the sense of the circulation.

For all other four pulsars which show modulated OPM switches synchronous with drifting subpulses, the driftbands observed in total intensity are generally dominated by one OPM, while the other one dominates in between the driftbands. However, during drift mode A of PSR B0031–07, the driftbands as observed in total intensity are dominated by different OPMs in different halves of the profile. This is accompanied by a slight change of the slope of the intensity driftband in the middle of the profile. This is somewhat reminiscent of what Edwards et al. (2003) observed in the intensity driftbands of PSR B0320 + 39, except that PSR B0320 + 39 shows a much larger discontinuity in the total intensity driftband: a subpulse phase step. Based on the frequency evolution of this subpulse phase step, this phenomenon was explained with two superposed out of phase ‘images’ of the carousel, which have offset centres (Edwards et al., 2003; Edwards & Stappers, 2004).

A symmetrical carousel which contracts or expands when switching between drift-modes, as was suggested by Smits et al. (2005, 2007) for PSR B0031–07, can only explain the behaviour as seen in total intensity. Additional effects would be required in order to explain our polarisation observations which show large asymmetries between the leading and trailing halves of the profile. We speculate this might be because of propagation effects in the pulsar magnetosphere which could in principle result in a coupling between the two OPMs (and with circular polarisation). If this coupling is asymmetric as function of pulse longitude, one could expect asymmetries to be observed, while the underlying carousel configuration is symmetric.
Chapter 3

A survey for modulated radio polarisation synchronous with drifting subpulses

In the previous Chapter, it was established that for PSR B0031−07 the radio emission is polarised in two orthogonal polarisation modes which switch dominance in a synchronous way with the drifting subpulses. This was the case for both drift modes observed at 1369 MHz. Excluding PSR B0031−07, there are only four pulsars for which this phenomenon was known to occur. In this Chapter we study a large sample of pulsars, observed with the Parkes radio telescope, with the aim to investigate how common this phenomenon is, and therefore whether the behaviour is a general property of the emission mechanism. Out of the 31 pulsars investigated, we found ten which showed both drifting subpulses and evidence for a mixture of two OPMs dominating. For eight of these, we demonstrate that a connection exists. Only for one of these pulsars, J0820−1350, a connection was previously established at a lower frequency in the literature. Hence, the work presented in this Chapter and the previous Chapter increases the number of pulsars with synchronous OPM switches with drifting subpulses from four to twelve. PSR J1932+1059 shows OPM mixture and drifting subpulses, however due to complex drift pattern a clear connection between the switching of OPMs and drifting was not established. Nevertheless, other more complex connections were identified between the linear and circular polarisation and the modulation. PSR J2048−1616 shows OPM mixture and drifting subpulses, however due to potentially large variations in the periodicity of drifting subpulses no clear OPM switches were seen synchronous with intensity variability. Regardless, a connection was established between linear polarisation and drifting subpulses. There were two pulsars for which OPM mixture was found,
however only non-random, but not periodic intensity modulation was identified. In all these cases, a connection was established between the polarisation properties of single pulses and the intensity of the single pulses, which could physically be because of a similar process as what causes the established links for pulsars with drifting subpulses. In this analysis, we discovered drifting subpulses for five pulsars (PSRs J1110–5637, J1453–6414, J1539–5626, J1605–5257 and J1651–5222) and periodic amplitude modulation for another three pulsars (J1048–5832, J1745–3040 and J1817–3618). For one pulsar in the sample, PSR J1932+1059, we discovered that there is a connection between the emission observed from both magnetic poles (the emission is modulated in phase). For one pulsar in the sample, PSR J1932+1059, we discovered that there is a synchronous periodic modulated emission observed from both magnetic poles, implying a physical connection between the emission regions at opposite sides of the star to regulate the observed modulation of the emission. It is unclear how this connection can be established.

3.1 Introduction

In Chapter 2, it was found that the radio emission of PSR B0031–07 is polarised in two orthogonal polarisation modes (OPMs; see Section 1.7), and that there is a periodic switching between the dominance of each OPM, which is synchronous with the drifting subpulses as seen in total intensity (see Section 2.3.3). This phenomenon occurs for both drift modes observable at 1369 MHz. There are only four other pulsars for which this phenomenon is known to occur (Ramachandran et al., 2002; Rankin & Ramachandran, 2003; Edwards, 2004). Polarisation studies at an individual pulse level are rare, and there are no systematic studies for this phenomenon in the pulsar population. Here we study a large sample of pulsars with the aim to investigate how common this phenomenon is, and therefore whether this behaviour is a general property of the emission mechanism. A sample of 31 pulsars was observed with the Parkes radio telescope under project ID P943, a project we proposed specifically with the aim of answering this question.

The sample was selected for this investigation based on the following criteria. Firstly, these sources showed evidence for different OPMs being present. Because in general there is no polarisation information available on an individual-pulse level, we looked for evidence in published time-averaged pulse profiles of different OPMs dominating at different rotational phases, indicating that both OPMs are active in these pulsars. In other words, we looked for evidence for steps of $\sim 90^\circ$ in the PA swing and the associated depolarisation. Note that this is
3.2 Observations

no guarantee for the dominant OPM to be switching from pulse-to-pulse. Also, the absence of steps in the PA swing does not imply that there cannot be OPM switching occurring at a pulse-to-pulse level. Nevertheless, this selection criterion increases the possibility for OPM switching to occur. Furthermore, for all the selected sources there is evidence for drifting subpulses, or at least non-random intensity modulation, based on literature (Weltevrede et al., 2006, 2007; Burke-Spolaor et al., 2012) or archival data without polarisation information. These two criteria maximises the probability of finding more sources for which OPM switching occurs synchronously with drifting subpulses.

PSR B0031–07 was observed as part of the observing programme and the results are described in Chapter 2. In this chapter the results from the rest of this survey are presented. The Chapter is structured as follows. In Section 3.2 we present a description of the observations performed and in Section 3.3 we present the techniques used in the analysis of the pulsars. The results for individual pulsars are presented and discussed in Section 3.4 and conclusions are drawn in Section 3.5.

3.2 Observations

Since PSR B0031–07 was observed as part of this survey, the details of the observational set-up and much of the analysis is similar to what was presented in Section 2.2. The H-OH receiver of the Parkes telescope was used, at a central frequency of 1369 MHz and a bandwidth of 256 MHz. The data was split into 512 frequency channels and were recorded with the Parkes Digital FilterBank PDBF4 backend system.

The observations were performed over five days: the 9th, 17th and, 26th of April 2016, and the 19th and 29th of August 2016. Some details of the observations are shown in Table 3.1. After being recorded, the data were de-dispersed, and each data-set was re-binned to 1024 pulse longitude bins per stellar rotation using DSPSR (van Straten & Bailes, 2011). Before the start of each observation, a short pulse calibration observation of two minutes was performed, which allowed a correction for differential gain and phase (two of the seven independent parameters of the Mueller matrix (e.g. Mueller, 1948; Heiles et al., 2001) used in the process of polarisation calibration). The data were calibrated using the program PAC from the PSRCHIVE\(^1\) software package. Finally, the individual frequency channels were averaged, and the data were re-ordered in the form of

\(^1\)http://psrchive.sourceforge.net/
a pulse-stack (see Section 1.2). If there were two observations performed, the results shown in the chapter is based on the combined data-set, in which case the observations were aligned using an up-to-date rotational ephemeris. It was checked that the results are consistent with those obtained from the individual observations.

3.3 Analysis techniques

In this Chapter, we employ similar tools to the ones used for PSR B0031–07, presented in Chapter 2. What follows is a brief summary of the process. In order to investigate whether the pulsar shows organised subpulse modulation in the form of drifting subpulses, fluctuation techniques were used, as explained in Section 2.3.1. The polarisation properties of each pulsar were investigated so that we could establish whether different OPMs dominate at different times. This was achieved by determining the position angle (PA) and ellipticity angle \(\chi\) distributions of individual pulses, as detailed in Section 2.3.2. To establish if there are correlated changes in PA and \(\chi\), the distribution of polarisation orientations was analysed in the form of a Hammer equal area projection of the Poincaré sphere (see Section 2.3.2).

Some pulsars have steep PA curves as function of pulse longitude. This is in general modelled with the Rotating Vector Model (RVM) (see Section 1.6), and is thought to arise because of a change in the orientation of the magnetic field lines on which the beamed observed emission is produced during the stellar rotation. In order to aid comparison of the PA distributions as observed at different pulse longitudes, we subtracted the best-fitting RVM description of the time-integrated PA-swing from the single pulse data. This is especially important when polarisation distributions were considered averaged over pulse longitude intervals, since otherwise smearing in PA is introduced. Not for all pulsars the RVM provided a good description of the PA swing. In those cases, no correction was done, and no longitude averaged polarisation distributions were considered. For the shown distributions where the RVM was subtracted, this is indicated. The fitting of the RVM was done using the tool \textsc{ppolFit} of the \textsc{psrsalsa} software package (Weltevrede, 2016) and it is described in detail by Rookyard et al. (2015); Weltevrede (2016).

For the pulsars where we identified drifting subpulses and a mixture of two OPMs dominating at the same pulse longitudes, the \(P_3\)-folding technique was applied (see Section 2.3.3). Here the data was averaged over the repetition period \(P_3\) of the drifting subpulse pattern, as seen in the pulse-stack. This allowed the
3.3. Analysis techniques

Table 3.1: Table summarising observation details. The first column shows the pulsar name. The period of each pulsar is displayed in the second column and was taken from the ATNF pulsar catalogue (Manchester et al., 2005). The duration of the observation is shown in the third column (in seconds) and the fourth column (in rotations). The final column shows if there were two observations performed, in which case the reported observation length is the sum of the two observations.


<table>
<thead>
<tr>
<th>Pulsar name</th>
<th>Period [s]</th>
<th>Obs length [s]</th>
<th>No. of individual pulses</th>
<th>No of obs</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0630–2834</td>
<td>1.244418</td>
<td>4052.7</td>
<td>3256</td>
<td>1</td>
</tr>
<tr>
<td>J0738–4042</td>
<td>0.374919</td>
<td>3605.5</td>
<td>9616</td>
<td>1</td>
</tr>
<tr>
<td>J0820–1350</td>
<td>1.238129</td>
<td>22138.6</td>
<td>17879</td>
<td>2</td>
</tr>
<tr>
<td>J1048–5832</td>
<td>0.123670</td>
<td>1805.6</td>
<td>14593</td>
<td>1</td>
</tr>
<tr>
<td>J1057–5226</td>
<td>0.197107</td>
<td>1805.6</td>
<td>9160</td>
<td>1</td>
</tr>
<tr>
<td>J1110–5637</td>
<td>0.558252</td>
<td>7205.8</td>
<td>12907</td>
<td>1</td>
</tr>
<tr>
<td>J1136+1551</td>
<td>1.187913</td>
<td>1546.6</td>
<td>1302</td>
<td>1</td>
</tr>
<tr>
<td>J1453–6413</td>
<td>0.179484</td>
<td>5411.8</td>
<td>30151</td>
<td>2</td>
</tr>
<tr>
<td>J1456–6843</td>
<td>0.263376</td>
<td>2305.8</td>
<td>8755</td>
<td>1</td>
</tr>
<tr>
<td>J1539–5626</td>
<td>0.243392</td>
<td>5405.4</td>
<td>22209</td>
<td>1</td>
</tr>
<tr>
<td>J1603–2531</td>
<td>0.283070</td>
<td>605.6</td>
<td>2138</td>
<td>1</td>
</tr>
<tr>
<td>J1605–5257</td>
<td>0.658013</td>
<td>6908.5</td>
<td>10500</td>
<td>2</td>
</tr>
<tr>
<td>J1645–0317</td>
<td>0.387689</td>
<td>3461.4</td>
<td>8928</td>
<td>2</td>
</tr>
<tr>
<td>J1651–5222</td>
<td>0.635055</td>
<td>3600.3</td>
<td>5678</td>
<td>1</td>
</tr>
<tr>
<td>J1720–2933</td>
<td>0.620448</td>
<td>3205.5</td>
<td>5166</td>
<td>1</td>
</tr>
<tr>
<td>J1722–3207</td>
<td>0.477157</td>
<td>2705.9</td>
<td>5671</td>
<td>1</td>
</tr>
<tr>
<td>J1731–4744</td>
<td>0.829828</td>
<td>905.4</td>
<td>1091</td>
<td>1</td>
</tr>
<tr>
<td>J1733–2228</td>
<td>0.871682</td>
<td>4503.1</td>
<td>5166</td>
<td>1</td>
</tr>
<tr>
<td>J1741–0840</td>
<td>2.043082</td>
<td>2165.8</td>
<td>1060</td>
<td>1</td>
</tr>
<tr>
<td>J1745–3040</td>
<td>0.367428</td>
<td>4741.1</td>
<td>19670</td>
<td>2</td>
</tr>
<tr>
<td>J1757–2421</td>
<td>0.234100</td>
<td>4026.5</td>
<td>17201</td>
<td>1</td>
</tr>
<tr>
<td>J1817–3618</td>
<td>0.387016</td>
<td>543.2</td>
<td>1404</td>
<td>1</td>
</tr>
<tr>
<td>J1825–0935</td>
<td>0.769005</td>
<td>11711</td>
<td>15229</td>
<td>2</td>
</tr>
<tr>
<td>J1847–0402</td>
<td>0.597769</td>
<td>3605.5</td>
<td>6032</td>
<td>1</td>
</tr>
<tr>
<td>J1900–2600</td>
<td>0.612209</td>
<td>5432.1</td>
<td>8874</td>
<td>2</td>
</tr>
<tr>
<td>J1921+2153</td>
<td>1.337302</td>
<td>4105.7</td>
<td>3070</td>
<td>1</td>
</tr>
<tr>
<td>J1932+1059</td>
<td>0.226517</td>
<td>1005.6</td>
<td>4439</td>
<td>1</td>
</tr>
<tr>
<td>J1946+1805</td>
<td>0.440618</td>
<td>1805.6</td>
<td>4099</td>
<td>1</td>
</tr>
<tr>
<td>J2046–0421</td>
<td>1.546938</td>
<td>4462.7</td>
<td>2883</td>
<td>1</td>
</tr>
<tr>
<td>J2048–1616</td>
<td>1.961572</td>
<td>10614.5</td>
<td>5411</td>
<td>2</td>
</tr>
<tr>
<td>J2346–0609</td>
<td>1.181463</td>
<td>7205.8</td>
<td>6099</td>
<td>1</td>
</tr>
</tbody>
</table>
investigation of whether the OPM switches at a single pulse level are modulated synchronously with the drifting subpulses.

3.4 Results and discussion of individual pulsars

Below we describe the results for each individual pulsar. Pulsars were grouped in the following categories: the pulsars for which we identified modulated OPM switches synchronous with drifting subpulses are presented in Section 3.4.1; the pulsars for which OPM switches and drifting subpulses were established, but without evidence for the two phenomenon being linked are described in Section 3.4.2. For some pulsars, OPM switches were identified, however only intensity modulation without a clear periodicity was seen. For these, we were unable to produce $P_3$-folds and they are described in Section 3.4.3. The pulsars which showed drifting subpulses, but no switches in the dominating OPM were identified at any pulse longitude, are described in Section 3.4.4. Pulsars for which we only identified OPM switches, but no intensity modulation or drifting subpulses are described in Section 3.4.5.

3.4.1 Pulsars with synchronous modulated OPMs and drifting subpulses

**PSR J0820–1350/B0818–13**

PSR J0820–1350 (B0818–13), discovered by Vaughan & Large (1970), was observed in two of the five observing sessions. In the first one, 10,180 individual pulses were collected, and in the second one 7,699 individual pulses, so a total of 17,879 individual pulses were recorded. The analysis from this Section was performed on a data-set obtained after combining the two observations, in which case the observations were aligned using an up-to-date rotational ephemeris. It was checked that the results are consistent with those obtained from the individual observations (see Section 2.3 for a description of the followed procedure of combining data-sets).

From the polarimetric profile displayed on the left-hand side of Fig 3.1, one can see that the pulsar has a narrow profile ($\sim 10^\circ$) with an average PA swing which has a very complex shape. There are no OPM transitions visible in the average PA swing, but several “wiggles” which cannot be accurately modelled with the RVM (red curve) are seen. The degree of linear polarisation $L$ is low, comparable to that of the circular polarisation $V$. 
Figure 3.1: Polarisation properties of PSR J0820–1350. In the top panels, the total intensity pulse profile is represented by the black curve, linear polarisation with the red curve, circular polarisation with the green curve and the total polarisation with the dashed blue line. The time averaged PA and $\chi$ are shown in the second and third row of panels respectively. The bottom two rows of panels display the PA and $\chi$ distribution obtained for individual pulses when the significance of $L$ exceeded 2$\sigma$, with the grey-scale corresponding to the number of occurrences. Left: The best fitting RVM is over-plotted in the second panel (red curve). Right: The best fitting RVM was subtracted from the PA, affecting the PA swing, and the PA distribution.
In the PA distribution (fourth panels of Fig. 3.1, with (right) or without (left) the RVM subtracted) a mixture of two dominating polarisation modes is seen around pulse longitude $\sim 103^\circ$. These modes are not separated by $90^\circ$; the separation appears to be less than $\sim 40^\circ$. Nevertheless, we will refer to this as two OPMs. In this chapter, OPMs refer to polarisation modes, rather than strictly orthogonal polarisation modes. A diagonal extending structure (similar to what was seen for PSR B0031–07 in Section 2.3.2) connects the two OPMs. The same structure can also be seen in the PA distribution at 328 MHz (see Edwards 2004), although more centrally in the profile. Furthermore, the two OPMs are orthogonal at 328 MHz. The $\chi$ distribution (bottom panels of Fig. 3.1) is very broad, extending between $-45^\circ$ and $30^\circ$.

In order to explore the connection between the PA and $\chi$ distributions, the distribution of polarisation orientations was explored on a Poincarè sphere. Due to the complex and changing nature from longitude to longitude of the observed PA distribution, the distributions of polarisation orientations were plotted for several pulse longitudes (Fig. 3.2). The RVM swing was subtracted, hence the polarisation is centred at zero PA.

The polarisation distribution has a complex evolution as a function of pulse longitude (Fig. 3.2). At pulse longitudes $98^\circ – 99^\circ$ (top plot of Fig. 3.2), the distribution is largely uni-modal. The distribution is elongated on either side of the equator, raising the possibility that there are two OPMs present which have a very close separation in PA and opposite signs of ellipticity. At later pulse longitudes, the separation between OPMs becomes clearer. One OPM appears to be situated near the bottom pole of the Poincarè sphere, i.e. it is highly elliptical, while the other OPM is near the equator. The distribution of polarised orientations is truly bi-modal at pulse longitudes $103^\circ – 104^\circ$, where the PA distribution is bi-modal as well (Fig. 3.1). This is different from the findings of Edwards (2004) at 328 MHz, which reported that at the longitude where they observe a broadly bi-modal distribution in the PA distribution (i.e. OPM mixture), they do not see a clear bi-modal distribution of polarisation orientations on the Poincarè sphere. Instead, an elongated broad distribution overlapping with the pole of the Poincarè sphere was observed, extending in two orthogonal PA directions.

In the pulse-stack (Fig. 3.3), relatively straight driftbands can be seen. At 645 MHz, Biggs et al. (1987) previously reported that the drift rate of the pulsar is shallower in the centre of the driftbands. Weltevrede et al. (2006) confirmed seeing this at 1380 MHz, accompanied by a drop in the modulation index at the same longitude. The authors did not observe a change in drift rate towards the leading edge of the profile. In our observation, the change of drift rate in the
3.4. Results and discussion of individual pulsars

Figure 3.2: Poincaré spheres of PSR J0820$-$1350 after subtracting the RVM for several pulse longitudes, as indicated by the vertical red lines on the left-hand side plots. Left: Polarimetric profiles as in Fig. 3.1. Right: For the Poincaré spheres, only emission with total polarisation exceeding 2σ were included in the distribution. The data was re-binned to 64 longitude bins after subtracting the RVM to boost the S/N per sample. The latitudes represent great circles of constant $\chi$. The north pole represents all polarisation being Stokes $+V$, while the south pole corresponds to $-V$. The equator represents pure $L$. The constant latitude lines are separated by 30° in $\chi$. The meridians represent lines of constant PA. These range from $-90^\circ$ (left) to $90^\circ$ (right), in steps of 15°. The number of samples in each polarisation direction is represented by the colour scale.
Chapter 3. Survey for modulated radio polarisation and drifting subpulses

Figure 3.3: PSR J0820–1350. Left: Fluctuation analysis using all of the 17,408 pulses (34 blocks with FFT size 512). The top panel shows the integrated pulse profile, as well as the modulation index (points with their associated uncertainties). The middle panel displays the LRFS and the left panel represents the horizontally integrated power. The bottom panels show the 2DFS, with two side panels, which display the integrated power in the horizontal, and vertical direction for the region situated in between the two dashed lines. Right: Small section of the pulse-stack, containing 80 consecutive individual pulses.
centre of the profile is not visible, however a drop in the modulation index (top left panel Fig. 3.3) occurs towards the centre of the profile. Edwards (2004) suggested that the behaviour of the intensity driftbands is connected to the complex behaviour of the polarisation, similarly to what was suggested for PSR B0320 + 39 (see Section 2.4). The drifting subpulses are very clear and regular, hence in the fluctuation analysis displayed in Fig. 3.3 a clear peak in the spectral power can be seen, indicating the presence of drifting subpulses with a stable $P_3$. Following the approach described in Section 2.3.1, it follows that $P_3 = (4.7 \pm 0.2)P$, which is consistent with previous reported values (Weltevrede et al., 2006; Basu et al., 2016, 2019).

The data were folded on the (slightly variable) drifting subpulse repetition rate and the resulting $P_3$-folds are shown in Fig. 3.4 (see Section 2.3.3 for a description of the method). The average total intensity driftbands are smooth with no obvious changing drift rate towards the centre of the profile. In the $L/I$, $V/I$ and $\chi P_3$-folds, periodic switches occur at all pulse longitudes. In the $\chi$ and $V/I P_3$-folds two discontinuities occur, such that the ellipticity changes sign at a pulse longitude of $\sim 99^\circ$ and $\sim 104^\circ$. A similar discontinuity, although in PA rather than $\chi$, is observed for PSR B0031 – 07 (Section 2.3.3). This implies that, as for PSR B0031 – 07, the polarisation driftbands are not symmetric with respect to the centre of the profile. An asymmetry is seen for this pulsar also in PA at 328 MHz (Edwards, 2004), which is not seen at our observing frequency. This is discussed in more detail in Section 2.4.

There are two main regions of interest in the PA $P_3$-folds. The first one is towards the trailing edge of the pulse, around pulse longitudes $102^\circ — 107^\circ$, where vertical structure in the PA $P_3$-fold is seen: periodic changes occur between a PA $\sim 90^\circ$ and a PA of $\sim -50^\circ$, which correspond to the two OPMs seen mixing at this longitude in the PA distribution (Fig. 3.1). Around longitude $105^\circ$, wrap in the PA can be seen (between black and white) as a result of the pulse longitude dependence of the PA swing. The vertical structure indicates that there is indeed a connection between polarisation mode switches and the periodicity of drifting subpulses for this pulsar.

A second region where periodic switches occur in the PA $P_3$-fold is between longitudes $95^\circ$ and $98^\circ$. Periodic changes occur between a PA $\sim -20^\circ$ and a PA of $\sim 20^\circ$ and the sign of the ellipticity alternates as well as seen in the $\chi P_3$-fold). This is consistent with what was observed in the Poincaré sphere at this longitudes (Fig. 3.2), where there were two OPMs closely separated in PA and with opposite ellipticity. Edwards (2004) were the first to investigate the polarisation properties of single pulses for this pulsar at 328 MHz. The authors reported...
Chapter 3. Survey for modulated radio polarisation and drifting subpulses

Figure 3.4: $P_3$-folds for PSR J0820$-$1350. On the top row, from left to right, Stokes $I$, $L/I$, $V/I$ are displayed. The bottom row shows the PA and ellipticity angle, $\chi$. Each driftband is shown twice for continuity.

Bi-modal switching in the PA $P_3$-fold, however they do not report variations in the $\chi P_3$-fold. In our observation, periodic switches occur in all the polarimetric $P_3$-folds. Furthermore, at their frequency, Edwards (2004) did not observe modulated OPM switches in two regions of the PA $P_3$-fold.

PSR J1048–5832/B1046–58

PSR J1048–5832 (B1046–58) was observed in one observing session, resulting in 4,439 collected individual pulses. The polarimetric properties are shown in Fig. 3.5. The pulsar has a triple component profile with high $L$ in the first two components and complete depolarisation in the trailing component. The degree of circular polarisation is low. The PA swing is smooth and steep and the RVM describes its shape well. On the right-hand side of Fig. 3.5, the data with the best fitting RVM subtracted is shown, hence the PA is centred at zero.

In the PA distribution (fourth panel of Fig. 3.5), one OPM can be seen dominating at most pulse longitudes. Starting with longitude 120$^\circ$, two OPMs can be seen, coincident with the depolarisation observed in the average profile. In the $\chi$ distribution (bottom panel), a uni-modal distribution is observed, mainly centred on zero, with a preference for positive ellipticity. To explore the connection between PA and $\chi$, the polarisation orientation distributions were plotted on a Poincaré sphere, for the data-set with the RVM subtracted, using all pulse longitudes. This is shown on the left-hand side of Fig. 3.6. In this plot, only one OPM stands out, which is the dominant OPM, seen in the PA distribution (fourth
3.4. Results and discussion of individual pulsars

Figure 3.5: Polarimetric profiles of PSR J1048–5832, as in Fig. 3.1. The PA distributions were saturated, in order to reveal less visible structures. Left: The best fitting RVM is over-plotted in the second panel (red curve). Right: The best fitting RVM was subtracted from the PA, affecting the PA swing, and the PA distribution.

Hence, the polarisation orientation distribution for longitude 120° (where OPM mixture was seen) is shown separately on the right-hand side of Fig. 3.6. Both OPMs can be seen on either side of the sphere. The OPM on the left-hand side of the sphere appears to have a preference for negative ellipticity, while the other OPM, although broad, has on average a slight positive ellipticity.

No drifting subpulses are reported for this pulsar. Burke-Spolaor et al. (2012) observed intensity modulation towards the edges of the profile. The fluctuation analysis performed for this pulsar is displayed on the left-hand side of Fig. 3.7. A relatively wide peak can be seen in the LRFS integrated panel (middle left). From the 2DFS panel, one can see that the power excess does not appear to be offset from zero, indicating that only intensity modulation and no drifting subpulses occur for the pulsar. The same conclusion can be reached by looking at the section of the pulse-stack displayed on the right-hand side of Fig. 3.7, where horizontal driftbands can be seen. As detailed in Section 2.3.1, a $P_3$ of $(17.5 \pm 0.2)P$ was measured.
Chapter 3. Survey for modulated radio polarisation and drifting subpulses

Figure 3.6: Distribution of polarisation orientations for PSR J1048–5832 using the pulse-stack with the best RVM subtracted from the PA points, on a Poincarè sphere using the Hammer equal area projection. For more details, refer to Fig. 3.2. Compared to Fig. 3.2, the Poincarè sphere has been rotated in the PA direction, such that central meridian corresponds to a PA of $-45^\circ$. Left: All pulse longitudes were used, re-binned to 64 longitude bins. Right: Pulse longitude $120^\circ$.

The clear intensity modulation allows $P_3$-folding to be performed, and the resulting $P_3$-folds are shown in Fig. 3.8 (see Section 2.3.3 for a method description). In the Stokes $I$ $P_3$-fold, horizontal driftbands can be seen. The driftband appears wider in the leading part of the pulse, compared to the trailing edge. The polarimetric $P_3$-folds do not show any vertical structure until pulse longitude $119^\circ$. This is expected since there is only one OPM dominating at these longitudes (see the PA distribution, fourth panel Fig. 3.5). The change in colour observed in the horizontal direction in the PA $P_3$-fold is due to the swing of the PA with pulse longitude. After longitude $119^\circ$, periodic switches occur in the PA $P_3$-fold between the two OPMs seen mixing at these longitudes in the PA distribution. The dominant OPM coincides with the location of the intensity driftband, while the weak OPM dominates in between. Vertical structure can also be seen in the same part of the profile in the $L/I$, $V/I$ and $\chi P_3$-folds.

**PSR J1110–5637/B1107–56**

PSR J1110–5637 (B1107–56) was observed in one observing session and 12,907 individual pulses were collected. The polarimetric profile and properties are shown in Fig. 3.9. The data-set with the best fitting RVM subtracted is shown on the right-hand side of Fig. 3.9. The pulsar has is a double component intensity profile with relatively low $L$. There are two OPM transitions in the PA swing
3.4. Results and discussion of individual pulsars

Figure 3.7: PSR J1048–5832. Left: Fluctuation analysis using 14,336 of the 14,593 pulses (28 blocks with FFT size 512). For details, refer to Fig. 3.3. Right: Small section of the pulse-stack containing 100 individual pulses.

Figure 3.8: $P_3$-folds for PSR J1048–5832. On the top row, from left to right, Stokes $I$, $L/I$, $V/I$ are displayed. The bottom row shows the PA and ellipticity angle, $\chi$. Each driftband is shown twice for continuity.
Chapter 3. Survey for modulated radio polarisation and drifting subpulses

Figure 3.9: Polarimetric profiles of PSR J1110–5637, as in Fig. 3.1. Left: The best fitting RVM is over-plotted in the second panel (red curve). Right: The best fitting RVM was subtracted from the PA, affecting the PA swing, and the PA distribution.
3.4. Results and discussion of individual pulsars

Figure 3.10: Distribution of polarisation orientations for PSR J1110–5637 after subtracting the RVM, using all pulse longitudes, on a Poincaré sphere using the Hammer equal area projection. For more details, refer to Fig. 3.2. Compared to Fig. 3.2, the Poincaré sphere has been rotated in the PA direction, such that central meridian corresponds to a PA of $-45^\circ$.

(longitudes $187^\circ$ and $198^\circ$). The average $\chi$ swing (third panel of Fig. 3.9) gradually decreases from zero ellipticity in the leading edge of the profile, towards high negative ellipticity near the second OPM transition.

Two OPMs can be seen in the PA distribution (fourth panels of Fig. 3.9), however switching between the dominant OPM only occurs at later longitudes ($\sim 195^\circ$), coincident with significant depolarisation in the integrated profile (top panels). In the $\chi$ distribution (bottom panels), a vertically elongated distribution can be seen towards the trailing edge. The polarisation orientations for all pulse longitudes, after subtracting the RVM, have been plotted on a Poincaré sphere (Fig. 3.10). This figure reveals that one OPM is almost entirely linearly polarised, while the other OPM is elliptical.

Drifting subpulses have not been previously reported in the literature for this pulsar, however Burke-Spolaor et al. (2012) reported intensity modulation towards the trailing component. In the fluctuation analysis displayed in Fig. 3.11, an excess of power in the LRFS is seen (second panel) in the second component of the profile, and in the trailing side of the first component, peaking at $\sim 0.1 P/P_3$ cpp. The broadness of the peak suggests there is variation in $P_3$ over time. The presence of drifting subpulses is confirmed in 2DFS displayed in the bottom panel in Fig. 3.11, which shows the presence of a preferred drift direction with a frequency of $\sim 48P/P_2$. Drifting subpulses can also be directly seen in the pulse-stack, especially for the second profile component (see right-hand side of Fig. 3.11). Following the approach described in Section 2.3.1, it follows that $P_3 = (9.7 \pm 0.3)P$. 
Chapter 3. Survey for modulated radio polarisation and drifting subpulses

Figure 3.11: PSR J1110–5637. Left: Fluctuation analysis using 12,800 of the 12,907 pulses (25 blocks with FFT size 512). For details, refer to Fig. 3.3. The bottom panel represents the 2DFS of the trailing component. Right: Small section of the pulse-stack, containing 100 consecutive individual pulses.
3.4. Results and discussion of individual pulsars

Figure 3.12: $P_3$-folds for PSR J1110−5637. On the top row, from left to right, Stokes $I$, $L/I$, $V/I$ are displayed. The bottom row shows the PA and ellipticity angle, $\chi$. Each driftband is shown twice for continuity.

The $I$, $L/I$, $V/I$, PA and $\chi$ $P_3$-folds are displayed in Fig. 3.12. In the Stokes $I$ $P_3$-fold (the top left panel), clear driftbands can be seen in the second component around pulse longitude 197°, as well as the modulation occurring towards the trailing edge of the first component (around pulse longitude 186°) which appears to be in phase with the drifting from the second component. Switches between the dominating OPM were observed between a pulse longitude of 195° and 200°. Clear vertical structure in the polarisation $P_3$-folds can be seen at those longitudes. In the PA $P_3$-fold, periodic switches between the two OPMs occur (dark red and yellow). One OPM coincides with the location of the total intensity driftband, while the other OPM occurs in between the driftbands. Almost complete depolarisation can be seen in the $L/I$ $P_3$-fold where the OPM switches occur. In the $V/I$ and $\chi$ $P_3$-folds, periodic switches between no and significant negative ellipticity can be observed, consistent with the fact that only one of the two OPMs is elliptical (see Fig. 3.10).

PSR J1453−6413/B1449−64

PSR J1453−6413 (B1449−64) was observed in two observing sessions, resulting in a total of 30,151 individual pulses. The analysis which follows was performed on a data-set obtained after combining the two observations, in which case the observations were aligned using an up-to-date rotational ephemeris. It was checked that the results are consistent with those obtained from the individual observations (see Section 2.3 for a description of the followed procedure of combining
Chapter 3. Survey for modulated radio polarisation and drifting subpulses

Figure 3.13: PSR J1453–6413. Left: Polarimetric profiles as in Fig. 3.1. Right: Distribution of polarisation orientations for pulse longitude 85°, where a mixture of OPMs dominating occurs, on a Poincaré sphere using the Hammer equal area projection. For more details, refer to Fig. 3.2.

data-sets).

The integrated polarimetric profile is displayed in Fig. 3.13. The pulse profile has multiple overlapping components, with a long extending trailing tail. The linear polarisation is moderately high, with one drop to zero coinciding with an OPM jump in the PA swing at longitude 85°. Another transition which is slightly non-orthogonal occurs at longitude 96°. The shape of the average PA swing (second panel) is much more complex as expected from the RVM. The average $\chi$ swing (third panel) varies significantly as a function of longitude and peaks at the longitude of the non-orthogonal transition.

In the PA distribution, displayed in the fourth panel of Fig. 3.13, two OPMs can be seen. Mixture of OPMs dominating occurs for only two longitudes, 84° and around 85°. The distribution of polarisation orientations was plotted on a Poincaré sphere for longitude 85° and this is displayed on the right-hand side of Fig. 3.13. Two OPMs can be seen with opposite ellipticity, confirming the presence of OPMs mixing at this longitude.
3.4. Results and discussion of individual pulsars

Figure 3.14: PSR J1453–6413. Left: Fluctuation analysis, using 29,696 out of 30,151 individual pulses (58 blocks with FFT size 512 pulses). Details of the panels can be found in Fig. 3.3. Right: Small section of the pulse-stack containing 80 individual pulses.
Chapter 3. Survey for modulated radio polarisation and drifting subpulses

Figure 3.15: $P_3$-folds for PSR J1453–6413. On the top row, from left to right, Stokes $I$, $L/I$, $V/I$ are displayed. The bottom row shows the PA and ellipticity angle, $\chi$. Each driftband is shown twice for continuity.

There are no reports in the literature whether the pulsar shows drifting subpulses. PSR J1453–6413 was chosen for this analysis based on findings from Burke-Spolaor et al. (2012), which show there is intensity modulation occurring towards the trailing edge. Fig. 3.14 shows a power excess in the LRFS peaking at $0.1P/P_3$ cpp ($P_3 = (10.2 \pm 0.2)P$) and the 2DFS (lower left panel) reveals an excess of power offset from zero towards negative $P_2$, thereby demonstrating drifting subpulses occur. In the small section of the pulse-stack, shown on the right-hand side of Fig. 3.14, driftbands can be observed, however they do not appear to be as regular as for example PSR J0820–1350 (Section 3.4.1).

The $P_3$-folds are displayed in Fig. 3.15. In the Stokes $I$ $P_3$-fold, driftbands can be seen with a similar shape to what was observed in the pulse-stack. Around pulse longitudes $84^\circ$ (where OPM mixture was seen) switches occur in tandem with the modulation cycle in the PA $P_3$-fold (left top bottom row), between a PA of $\sim -50^\circ$ (dark brown) and a PA of $\sim 50^\circ$ (yellow). Furthermore, switches might be happening at the same longitude in the $V/I$ $P_3$-fold, however it is not very clear if the same can be seen in the $\chi$ $P_3$-fold. These findings are consistent with the two OPMs seen mixing in the Poincaré sphere, shown in Fig. 3.13. Note that the vertical structure around longitudes $90^\circ – 92^\circ$ is caused by the PA wrapping from $90^\circ$ (white) to $-90^\circ$ (black), due to the PA swing. At these longitudes, no OPM switches were seen in the PA distribution, however the PA appears to be shifting periodically by a small amount, synchronous with the drifting subpulses.
3.4. Results and discussion of individual pulsars

Figure 3.16: Polarimetric profiles of PSR J1645–0317, as in Fig. 3.1.

PSR J1645–0317/B1642–03

PSR J1645–0317 (B1642–03), which was one of the first pulsars to be discovered (Huguenin & Taylor, 1969), was observed in two of the five observing sessions for a total of 8,928 pulses and a combined data-set was used for the following analysis. The polarimetric analysis is shown in Fig. 3.16. PSR J1645–0317 has an intensity profile with a central component, a pre- and a post-cursor. \( L \) and \( V \) are low. The PA swing (second panel) has a complex shape which could not be fitted with the RVM, with two OPM transitions (around pulse longitude \( \sim 88^\circ \) and \( \sim 99^\circ \)) as well as some “wiggles” in the central region of the PA swing. There is a change of sign in \( V \) towards the centre of the profile around pulse longitude \( 92^\circ \) which coincides with a “dip” in the average PA swing.

The PA distribution (fourth panel in Fig. 3.16) indicates that there is some mixture of OPMs towards the leading edge of the profile, around pulse longitudes \( 86^\circ – 92^\circ \). However, the two OPMs are not distributed along two tracks separated by \( 90^\circ \), so the polarisation modes are not orthogonal. The separation in PA between the two OPMs starts at \( 90^\circ \) and becomes gradually smaller as a function of longitude. After pulse longitude \( 92^\circ \) the two polarisation tracks combine, but up
Chapter 3. Survey for modulated radio polarisation and drifting subpulses

Figure 3.17: Poincaré spheres of PSR J1645–0317 for several pulse longitudes, as indicated by the vertical red lines on the left-hand side plots. Left: Polarimetric profiles as in Fig. 3.1. Right: Distribution of polarisation orientations for a specific longitude on a Poincaré sphere using the Hammer equal area projection. For more details, refer to Fig. 3.2.
to pulse longitude 94° the PA track appears to be vertically elongated, suggesting that the two polarisation modes still exist although with an almost identical PA. Also the $\chi$ distribution (bottom panel) is broad, extending between negative and positive ellipticity.

Because of the complex evolution of OPM separation as a function of pulse longitude, the distribution of polarisation orientations in the form of Poincaré spheres were produced for several different pulse longitudes (Fig. 3.17). At pulse longitude 91° (top panel), two OPMs can be seen mixing (the distribution is bi-modal). These have a relatively small PA separation and opposite ellipticity signs. At longitudes $92° - 95°$, the distribution of polarisation orientations is no longer bi-modal, but is elongated in the PA direction, indicating the polarisation modes are merging. At longitude 97° (bottom panel), the polarisation is more elliptical (evolves towards the north pole) and any evidence for bi-modality disappeared.

Drifting subpulses have been previously confirmed for this pulsar at our observing frequency by Weltevrede et al. (2006). Indeed the 2DFS (Fig. 3.18) shows a broad spectral response centred on $0.09P/3\text{ cpp} (P_3 = (11.8 \pm 0.3)P)$ and $20P/P_2$, consistent with Weltevrede et al. (2006). In the small section of the pulse-stack, displayed on the right-hand side of Fig. 3.18, clear driftbands can be seen with a changing drift rate which becomes steeper at the trailing edge of the profile.

The $P_3$–folds are displayed in Fig. 3.19. In the Stokes $I$ $P_3$–fold, curved driftbands can be seen between longitudes $90°$ and $95°$. In the PA $P_3$–fold (bottom left), vertical structure can be seen starting from pulse longitude $88°$ up to $\sim 95°$. The structure is clearer at the start of this range, as expected because there the separation between the OPMs is largest. Also the $V/I$ and $\chi$ $P_3$–folds show vertical structure corresponding to sign changes of the circular polarisation.

**PSR J1720–2933/B1717–29**

PSR J1720–2933 (B1717–29) was observed in only one observing session, for a total of 5,166 individual pulses. The polarimetric profile is shown in Fig. 3.20. The pulsar has a multiple component intensity profile, with low average $L$ and $V$. The PA curve has a smooth steep swing well described by the RVM. The right-hand side of Fig. 3.20 shows the results after subtraction of the best fit RVM.

In the PA distributions, shown in the fourth panels of Fig. 3.20, a mixture of OPMs can be seen at several longitudes around $\sim 81°$. PA distributions at 333 MHz and 618 MHz have been presented by Mitra et al. (2016) and are very similar to our observation. The $\chi$ distribution (bottom panel) is broad, with preference for positive ellipticity in the early parts of the profile. The Poincaré sphere
Figure 3.18: PSR J1645–0317. *Left*: Fluctuation analysis, using 8,704 of the 8,928 individual pulses (17 blocks with FFT size 512 pulses). Details of the panels can be found in Fig. 3.3. *Right*: Small section of the pulse-stack containing 80 individual pulses.

Figure 3.19: \( P_3 \)-folds for PSR J1645–0317. On the top row, from left to right, Stokes \( I, L/I, V/I \) are displayed. The bottom row shows the PA and ellipticity angle, \( \chi \). Each driftband is shown twice for continuity.
3.4. Results and discussion of individual pulsars

Figure 3.20: Polarimetric profiles of PSR J1720–2933, as in Fig. 3.1. Left: The best fitting RVM is over-plotted in the second panel (red curve). Right: The best fitting RVM was subtracted from the PA, affecting the PA swing, and the PA distribution.
in Fig. 3.21 was obtained after subtracting the RVM and a linearly polarised OPM can be seen. A hint of the other OPM can be seen on the left-hand side of the sphere, however it is not very clear. This is not surprising, considering the low intensity of this OPM in the PA distribution (Fig. 3.20).

Weltevrede et al. (2006) were the first to report drifting subpulses for this pulsar, and their observation was at a similar frequency compared to ours. Basu et al. (2016); Basu & Mitra (2018); Basu et al. (2019) later confirmed the drifting subpulses. The fluctuation analysis of the pulsar is shown in Fig. 3.22. A very strong narrow feature is visible around 0.41\( P / P_3 \) cpp. Another weaker peak can be seen at 0.18\( P / P_3 \) cpp, which is the first harmonic of the fundamental frequency of the main peak. The first harmonic is expected to occur at twice the fundamental frequency, i.e. at 0.82\( P / P_3 \) cpp. The corresponding period is less than 2\( P \), hence because we are sampling the drifting subpulses only once per period \( P \), aliasing will occur as described by the Nyquist-Shannon sampling theorem. The perceived period of the first harmonic is expected to be at \( 1 - 0.82 = 0.18P / P_3 \) cpp, which is indeed where it is observed. The 2DFS shows that the fundamental has a negative \( P / P_2 \), while the first harmonic has twice the magnitude of \( P / P_2 \). Furthermore, since the first harmonic has crossed the alias border, the sign of \( P_2 \) changed as well (drifting subpulses at the frequency of the first harmonic will appear to drift in the opposite direction). All this confirms the two peaks correspond to the fundamental and first harmonic. The sharpness of the peaks indicate that \( P_3 \) is unusually stable, and \( P_3 \) was determined to be \( (2.45 \pm 0.05)P \) (consistent with previous published results).
3.4. Results and discussion of individual pulsars

**Figure 3.22:** PSR J1720–2933. *Left:* Fluctuation analysis using 5,120 of the 5,166 pulses (10 blocks with FFT size 512). For details, refer to Fig. 3.3. *Right:* A small section of the pulse-stack containing 100 individual pulses.

**Figure 3.23:** $P_3$-folds for PSR J1720–2933, re-binned to 512 pulse longitude bins. On the top row, from left to right, Stokes $I$, $I/L$, $V/I$ are displayed. The bottom row shows the PA and ellipticity angle, $\chi$. Each driftband is shown twice for continuity.
Chapter 3. Survey for modulated radio polarisation and drifting subpulses

Figure 3.24: PSR J1921+2153. Left: Polarimetric profiles as in Fig. 3.1. Right: Distribution of polarisation orientations for pulse longitude 265°, on a Poincaré sphere using the Hammer equal area projection. For more details, refer to Fig. 3.2.

$P_3$-folds were obtained for $P_3 = (2.45 \pm 0.05)P$ (Fig. 3.23). In the Stokes $I$ $P_3$-fold (top left panel of Fig. 3.23), a smooth driftband can be seen, with the intensity changing as a function of pulse longitude across the band. In the PA $P_3$-fold, at longitudes 80°–81°, switching occurs between the OPMs (orange and white) observed mixing in the PA distribution. Similar switches are seen in the $L/I$, $V/I$ and $\chi$ $P_3$-folds, confirming this is another pulsar for which the OPM switches at a single pulse level are connected to the frequency of drifting subpulses.

PSR J1921+2153/B1919+21

PSR J1921+2153 (B1919+21) was the first pulsar to be discovered (Hewish et al., 1968). We observed this pulsar in one session, where 3,070 individual pulses were obtained. The pulsar was selected for this analysis based on its very low average $L$ and complex PA swing, as judged from archival data, indicating that OPM mixture might occur. The polarimetric properties as shown in Fig. 3.24 indeed confirms this. At longitude 259°, a non-orthogonal transition occurs in the
3.4. Results and discussion of individual pulsars

Figure 3.25: PSR J1921+2153. Left: Fluctuation analysis using 2,560 of the 3,070 pulses (5 blocks with FFT size 512). For details, refer to Fig. 3.3. Right: A small section of the pulse-stack containing 100 individual pulses.

PA swing similar to that observed by Mitra et al. (2015) at 1.5 GHz. Note that the linear polarisation remains constant during the transition, which is unusual. Generally, transitions are believed to occur when the intensity of the two OPMs is comparable, hence a drop in linear polarisation is expected to occur. Dyks (2017) modelled the complex polarisation properties of this pulsar and was able to explain the non-orthogonal jump in the PA swing using coherent polarisation mode addition (see Section 1.7). The $\chi$ swing (third panel) is complex as well, with a lot of changes between positive and negative ellipticity. Furthermore, a discontinuity can be seen at longitude $257^\circ$. The $\chi$ distribution (bottom panel) follows the $\chi$ swing with a large spread in the $\chi$ direction.

In the PA distribution, shown on the fourth panel of Fig. 3.24, mixture of OPMs is potentially occurring at longitude $257^\circ$, however it is not very clear. Mixture also appears at longitude $259^\circ$, however the separation in PA is less than $90^\circ$. After longitude $262^\circ$, the PA distribution appears elongated in the vertical direction compared to earlier longitudes, indicating that there might be polarisation modes with similar PA in this region. Mitra et al. (2015) observed a similar looking PA distribution at 1.5 GHz, while at 616 MHz Mitra et al. (2016) observed OPM mixture occurring at all longitudes, with the OPMs separated by $90^\circ$. Due to the
Chapter 3. Survey for modulated radio polarisation and drifting subpulses

Figure 3.26: $P_3$-folds for PSR J1921 + 2153. On the top row, from left to right, Stokes $I$, $L/I$, $V/I$ are displayed. The bottom row shows the PA and ellipticity angle, $\chi$. Each driftband is shown twice for continuity.

A low number of individual pulses where significant polarisation was measured, it was not possible to obtain meaningful Poincaré spheres for pulse longitudes $257^\circ$ and $259^\circ$. The Poincaré sphere for longitude $265^\circ$ is shown on the right-hand side of Fig. 3.24, and as expected reveals a wide distribution as the PA direction which also extends from positive to negative ellipticity.

The fluctuation analysis shows a spectral peak at $0.24P_3/\sigma_{P_3}$ (4.2 ± 0.2)$P$ and the 2DFS shows a power excess at negative $P_3$ (see left-hand side of Fig. 3.25). This confirms the drifting subpulses as reported by (Weltevrede et al., 2006; Basu et al., 2016, 2019). Clear driftbands can also be seen for both profile components in the pulse-stack (see right-hand panel of Fig. 3.25). It looks like a discontinuity occurs mid-way through the first profile component, hence it will be further investigated from the $P_3$-fold.

$P_3$-folding was performed on the pulse-stack, and the results are shown in Fig. 3.26. In the intensity $P_3$-fold (top left), the driftbands show a clear discontinuity in the leading component of the pulse profile. This leading component appears to have an overlapping double structure itself (see Fig. 3.24). This is similar to the phase modulation jump observed for PSRs B0809 + 74 and B0320 + 39, discussed in more detail in Section 2.4. This has been previously reported in the literature (Proszynski & Wolszczan, 1986; Weltevrede et al., 2006; Basu et al., 2016, 2019). In the trailing component of the profile, the driftbands are in phase with those observed in the second half of the leading component. In the PA $P_3$-fold, vertical structure can be seen at several longitudes. At longitude $257^\circ$, periodic switches occur between two OPMs. These correspond to the OPMs seen
mixing in the PA distribution (Fig. 3.24). Between longitudes 257° and 266°, no switches between two values of the PA are seen. However, the PA appears to be continuously changing with a small amount over the modulation cycle. This is similar to what we see for J1453–6413 (see Section 3.4.1). At the same longitudes, periodic switches are seen in the $L/I$, $V/I$ and $c P_3$-folds. Interestingly, the continuous changes only occur in the PA $P_3$-fold.

**PSR J2046–0421/B2043–04**

PSR J2046–0421 (B2043–04) was observed in one observing session for 2,883 stellar rotations. This pulsar has an overlapping double component intensity profile with low average $L$ and moderately high Stokes $V$ (Fig. 3.27). The average PA swing (second panel) is very steep with several gradient changes, hence the RVM fails to accurately describe its behaviour. The average $\chi$ swing (third panel) shows a smooth wiggle, except the discontinuity at the leading edge. The PA distribution (fourth panel) shows a very complex behaviour. At longitude 132° OPM switching can be seen between an OPM at PA $\sim$ 50° and an OPM at PA $\sim$ −30°. After this longitude, the PA distribution does not appear to be bi-modal, but it is
instead elongated in the PA direction, suggesting two polarisation modes might still be active. Mitra et al. (2016) observed a similar broad PA distribution at 333 MHz. At 618 MHz, the authors saw two clearly separated OPMs mixing at all pulse longitudes.

The $\chi$ distribution (bottom panel of Fig. 3.27) is also broad in the vertical direction, extending from $-45^\circ$ to $45^\circ$, with a concentration towards negative ellipticity. Due to the low count rate, in both the PA and $\chi$ distributions, meaningful Poincarè spheres could not be produced for longitudes before $134^\circ$. A Poincarè sphere was produced for the longitudes $134^\circ - 136^\circ$ averaged together, and it is shown on the right-hand side of Fig. 3.27. The distribution of polarisation orientations creates an arc around the south pole of the sphere, extending all the way to the equator on the right-hand side of the sphere. A similar distribution was seen for PSR J0820$-$1350 (see Section 3.4.1).

The pulsar is known to show drifting subpulses (Weltevrede et al., 2006; Basu et al., 2016, 2019) and indeed a clear spectral responds can be seen around $0.38P/P_3$ cpp ($P_3 = (2.75 \pm 0.05)P$) with a positive $P_2$ (left-hand side of Fig. 3.28). Drifting subpulses can also be seen directly in the pulse-stack (the right-hand side of Fig. 3.28).
3.4. Results and discussion of individual pulsars

![Figure 3.29: $P_3$-folds for PSR J2046–0421. On the top row, from left to right, Stokes $I$, $L/I$, $V/I$ are displayed. The bottom row shows the PA and ellipticity angle, $\chi$. Each driftband is shown twice for continuity.](image)

The Stokes $I$ $P_3$-fold (top left panel of Fig. 3.29) clear diagonal driftbands. In the PA $P_3$-fold (bottom left), vertical structure can be seen at several pulse longitudes indicating periodic switches between OPMs. At longitudes $133^\circ - 134^\circ$, where mixture of OPMs was observed in the PA distribution (Fig. 3.27), periodic switches modulated by the frequency of drifting subpulses can be seen between the two OPMs (changes between orange and yellow). Between longitudes $134^\circ$ and $138^\circ$, periodic changes occur from a dark yellow driftband (PA~ $10^\circ$) to a white yellow driftband (PA~ $50^\circ$), which are possibly more continuous as switching between two discrete states. These variations will contribute to the broadness of the observed PA distribution (Fig. 3.27). In the same regions of the profile, $L/I$, $V/I$ and $\chi$ appear to be modulated with the same periodicity as well.

3.4.2 Pulsars with non-synchronous modulated OPMs and drifting subpulses

**PSR J1932+1059/B1929+10**

PSR J1932+1059 (B1929+10) was observed in one observing session and 4,439 individual pulses were collected. The pulsar is known to have a main pulse (MP) and a weak interpulse (IP) separated by $180^\circ$ in pulse longitude, and is observed at several frequencies above 400 MHz (Gould & Lyne, 1998). The MP and IP are believed to originate from two different magnetic poles (e.g. Maciesiak et al.
Chapter 3. Survey for modulated radio polarisation and drifting subpulses

Figure 3.30: Polarimetric profiles of PSR J1932+1059, as in Fig. 3.1. Left: Main Pulse. The PA distribution was saturated, in order to reveal less visible structures. Right: Interpulse.

2011). The MP has a multiple component intensity profile with a weak slow-rising leading component. L is high and V is low (see left panel in Fig. 3.30). The PA swing (second panel) is relatively steep with an OPM jump around longitude 70°. At the longitude of the transition, a peak in the average \( \chi \) swing occurs corresponding to positive ellipticity.

The IP has a single component intensity profile with high \( L \) and little \( V \) as well. Its PA and \( \chi \) swings are flat (second and third panels). In the PA distribution of the IP (fourth panels), only one OPM (PA \( \sim 80° \)) can be seen dominating at all longitudes. In the MP PA distribution, only one OPM is observed until longitude 89°. After this longitude, OPM switching is seen, although one OPM is much rarer than the other. The \( \chi \) distribution of both the MP and IP are mostly centred on zero, as expected given the low observed average V. In Fig. 3.31, a Poincarè sphere for the pulse longitude where OPM mixture was identified in the MP, is shown. Unlike the strong OPM, the weak OPM has a positive ellipticity.

The fluctuation analysis of the pulsar for both the MP and the IP is shown on the top row of Fig. 3.32. In the LRFS of the MP (middle left panel), two broad
peaks are identified. One of them peaks around $0.09P/P_3$ cpp, while the other peaks around $0.19P/P_3$ cpp, which is consistent with Weltevrede et al. (2006) (at a similar frequency) and studies at different frequencies (420 MHz, 606 MHz, 1.7 GHz and 2.7 GHz; e.g. Backer 1973; Nowakowski et al. 1982). Weltevrede et al. (2006) reported that these peaks correspond to drift modes with opposite drift directions. This is confirmed in our analysis for the MP, since in the 2DFS the spectral feature at $0.09P/P_3$ cpp has a clear offset towards positive $P_2$, while the peak at $0.19P/P_3$ cpp has a slight excess towards negative $P_2$. Following the methodology of Section 2.3.1, it follows that $P_3 = (10.1 \pm 0.3)P$ and $P_3 = (5.2 \pm 0.3)P$ for these two spectral features.

In the 2DFS of the IP (top left plot of Fig. 3.32), only the feature at $0.09P/P_3$ cpp is visible, which is centred at $P/P_2 = 0$. This indicates that only intensity modulation occurs in the IP, with the periodicity of one of the spectral features from the MP. In the pulse-stacks (bottom row of Fig. 3.32), it is not immediately obvious how the two periodicities manifest themselves in the MP, while the periodicity is clearer in the IP. Visual inspection of the pulse-stack does not reveal obvious instances of drift-mode changes. In previous single pulse studies of the pulsar, other authors (e.g. Backer 1973; Oster et al. 1977) reported that the pulses have a large number of complex overlapping components. Possibly different subpulses drift in different directions at the same time, giving rise to a complex structure. For this pulsar, we were not able to separate the pulse-stack in different drift modes, and hence do not perform an analysis as for PSR B0031−07 (Section 2.3.1).

$P_3$-folding was performed on the MP, using the repetition rate of both drift modes. The resulting plots are displayed in Fig. 3.33 (using $P_3 = 10.1P$) and in
Figure 3.32: PSR J1932+1059. Top: Fluctuation analysis for the MP and IP using 4,096 of the 4,439 pulses (8 blocks with FFT size 512). Bottom: Small section of the pulse-stack containing 100 individual pulses for the MP (left) and IP (right).
3.4. Results and discussion of individual pulsars

**Figure 3.33:** $P_3$-folds for PSR J1932 + 1059, using $P_3 = 10.1P$. On the top row, from left to right, Stokes $I$, $L/I$, $V/I$ are displayed. The bottom row shows the PA and ellipticity angle, $\chi$. Each driftband is shown twice for continuity.

**Figure 3.34:** $P_3$-folds for PSR J1932 + 1059, using $P_3 = 5.2P$. On the top row, from left to right, Stokes $I$, $L/I$, $V/I$ are displayed. The bottom row shows the PA and ellipticity angle, $\chi$. Each driftband is shown twice for continuity.
Chapter 3. Survey for modulated radio polarisation and drifting subpulses

Figure 3.35: $P_3$-folds for PSR J1932 +1059 IP (left) and MP (right). Both were folded using the fold phases obtained from the IP. Each driftband is shown twice for continuity.

Fig. 3.34 (using $P_3 = 5.2P$). From the Stokes I $P_3$-folds (top left panels), complex behaviour can be seen. In the $P_3$-fold obtained using $P_3 = 5.2P$, a single driftband is seen with a relatively shallow, negative slope. This is consistent with what was seen in the 2DFS. In the $P_3$-fold obtained using $P_3 = 10.1P$, the driftbands are less clear: two driftbands appear instead of one. This is maybe not surprising, considering that the fold period is twice that of the other drift periodicity. Hence it is not clear how the $P_3 = 10.1P$ periodicity manifests itself in the plot.

It is important to note that one periodicity is not simply the harmonic of the other. Therefore there are two possible scenarios. The first possibility is that the two periodicities and the related drifting subpulse patterns are independent from each other, however we are not able to isolate the $P_3 = 10.1P$ pattern in the $P_3$-fold because the long period folding picked up two cycles of the quicker pattern instead. The second possibility is that the two periodicities are not independent and are harmonically related. This implies that there are no $P_3 = 10.1P$ driftbands, but there are driftbands with $P_3 = 5.2P$ which change systematically in every other driftband. If this were true, the change from each $P_3 = 5.2P$ driftband to the next should involve power drifting in pulse longitude, hence resulting in the observed $P_2$ in the 2DFS.

No vertical structure can be seen in either PA $P_3$-fold around pulse longitude 90°, where OPM mixture was identified. However, in the $L/I$, $V/I$ and $\chi$ $P_3$-folds, vertical structure occurs at longitude 90°, in both Fig. 3.33 and Fig. 3.34. It can be speculated that there are PA switches which are causing the periodic switches seen in $L/I$, although they do not show up in the PA $P_3$-fold. The observed decrease in $L/I$ occurs between where the intensity driftbands occur, and could indicate that the weaker OPM dominates more often in that part of the modulation cycle. However it could be too rare to show up in the PA $P_3$-fold. Here it is important to note that the complexity of the drift pattern is likely to result in
smearing in the $P_3$-fold, which would make it less likely for the rarer OPM to dominate at any point in the PA $P_3$-fold. Independent of if OPM switches occur synchronous with the subpulse modulation, it is clear that a connection between polarisation and drifting subpulses is established for this pulsar.

Since both the MP and IP show a $P_3 = 10.1P$ periodicity, one can wonder up to what level the periodicities are related. To further investigate the connection between the variability seen for the MP and IP for PSR J1932 + 1059, a total intensity $P_3$-fold was obtained for the IP (left of Fig. 3.35). Furthermore, the MP was folded using the $P_3$ folding phases obtained for the IP (right of Fig. 3.35). Polarisation $P_3$-folds for the IP were produced, however no vertical structure was seen, hence they are not displayed. The $P_3$-fold of the IP shows horizontal drift-bands, as expected from the pulse-stack (bottom right Fig. 3.32). The MP $P_3$-fold shows clear vertical structure, demonstrating that the modulation in the MP and IP are phase-locked. So despite the periodicity being inherently variable (as indicated by the broadness of the spectral feature in the LRFS, see Fig. 3.32), the modulation in the MP and IP keep a fixed phase relationship. This points towards a connection between the emission of the MP and IP such that they do no operate independent from each other. Furthermore, by using the IP $P_3$-fold phases, we were able to more clearly isolate the $P_3 = 10.1P$ periodicity in the MP. One can see two $10.1P$ periodicities are visible, such that the periodicity is out of phase in the leading and trailing half of the on-pulse region. This is suggestive of the $P_3 = 5.2P$ periodicity seen in the fluctuation analysis of the MP is due to the mixing of the two out of phase modulation patterns. Therefore, there are not two independent drift modes present.

**PSR J2048–1616/B2045–16**

PSR J2048–1616 (B2045–16) is one of the first pulsars discovered (Turtle & Vaughan, 1968). It was observed in two sessions, resulting in a total of 5,411 individual pulses being collected and the results from the analysis of the combined data-set are presented here. PSR J2048–1616 has a triple component intensity profile with moderately high $L$ and low $V$ (Fig. 3.36). The PA swing (second panel) is smooth without OPM jumps and the RVM describes it well. The RVM subtracted data is shown in the right-hand side of Fig. 3.36, and a small residual “wiggle” in the PA curve remains around longitude $35^\circ$, which coincides with a change of sign in Stokes $V$ (top panel). The PA distribution (fourth panel), reveals one OPM dominating at most pulse longitudes, with the exception of the edges of the profile where two OPMs are mixing and depolarisation occurs. Mitra
Chapter 3. Survey for modulated radio polarisation and drifting subpulses

Figure 3.36: Polarimetric profiles of PSR J2048–1616, as in Fig. 3.1. Left: The best fitting RVM is over-plotted in the second panel (red curve). Right: The best fitting RVM was subtracted from the PA, affecting the PA swing, and the PA distribution.
3.4. Results and discussion of individual pulsars

Figure 3.37: Distribution of polarisation orientations for PSR J2048–1616 on a Poincarè sphere, using the Hammer equal area projection. For more details, refer to Fig. 3.2. Compared to Fig. 3.2, the Poincarè sphere has been rotated in the PA direction, such that central meridian corresponds to a PA of $-45^\circ$. Left: Produced using the pulse-stack with the best RVM subtracted from the PA points, re-binned to 80 pulse longitude bins. Right: Produced for pulse longitude 38°.

et al. (2016) also reported mixture of OPMs at the edges of the profile at different frequencies of 333 MHz and 618 MHz.

The $\chi$ distribution (bottom panel) is relatively broad and centred on zero, as expected from the low Stokes $V$. Fig. 3.37 shows the Poincarè sphere for our profile using the RVM subtracted data-set. One clear OPM can be seen on the right-hand side of the sphere and a hint of an OPM can be seen on the left-hand side. The Poincarè sphere for longitude 38° is shown on the right-hand side of Fig. 3.37. Two OPM are clearly visible, both being almost entirely purely linearly polarised. The OPM at the right-hand side of the Poincarè sphere, which is the OPM which dominates in the middle of the profile, appears to have a slight positive ellipticity.

Drifting subpulses have been previously reported for the pulsar at several different frequencies, including our observing frequency (e.g. Oster & Sieber 1977; Nowakowski et al. 1982; Weltevrede et al. 2006, 2007). Oster & Sieber (1977) observed drifting subpulses at 1720 MHz in two components of the profile with a wide range of $P_3$ values (between $2P$ and $3P$), while Weltevrede et al. (2006) at 1420 MHz only saw drifting in the trailing component of the profile in a narrow peak around $0.3P/P_3$ cpp. Basu et al. (2016, 2019) only reported observing amplitude modulation with a broad range of $P_3$ at 333 MHz and 618 MHz. The fluctuation analysis for our observation is shown in Fig. 3.38. In the LRFS (middle panel), modulation occurs towards low frequencies (due to long periodicities in the pulse-stack). In addition, a wide range of fluctuation frequencies between
Chapter 3. Survey for modulated radio polarisation and drifting subpulses

Figure 3.38: PSR J2048–1616. Left: Fluctuation analysis using 5,120 of the 5,411 pulses (10 blocks with FFT size 512). Right: Small section of the pulse-stack containing 100 individual pulses.

0.25\(P_3\)/cpp and 0.45\(P_3\)/cpp can be seen in the trailing component of the profile. The narrow peak, as reported by Weltevrede et al. (2006) from their observation of 384 individual pulses, is not visible in Fig. 3.38. The peak from their observation might be caused by randomly occurring bright pulses, which may appear periodic in a short observation. In the 2DFS panel (bottom panel), the power excess between fluctuation frequencies of 0.25\(P_3\)/cpp and 0.45\(P_3\)/cpp appears to have no preference for any \(P_2\) values. This indicates that only amplitude modulation occurs for the pulsar with a range of \(P_3\) values.

\(P_3\)-folding was performed with a \(P_3 = 2.8P\) (Fig. 3.39). In the Stokes I \(P_3\)-fold (top left), the intensity can be seen changing from lower to higher values in the third profile component, as expected from the fluctuation analysis. At the longitudes where OPM mixture was identified in the PA distribution (25°–26° and 38°–40°), no vertical structure can be seen in the PA \(P_3\)-fold (bottom left). However, at longitudes 38°–40° modulation is observed in the \(L/I\) \(P_3\)-fold. A decrease in \(L/I\) occurs in between the intensity driftbands, indicating that the weaker OPM might dominate more often in this part of the modulation cycle.
3.4. Results and discussion of individual pulsars

Figure 3.39: $P_3$-folds for PSR J2048$-$1616. On the top row, from left to right, Stokes $I$, $L/I$, $V/I$ are displayed. The bottom row shows the PA and ellipticity angle, $\chi$. Each driftband is shown twice for continuity.

However, due to its rarity as well as due to the large variability of $P_3$ (smearing out), it may not show up in the PA $P_3$-fold. Regardless of whether OPM switches occur synchronous with the subpulse modulation, it is clear that for PSR J2048$-$1616 a connection between polarisation and drifting subpulses exists. As was seen for PSRs J1453$-$6413 (Sect 3.4.1) and J1921 + 2153 (Sect 3.4.1), around longitude 35° the PA appears to be periodically shifting by a small amount, synchronous with the organised intensity modulation. At this longitude only one OPM was seen dominating in the PA distribution.

3.4.3 Pulsars with mixture of OPMs and non-random modulated intensity

PSR J0738$-$4042/B0736$-$40

PSR J0738$-$4042 (B0736$-$40) is one of the first pulsars discovered (Large et al., 1968). It was observed once and 9,616 individual pulses were collected. The pulsar has a wide ($\sim 40^\circ$) multiple component intensity profile profile with moderately high $L$ and low $V$ (Fig. 3.40). The PA swing (second panel) displays a complex shape with five OPM jumps, coincident with drops in $L$. The RVM was fitted to the PA curve by accounting for the OPM jumps (red curve in the left hand-side of Fig. 3.40), and was subtracted from the observed PA (right hand-side of Fig. 3.40). As reported by Karastergiou et al. (2011), the integrated pulse
Chapter 3. Survey for modulated radio polarisation and drifting subpulses

Figure 3.40: Polarimetric profiles of PSR J0738–4042, as in Fig. 3.1. Left: The best fitting RVM is over-plotted in the second panel (red curve). Right: The best fitting RVM was subtracted from the PA, affecting the PA swing, and the PA distribution.

profile of this pulsar changes gradually over time in both intensity and polarisation (most notably the component around pulse longitude 165° is either present or absent). In our observation, the component around pulse longitude 165° is present, but is relatively weak, compared to a profile observed in 2010 (Karastergiou et al., 2011). Interestingly, the PA swings of PSR J0738–4042 shown in Karastergiou et al. (2011) have either three or four OPM transitions, but there are five in our observation. The intensity and polarisation profile are similar to more recent published polarimetry profiles (e.g. Johnston & Kerr 2018; Ilie et al. 2019). At all pulse longitudes where the OPM transitions are seen, peaks occur in the average $\chi$ swing (see third panel).

It is clear from both PA distributions from Fig. 3.40 (fourth panels, with or without the RVM subtracted) that at most pulse longitudes there is a mixture of OPMs. We will refer to the OPM at a PA of $\sim 0^\circ$ in the RVM subtracted data as the strong OPM and the OPM at a PA of $\sim -50^\circ$ as the weak OPM. Around pulse longitude 170°, the only OPM visible is the weak OPM, while between longitudes 170° and 180°, the weak OPM is almost invisible. Mitra et al. (2016) also observed mixture of OPMs for this pulsar at 333 MHz and 618 MHz. Also the $\chi$ distribution
3.4. Results and discussion of individual pulsars

Figure 3.41: Distribution of polarisation orientations for all pulse longitudes re-binned to 64 pulse longitude bins, using the pulse-stack where the best fitting RVM was subtracted, on a Poincaré sphere using the Hammer equal area projection. For more details, refer to Fig. 3.2. Compared to Fig. 3.2, the Poincaré sphere has been rotated in the PA direction, such that central meridian corresponds to a PA of $-50^\circ$.

(bottom panels) reveals a bi-modal distribution at most pulse longitudes except for the central part of the profile suggestive of the two OPMs being elliptical such that the strong OPM has a negative ellipticity, while the weak OPM has a positive ellipticity. This is confirmed in the Poincaré sphere (Fig. 3.41).

There are no reports in the literature on whether this pulsar shows drifting subpulses. Burke-Spolaor et al. (2012) showed that the intensity is modulated strongest in the trailing edge. From the fluctuation analysis displayed on the left-hand side of Fig. 3.42, a power excess can be seen in the integrated LRFS (middle panel) in the shape of a wide peak close to zero, suggestive of a red-noise like process rather than drifting subpulses. Most modulation indeed occurs in the trailing component of the pulse profile as indicated by the modulation index (top panel), thus confirming previous findings. The pulse stack, displayed on the right-hand side of Fig. 3.42, shows clear intensity variations in both profile components, but no drifting subpulses can be identified.

Since $P_3$-folding is not possible in this case, an alternative method was explored to further investigate if a connection between the non-randomly varying pulse intensity and OPM switches exists. The pulses in the pulse-stack were separated based on their energies (high or low). The pulse energy of each pulse was calculated as the time-integrated on-pulse intensity. This analysis is motivated by the found connections between polarisation and intensity at a single pulse level from the four pulsars which show synchronous modulated OPM switches and drifting subpulses (Ramachandran et al., 2002; Edwards, 2004). As discussed in
Figure 3.42: PSR J0738–4042. Left: Fluctuation analysis using 9,216 of the 9,616 pulses (28 blocks with FFT size 512). For details, refer to Fig. 3.3. Right: Small section of the pulse-stack containing 100 individual pulses.
Section 2.4, often one OPM is observed to dominate coincident with the intensity driftband, while the other OPM dominates in between. A similar behaviour was observed in the additional pulsars with a connection between drifting subpulses and OPM switching identified in our sample, as discussed in Section 3.4.1. Hence, it can be expected that if a connection between the non-random modulated intensity and polarisation properties exists for PSR J0738—4042, then the two OPMs might have a different rate of occurrence depending on the pulse energy. The pulse-stack (Fig. 3.42) reveals bright pulses occurring on relatively short timescales. To probe the red-noise like longer period variations (at timescales \( \gtrsim 10P \)), every five pulses were averaged together in the pulse-stack. The classification of low/bright energy pulses obtained for this partially averaged pulse-stack was applied to the original pulse-stack, and a separation was performed to quantify if the polarimetric properties depend on pulse intensity. To quantify the level of differences expected from the different S/N of bright and weak pulses, uniform Gaussian noise was added to the data containing bright pulses to match the S/N of the average single pulse in both data sets.

The polarimetry properties obtained for the energy separated data are shown in Fig. 3.43 (low and high energy, as well as high energy stack with added noise). Some subtle differences can be seen between the low- and high-energy pulses. For example, a difference is seen in the third OPM jump from the left in the PA swing. The jump occurs at a slightly earlier longitude in the low energy pulse-stack compared to the high-energy pulse-stack, due to potentially different amounts of mixture of OPMs. In the PA distribution of the high energy pulses, around longitude 170° (where the third OPM jump occurs in the PA swing) the bright OPM dominates most often over the weak OPM. However in the PA distribution of the low energy pulses, the two OPMs have comparable occurrence rates. This subtle difference might be the cause of the observed offset in the third OPM jump in the average PA swing. Around longitude 190° the average \( \chi \) swings are slightly different, in the sense that the peak in \( \chi \) extends towards more negative values for the high energy pulse-stack. Another difference which can be seen is that the fraction of linear polarisation is greater for the low energy pulses compared to the high energy pulses. For PSR J0738—4042, there appears to be a subtle connection between the OPM switches and the non-random modulated intensity.

**PSR J1456—6843/B1451—68**

PSR J1456—6843 (B1451—68) was observed in one observing session, and 8,755 individual pulses were recorded. The pulse profile is relatively wide (\( \sim 40° \)) and although there are no OPM jumps observed, the PA swing is complex with several
Chapter 3. Survey for modulated radio polarisation and drifting subpulses

Figure 3.43: Polarisation properties of PSR J0738–4042 for the energy separated data. For more details on what is displayed in each panel, refer to Fig. 3.1. Top left: Properties of the low-energy pulses. Top right: Properties of the high-energy pulses. Bottom: Properties of the high-energy pulses with additional Gaussian noise.
kinks and changes of the sign of the slope (see Fig. 3.44). The degree of linear polarisation is low and the magnitude of Stokes $V$ is comparable. The average $\chi$ swing (third panel) is also very complex with several swings from positive to negative ellipticity. The PA distribution (fourth panel) indicates that there is mixture of OPMs throughout the on-pulse region. The average separation in PA between the polarisation modes appears to be less than $90^\circ$, i.e. the OPMs are not orthogonal at any pulse longitude. The $\chi$ distribution (bottom panel), reveals a complex behaviour, by having a ‘bow tie’ like shape.

The Poincaré sphere was produced for several pulse longitudes (Fig. 3.45) and confirms that the ellipticity of the two OPMs changes significantly as a function of pulse longitude. In the leading edge of the profile, the two OPMs are almost entirely linearly polarised. Their ellipticity then increased towards longitude $112^\circ$, where the OPMs are situated on opposite poles of the Poincaré sphere, with essentially $100\%$ circular polarisation. In the centre of the profile, around longitude $119^\circ$, the OPMs are mostly linearly polarised again. Towards the trailing edge of the profile, the ellipticity of the OPMs increases again and at longitude $121^\circ$ they are purely linearly polarised again. In the leading half of the profile, the
Chapter 3. Survey for modulated radio polarisation and drifting subpulses

Figure 3.45: Distribution of polarisation orientations for PSR J1456−6843 for pulse longitudes $102^\circ$, $109^\circ$, and $112^\circ$ (top), $119^\circ$, $121^\circ$, and $127^\circ$ (bottom), on Poincaré spheres using the Hammer equal area projection. For more details, refer to Fig. 3.2.

OPM from the left-hand side of the sphere has positive ellipticity, while the OPM on the right-hand side of the sphere has negative ellipticity (Poincaré sphere at longitude $109^\circ$). In the trailing half, the ellipticity sign of the two OPMs changes (see Poincaré sphere at longitude $127^\circ$). When the OPMs are around the North and South pole of the Poincaré sphere, they form an arc-like structure extending from high ellipticity towards the equator of the sphere. Such behaviour was seen for one of the OPMs of PSR B0329+54 (Edwards & Stappers, 2004), and the authors explained it in the context of Generalised Faraday Rotation (GFR; Kennett & Melrose 1998) affecting the OPMs as they propagate through the magnetosphere (see also Section 2.4).

No drifting subpulses are revealed by our fluctuation analysis (Fig. 3.46). The modulation index (top panel) suggests that most intensity fluctuations occur towards the edges of the profile. The spectra reveal a slightly red spectrum such that there is no particular preferred fluctuation frequency. Instead, there is a gradient in the fluctuation power towards low fluctuation frequencies.

As for PSR J0738−4042 (see Section 3.4.3), we investigated whether there is a connection between the non-random intensity fluctuations and the occurrence rate of each OPM since $P_3$-folding is not possible. The data was separated into bright and weak pulses based on their single-pulse energies (without any time-averaging) and analysed separately. Unlike for PSR J0738−4042, a strong connection between polarisation and intensity at a single pulse level for this pulsar was established using this method (see Fig. 3.47). The average $L$, $V$, PA and $\chi$
3.4. Results and discussion of individual pulsars

Figure 3.46: PSR J1456–6843. Left: Fluctuation analysis using 8,704 of the 8,755 pulses (17 blocks with FFT size 512). For details, refer to Fig. 3.3. Right: Small section of the pulse-stack containing 100 individual pulses.
Figure 3.47: Polarisation properties of PSR J1456–6843 for the energy separated data. For more details on what is displayed in each panel, refer to Fig. 3.48. Left: Properties of the low-energy pulses. Right: Properties of the high-energy pulses.
3.4. Results and discussion of individual pulsars

Figure 3.48: Analysis of PSR J0630–2834. Left: Polarisation properties. Details of what is displayed in each panel are discussed in Fig. 3.1. Right: Fluctuation analysis using 3,072 of the 3,526 pulses (6 blocks with FFT size 512). For details, refer to Fig. 3.3.

Swings are significantly different for bright and weak pulses. Also, in the PA and $\chi$ distributions, different parts of the tracks have a higher occurrence rate. For example, between longitudes 124° and 134°, in the stronger pulses both OPMs are regularly detected in the PA distribution, while for the weaker pulses, the OPM at $\sim -50°$ dominates.
3.4.4 Pulsars with periodic modulation, and no OPM mixture

**PSR J0630–2834/B0628–28**

PSR J0630–2834, discovered by Large et al. (1969), has been observed by us once resulting in 3,256 individual pulses being collected. Drifting subpulses have been reported by (Weltevrede et al., 2006, 2007; Basu et al., 2016, 2019). Basu et al. (2016, 2019) observed variable \( P_3 = (6.9 \pm 1.5)P \) drift in the positive direction at 618 MHz. We also observe a wide feature in our spectra (Fig. 3.48), which is offset from the vertical axis in the 2DFS confirming positive drift, consistent with Weltevrede et al. (2006) who observed this pulsar at the same observing frequency.

PSR J0630–2834 has a single component intensity profile, with moderately high average linear polarisation \( L \) and low average circular polarisation \( V \) (see top-left panel of Fig. 3.48). The PA swing is smooth and relatively steep, with no OPM transitions, as previously reported (Weltevrede & Johnston, 2008; Johnston et al., 2008). In the integrated profile, depolarisation occurs at the edges of the profile, which in principle could be because of the presence of two OPMs. However, the PA and \( \chi \) distributions (left bottom panels in Fig. 3.48) reveal that for this pulsar there is only one OPM is observed at all times, which is almost purely linearly polarised. Due to there being only one OPM present, no further analysis was performed.

**PSR J1057–5226/B1055–52**

PSR J1057–5226 (B1055–52) was observed in only one observing session for 9,160 stellar rotations. The pulsar has both a Main Pulse (MP) and an Interpulse (IP), separated by roughly half a turn. Biggs (1990) were the first to attempt explore the intensity modulation of pulses at 645 MHz. More recently, Weltevrede et al. (2012a) performed a detailed fluctuation analysis and concluded that the intensity of both the MP and IP is modulated with a period of \( \sim 20P \). Furthermore, the authors argued that the modulation is synchronous in the MP and IP, indicating a connection between the emission from both magnetic poles. The features in our fluctuation spectra (Fig. 3.49) are similar to those reported by Weltevrede et al. (2012a). Both the MP (left hand-side) and IP (right hand-side) show a spectral feature at \( \sim 0.05P / P_3 \) cpp \( (P_3 \simeq 20P) \). There does not appear a significant horizontal offset of the feature in the 2DFS, indicating that although there is intensity modulation for the pulsar, drifting might not be present. For the MP, a wider range of periodicities can be seen compared to the IP.
3.4. Results and discussion of individual pulsars

Figure 3.49: Fluctuation analysis for PSR J1057–5226 using 8,704 of the 9,160 pulses (17 blocks with FFT size 512). Left: Main Pulse. Right: Interpulse.

The polarimetry properties are shown in Fig. 3.50 for both the MP (left) and the IP (right). The MP has a complex intensity profile which is almost entirely linearly polarised. The IP shows depolarisation in the trailing half of the profile, indicating the potential presence of two mixing OPMs. However, no such mixing is observed in the PA distributions (fourth panels of Fig. 3.50). Without evidence for mixing OPMs, no further analysis was performed for this pulsar.

**PSR J1539–5626/B1535–56**

22,209 individual pulses were recorded for PSR J1539–5626 (B1535–56) in one observing session. There are no reports in the literature whether the pulsar shows drifting subpulses. Burke-Spolaor et al. (2012) concluded from the pulse longitude resolved modulation index that most intensity fluctuations occur at the edges of the profile. Our fluctuation analysis (see right-hand side of Fig. 3.51) reveals a broad peak at a low fluctuation frequencies. The 2DFS (bottom panel), suggest that the spectral power has a skew towards positive $P_2$. This points towards the presence of drifting subpulses with a somewhat variable $P_3$.

The intensity profile of PSR J1539–5626 (see left-hand side of Fig. 3.51) has two largely overlapping components with low $L$ in the leading half of the profile.
Figure 3.50: Polarisation properties of PSR J1057–5226. Details of what is displayed in each panel are discussed in Fig. 3.1. Left: Main Pulse. Right: Interpulse.
3.4. Results and discussion of individual pulsars

Figure 3.51: Analysis of PSR J1539−5626. Left: Polarisation properties. Details of what is displayed in each panel are discussed in Fig. 3.1. Right: Fluctuation analysis using 22,016 of the 22,209 pulses (43 blocks with FFT size 512). For details, refer to Fig. 3.3.
Chapter 3. Survey for modulated radio polarisation and drifting subpulses

Figure 3.52: Analysis of PSR J1603–2531. Left: Polarisation properties. Details of what is displayed in each panel are discussed in Fig. 3.1. Right: Fluctuation analysis using 2,048 of the 2,138 pulses (8 blocks with FFT size 256). For details, refer to Fig. 3.3.

and moderately half \( L \) in the trailing half, consistent with previously published profiles at this frequency (e.g. Johnston & Kerr 2018). The average PA swing (second panel) shows an OPM jump indicating the potential presence of two OPM dominating for the pulsar. In the PA distribution (fourth panel), two OPMs can be seen, however no mixture of them occurs at any longitudes.

**PSR J1603–2531**

PSR J1603–2531 was observed in a single observing session and 2,138 individual pulses were recorded. Weltevrede et al. (2007) reported flat (i.e. white) fluctuation spectra at a wavelength of 92 cm for this pulsar. More recently, Basu et al. (2016) discovered amplitude modulation at 618 MHz. The fluctuation analysis performed on our data-set shows a broad spectral feature at low fluctuation frequencies (see right-hand side of Fig. 3.52). In the 2DFS panel (bottom), the spectral power appears centred on zero, suggesting that this is intensity modulation rather than drifting, confirming the result of Basu et al. (2016).
3.4. Results and discussion of individual pulsars

Figure 3.53: Analysis of PSR J1605–5257. Left: Polarisation properties. Details of what is displayed in each panel are discussed in Fig. 3.1. Right: Fluctuation analysis using 9,728 of the 10,500 pulses (19 blocks with FFT size 512). For details, refer to Fig. 3.3.

The polarimetry properties are shown in the left-hand side of Fig. 3.52. The pulsar has a single-component intensity profile with low $L$ and no significant $V$. The average PA swing (second panel) is remarkably flat without OPM transitions. The pulsar was chosen for the analysis based on the low level of linear polarisation and depolarisation occurring towards the trailing edge of the profile, indicating the potential presence of two OPMs. In the PA distribution (fourth panel), only one OPM is detectable, and no further analysis was done.

PSR J1605–5257/B1601–52

PSR J1605–5257 (B1601–52) was observed twice for a total of 10,500 individual pulses. Basu et al. (2019) reported no drifting subpulses for this pulsar. The fluctuation analysis of our data is displayed in Fig. 3.53 (right-hand side). A broad spectral peak occurs around $0.09P/P_3$ cpp. The modulation appears in all components of the profile. The power excess in the 2DFS panel is skewed to negative $P_2$, indicating the presence of drifting subpulses.
Chapter 3. Survey for modulated radio polarisation and drifting subpulses

The pulsar has a multiple component intensity profile, with moderately high $L$ and low $V$ (see Fig. 3.53). Four OPM jumps occur in the average PA swing with the corresponding drops in $L$. In the PA distribution (fourth panel), the two OPMs can be seen dominating at different parts of the profile, however we could not identify any longitudes where there were two OPMs mixing. Thus, no further analysis was performed.

**PSR J1651−5222/B1647−52**

PSR J1651−5222 (B1647−52) was observed once for 5,678 periods. No drifting subpulses are were known for this source. Burke-Spolaor et al. (2012) reported intensity modulation at the edges of the profile. Our fluctuation analysis (right-hand side of Fig. 3.54) shows a wide peak around $0.19P/P_3$ ccpp in the trailing half of the profile. A clear positive $P_2$ is found (fluctuation frequency is $\sim 50P/P_2$), indicating the presence of drifting subpulses with a positive drift rate and a $P_3 \sim 5.3P$. 

*Figure 3.54: Analysis of PSR J1651−5222. Left: Polarisation properties. Details of what is displayed in each panel are discussed in Fig. 3.1. Right: Fluctuation analysis using 5,632 of the 5,678 pulses (11 blocks with FFT size 512). For details, refer to Fig. 3.3.*
3.4. Results and discussion of individual pulsars

Figure 3.55: Analysis of PSR J1722–3207. Left: Polarisation properties. Details of what is displayed in each panel are discussed in Fig. 3.1. Right: Fluctuation analysis using 5,632 of the 5,671 pulses (11 blocks with FFT size 512). For details, refer to Fig. 3.3.

The linear and circular polarisation are low (see left-hand side of Fig. 3.54). The pulsar has an intensity profile with a central component which has a flattened top, suggestive of there being two profile components which are mostly overlapping. This would be consistent with the fact that drifting subpulses only occur in the trailing half of the profile. The PA swing (second panel) is steep with a possible OPM jump around longitude 119°. The jump does not appear to be orthogonal and in fact might be a very rapid swing instead. Only one OPM is seen in the PA distribution (fourth panel), hence no further analysis was done for the pulsar.

PSR J1722–3207/B1718–32

PSR J1722–3207 (B1718–32) was observed in one observing session and 5,671 pulses were obtained. Basu et al. (2016) were the first to report amplitude modulation with $P_3 = (22.7 \pm 9.4)P$ for the pulsar. The fluctuation analysis performed on our data-set is shown on the right-hand side of Fig. 3.55 and shows a spectral
Chapter 3. Survey for modulated radio polarisation and drifting subpulses

Figure 3.56: Analysis of PSR J1733–2228. Left: Polarisation properties. Details of what is displayed in each panel are discussed in Fig. 3.1. Right: Fluctuation analysis using 5,120 of the 5,166 pulses (10 blocks with FFT size 512). For details, refer to Fig. 3.3.

feature at $0.04P_3/\text{cpp}$, indicating $P_3 \sim 25P$. In the 2DFS panel (bottom panel), a broad power excess centred on $P/P_2 = 0$, indicating that this pulsar does not show drifting subpulses, and only shows amplitude modulation.

The pulsar has a double component intensity profile with low $L$ and $V$ (see left-hand side of Fig. 3.55). The average PA swing (third panel) is flat until longitude $270^\circ$, followed by a steep gradient. In the PA distribution, shown on the fourth panel of Fig. 3.55, only one OPM can be seen, hence no further analysis was performed.

**PSR J1733–2228/B1730–22**

PSR J1733–2228 (B1730–22) was observed once and 5,166 pulses were collected. Weltevrede et al. (2007) were the first to discover drifting subpulses for the pulsar at a wavelength of 92 cm. At our observing frequency, however, Weltevrede et al. (2006) reported a flat fluctuation spectrum. Basu et al. (2016, 2019) observed only amplitude modulation at 619 MHz. For our observation,
3.4. Results and discussion of individual pulsars

The fluctuation analysis is displayed in the right-hand side of Fig. 3.56. There is a broad spectral response at low fluctuation frequencies for both component of the profile, although the modulation is clearer for the trailing profile component. In the 2DFS panel (bottom), the power excess occurs around $P/P_2 = 0$, however a skew towards negative $P_2$ is seen, confirming the presence of drifting subpulses at our observing frequency.

The intensity profile has a double component with low $L$ and comparable $V$ see (left-hand side of Fig. 3.56). The PA swing (second panel) has a complex shape at the leading side of the profile with two OPM jumps and a “wiggle” in between the jumps, although the PA swing is flat. The $\chi$ swing has also a very complex swing, extending between $-45^\circ$ to $45^\circ$ ellipticity. There is no evidence for mixing PAs in the PA distribution (fourth panel). At 333 MHz, Mitra et al. (2016) observed OPMs mixing in the trailing half of the profile, however the authors did not observe OPM mixing at 618 MHz. No further analysis was done.

**PSR J1741–0840/B1738–08**

1,060 individual pulses were collected for PSR J1741–0840 (B1738–08) in a single observation. Weltevrede et al. (2006, 2007) were the first to report drifting subpulses for this pulsar at 325 MHz and 1420 MHz. More recently, Basu et al. (2016); Gajjar et al. (2017); Basu et al. (2019) confirmed these findings and reported that the pulsar nulls for around 30% of the time (see Section 1.3 for an explanation of nulling). Visual inspection of the pulse-stack shows that nulls occur in our observation as well. PSR J1741–0840 has an unusual drifting behaviour. The leading half of the profile shows amplitude modulation with a certain $P_3$, while the trailing half shows drifting with positive $P_2$ and two different $P_3$ values (e.g. Gajjar et al. 2017). Interestingly, the measured $P_3$ for the leading component is different from the trailing component $P_3$ values (Gajjar et al., 2017). After detailed analysis, Gajjar et al. (2017) concluded that the drifting in the trailing component is irregular without clear drift mode switches. A broad drift feature can be seen around $\sim 0.2P/P_3$ cpp in our fluctuation analysis spectra (see right-hand side of Fig. 3.57), especially in the trailing component of the profile. The power excess seen in the 2DFS panel is clearly offset towards positive $P_2$.

The profile has a complex shape with moderately high $L$ and almost no $V$ (see left-hand side of Fig. 3.57). The PA curve swing is S-shaped without OPM transitions, and only one OPM can be seen in the PA distribution (fourth panel), hence no further analysis was performed. Mitra et al. (2016) observed mixture
Chapter 3. *Survey for modulated radio polarisation and drifting subpulses*

Figure 3.57: Analysis of PSR J1741−0840. *Left:* Polarisation properties. Details of what is displayed in each panel are discussed in Fig. 3.1. *Right:* Fluctuation analysis using 1,024 of the 1,060 pulses (2 blocks with FFT size 512). For details, refer to Fig. 3.3.
3.4. Results and discussion of individual pulsars

Figure 3.58: Analysis of PSR J1745–3040. Left: Polarisation properties. Details of what is displayed in each panel are discussed in Fig. 3.1. Right: Fluctuation analysis using 11,776 of the 12,286 pulses (23 blocks with FFT size 512). For details, refer to Fig. 3.3.

of two OPMs in the trailing half of the profile at 333 MHz, but no mixture at 618 MHz.

PSR J1745–3040/B1742–30

PSR J1745–3040 (B1742–30) was observed in two of the five observing sessions for a total of 19,670 periods and the analysis presented here was performed on the combined data-set. There are no reports whether the pulsar shows drifting subpulses. Burke-Spolaor et al. (2012) observed this pulsar and reported intensity modulation towards the edges of the profile. Basu et al. (2019) did not find drifting subpulses at 333 MHz and 618 MHz. Our fluctuation analysis (see right-hand side of Fig. 3.58) reveals two spectral peaks: a large peak near zero fluctuation frequency, cause by long term periodicities in the pulse-stack and nulling, and a weaker and broader excess of power around $0.07P/P_3$ cpp. The modulation mostly occurs in the component around pulse longitude $306^\circ$. The power in the
Chapter 3. Survey for modulated radio polarisation and drifting subpulses

2DFS panel appears symmetric in the $P_2$, hence the pulsar shows low-level periodic intensity modulation rather than drifting subpulses.

The pulse profile has a multiple component profile with moderately high $L$ and no $V$ (see left-hand side of Fig. 3.58). The PA swing is flat throughout the whole profile, except OPM jumps at a pulse longitude of 296° and 318°. Around 310°, a “wiggle” in the PA swing occurs coinciding with a change in the sign of the circular polarisation. In the PA distribution (fourth panel), two OPMs can be seen at pulse longitudes 294° – 297, however no mixture of OPMs was observed. Around pulse longitude 308°, the PA distribution shows an unusual bump (which was also seen in the PA swing). Mitra et al. (2016) observed the pulsar at lower frequencies (333 MHz and 618 MHz) and reported OPM mixture in the central region of the profile: one of the OPMs showed a similar bump as in our observation and the other OPM was situated 90° away in the PA distribution. Since no OPM mixture was identified, no further analysis was performed.

**PSR J1757–2421/B1754–24**

PSR J1757–2421 (B1754–24) was observed once for 17,201 pulse periods. Weltevrede et al. (2006) were the first to investigate the fluctuation properties of this pulsar and observed non-random intensity modulations resulting in a red spectrum, however no drifting subpulses were identified. More recently, Basu et al. (2019) did not observe drifting subpulses either. Our fluctuation analysis (see right-hand side of Fig. 3.59) reveals the same spectral shape which is red, without a specific preferred $P_3$ or $P_2$.

The polarisation properties are displayed on the left-hand side of Fig. 3.59 and show that this pulsar has a multiple component intensity profile with low $L$ and $V$. The average PA-swing (second panel) has one OPM transition around longitude 166°, coincident with a drop in $L$. In addition, the PA-swing is very steep around longitude 174°. The PA distribution (fourth panel) reveals the presence of two OPMs at different longitudes, however we did not identify any longitudes where the OPMs were mixing. This is consistent with Mitra et al. (2016) who did not see OPM mixture at 618 MHz either. No further analysis was done.

**PSR J1817–3618/B1813–36**

1,404 pulses were recorded in a single observing session for PSR J1817–3618 (B1813–36). No drifting subpulses were reported by Burke-Spolaor et al. (2012) at 1352 MHz, but random intensity modulation was observed at the edges of the profile. Our fluctuation analysis shows power at low fluctuation frequencies (see
3.4. Results and discussion of individual pulsars

Figure 3.59: Analysis of PSR J1757−2421. Left: Polarisation properties. Details of what is displayed in each panel are discussed in Fig. 3.1. Right: Fluctuation analysis using 16,896 of the 17,201 pulses (33 blocks with FFT size 512). For details, refer to Fig. 3.3.
Figure 3.60: Analysis of PSR J1817–3618, re-binned to 512 pulse longitude bins. Left: Polarisation properties. Details of what is displayed in each panel are discussed in Fig. 3.1. Right: Fluctuation analysis using 1,280 of the 1,404 pulses (5 blocks with FFT size 256). For details, refer to Fig. 3.3.
3.4. Results and discussion of individual pulsars

**FIGURE 3.61:** Polarimetric profiles of PSR J1825–0935, as in Fig. 3.1. *Left:* Main Pulse. *Right:* Interpulse.

right-hand side of Fig. 3.60), suggestive of amplitude modulation with a relatively long period. We do not detect drifting subpulses.

$L$ and $V$ are both low and the pulse profile has a single peak with a long tail (see left-hand side of Fig. 3.60). The average PA swing is relatively flat with an OPM transition at longitude $210^\circ$ coincident with a drop in $L$. The two OPMs can be seen in the PA distribution (fourth panel), however there is no evidence for different OPMs dominating at different times at the same pulse longitude (mixing). At lower frequencies (333 MHz) Mitra et al. (2016) observed OPM mixture towards the trailing edge. No further analysis was done.

**PSR J1825–0935/B1822–09**

PSR J1825–0935 (B1822–09) is a well known pulsar and was observed in two sessions for a total of 14,846 pulses. The analysis from this Section was performed on the combined data-set. The pulsar has both a MP and an IP, and it is believed to be an orthogonal rotator (e.g. Backus et al. 2010). The MP has a double component intensity profile, with high $L$ in the first component and low $L$ in the second component (see Fig. 3.61). $V$ is low across the entire profile. The IP has
Figure 3.62: PSR J1825–0935. Left: Fluctuation analysis for the whole pulse-stack using 14,336 of the 14,846 pulses (28 blocks with FFT size 512). Right: A small section of the pulse-stack, containing 100 individual pulses.

a single component profile with low polarisation and a flat PA-swing. The PA-swing of the MP has a complex shape with several changes of gradient and rapid transitions. In both the PA distribution of the MP and IP only one OPM can be seen at all pulse longitudes.

The results of the fluctuation analysis, as well as a small section of the pulse-stack of the MP of PSR J1825–0935 are shown in Fig. 3.62. No features could be detected in the fluctuation spectra of the IP, hence it was not displayed in Fig. 3.62. From the section of the pulse-stack (right panel), two distinct modes of emission can be seen: from pulse number 960 to 1,030, emission occurs in both profile components; after pulse number 1,030, emission from the first profile component disappears. These modes of emission are referred to as 'B' (burst mode) and 'Q' (quiescent mode) (Fowler et al., 1981). In the 'B' mode, both profile components of the MP are active, while in the 'Q' mode, only the second profile component of the MP can be seen. Fowler et al. (1981) reported drifting subpulses at 1670 MHz in both the 'B' mode, with $P_3 \sim 11P$, and the 'Q' mode, with $P_3 \sim 40P$. Our 2DFS (bottom-left panel of Fig. 3.62) shows a large broad feature skewed towards positive $P_2$ in the 2DFS panel, consistent with the 'B' mode. Another feature can be seen around $0.02P/P_3$ cpp in the 2DFS panel, however this feature does not appear to be off-set from zero in the positive $P_2$
3.4. Results and discussion of individual pulsars

Figure 3.63: PSR J1847–0402. Left: Polarisation properties. Details of what is displayed in each panel are discussed in Fig. 3.1. Right: Fluctuation analysis using 5,632 of the 6,139 pulses (11 blocks with FFT size 512). For details, refer to Fig. 3.3.

direction, indicating amplitude modulation with large periodicity. This is potentially caused by observed nulling in the pulse-stack. These finding are consistent with what Weltevrede et al. (2006) found at 1420 MHz. For this pulsar no further analysis was performed.

PSR J1847–0402/B1844–04

PSR J1847–0402 (B1844–04) was observed for 6,139 individual pulses in a single observing session. Weltevrede et al. (2006) were the first to report drifting for this pulsar and their observations were at a similar frequency compared to our observation. At lower frequencies (333 MHz and 618 MHz), Basu et al. (2016) were not able to confirm this. The fluctuation analysis of our data (right-hand side of Fig. 3.63) reveals a spectral peak occurs around $\sim 0.1P/P_3$ ccpp, or $P_3 \sim 10P$. This is clearest in the trailing half of the profile. In the 2DFS panel (bottom), one can see that this modulation corresponds to a positive drift given the skew towards positive $P_2$. These results are consistent with those reported in Weltevrede et al. (2006).
Chapter 3. Survey for modulated radio polarisation and drifting subpulses

The polarimetric profile (left-hand side of Fig. 3.63) shows that the pulsar has a multiple component intensity profile with low $L$ in the leading half and moderately high $L$ in the trailing half. $V$ is low across the on-pulse region. The average PA-swing is complex with several gradient sign changes and “wiggles”. In the PA distribution (fourth panel), there were no longitudes where a mixture of OPMs occurred, hence no further analysis was done for the pulsar. Also Mitra et al. (2016) did not find OPM mixture at both 333 MHz and 618 MHz.

**PSR J1900–2600/B1857–26**

PSR J1900–2600 (B1857–26) was observed twice and the data was combined resulting in a total of 8,874 individual pulses. Weltevrede et al. (2006, 2007) discovered drifting subpulses with a positive drift rate for this pulsar at both 325 MHz and 1420 MHz, however Basu et al. (2016, 2019) only detected amplitude modulation without drift at 333 MHz and 618 MHz. The 2DFS (bottom-right panel of Fig. 3.64) reveals a clear power excess skewed towards positive $P_2$.
3.4. Results and discussion of individual pulsars

Figure 3.65: Analysis of PSR J1946+1805. Left: Polarisation properties. Details of what is displayed in each panel are discussed in Fig. 3.1. Right: Fluctuation analysis using 4,096 of the 4,099 pulses (8 blocks with FFT size 512). For details, refer to Fig. 3.3.

peaking at $\sim 0.12P/P_3$ (P$_3 \sim 8.3P$). This is consistent with the findings of Weltevrede et al. (2006, 2007). The LRFS (middle panel) shows that the drifting subpulses are clearest at both edges of the profile, with little modulation seen in the middle.

The average PA swing (second panel) is steep with a non-orthogonal jump with a magnitude of around $\sim 50^\circ$ at pulse longitude 140$^\circ$. The ellipticity is varying greatly and shows a peak coinciding with the PA jump. The PA and $\chi$ distributions (fourth panel) are well defined given the moderately high $L$ and $V$. A rapid change in PA can be seen at pulse longitude 140$^\circ$, but no evidence for mixing of polarisation modes was found. Similar polarisation properties were seen by Mitra et al. (2016) at 333 MHz and 618 MHz. No further analysis was done.

PSR J1946+1805/B1944+17

Deich et al. (1986) found both drifting subpulses and nulling in PSR J1946 + 1805
Chapter 3. Survey for modulated radio polarisation and drifting subpulses

(B1944 + 17). Moreover, they established that the pulsar changes between four stable states: drift modes A and B (with $P_3 = 13P$ and $P_3 = 6.4P$), a mode C with only amplitude modulation ($P_3 = 22P$), and mode D without organised modulation. The fluctuation analysis of our single observation of 4,099 pulses shows a red spectrum, which in the 2DFS appears at $P/P_2 = -30^\circ$.

The PA swing is flat with a possible OPM jump in the very leading edge of the profile (around pulse longitude $230^\circ$ in Fig. 3.65). The pulsar has moderately high $L$ throughout the profile, but low $V$. At 333 MHz, Mitra et al. (2016) observed a mixture of OPMs dominating around an OPM transition, while at 618 MHz the OPM transition occurred at an earlier pulse longitude and no OPM mixture was seen. Our PA distribution (fourth panel) shows a single OPM track at all pulse longitudes, hence no further analysis was done.

Figure 3.66: Analysis of PSR J2346-0609. Left: Polarisation properties. Details of what is displayed in each panel are discussed in Fig. 3.1. Right: Fluctuation analysis using 5,632 of the 6,099 pulses (11 blocks with FFT size 512). For details, refer to Fig. 3.3.
3.4. Results and discussion of individual pulsars

PSR J2346–0609

PSR J2346–0609 was observed in one observing session for 6,099 stellar rotations. Weltevrede et al. (2006) discovered that the pulsar shows drifting subpulses (at \( \sim 1420 \) MHz) with a positive drift rate, but Basu et al. (2016, 2019) could not confirm this result at 333 MHz and 618 MHz. In the trailing peak of the double-peaked profile a broad spectral feature around \( \sim 0.43P/P_3 \) cpp is seen in the LRFS of our data (see right-hand side of Fig. 3.66). Indeed there is a slight skew towards positive \( P_2 \) in the 2DFS, consistent with the findings of Weltevrede et al. (2006).

The linear polarisation is moderately high and \( V \) is low (see left-hand side of Fig. 3.66). The PA curve has a very smooth steep swing without OPM jumps, which would be well described by the RVM. The PA distribution (fourth panel), only shows a single track. So although Mitra et al. (2016) observed hints of OPM mixture at 618 MHz, this is not detected at our frequency. Therefore no further analysis was done for the pulsar.

3.4.5 Pulsars with OPM mixture, and no periodic modulation

PSR J1136+1551/B1133+16

PSR J1136+1551 (B1133+16) is another pulsar in our sample which was discovered (Pilkington et al., 1968) shortly after the first pulsar and we observed it once and 1,302 pulses were recorded. The pulsar has a double-peaked profile with a bridge in between (see left-hand side of Fig 3.67). It has a low average \( L \) and \( V \). The PA swing (second panel) is interrupted by a discontinuity around pulse longitudes \( 210^\circ \) to \( 212^\circ \). This coincides with a reduction in \( L \). The discontinuity is clearly related to two active OPMs, which can both be seen in the the PA distribution (fourth panel). The \( \chi \) distribution (bottom) is very broad, with a preference for negative ellipticity. The Poincaré sphere (right-hand side of Fig 3.67), was produced for a pulse longitude range where OPM mixture was identified and both OPMs are visible. The radiation is mostly linear at the pulse-longitude region where both OPMs are visible, hence the OPMs occur close to the equator. One OPM, the mode which is seen throughout the profile has a slight negative ellipticity. Also Mitra et al. (2016) observed mixture of OPMs in the leading edge of the profile, although at lower frequencies (333 MHz and 618 MHz).

Several authors reported drifting subpulses with a long periodicity in the trailing component of the pulsar (e.g. Backer 1973; Nowakowski 1996; Weltevrede
Figure 3.67: Polarimetric properties of PSR J1136 + 1551. Left: Integrated polarisation profile. For details of individual panels, refer to Fig. 3.1. Right: Distribution of polarisation orientations for pulse longitude 210°, where we see a mixture of OPM dominating, on a Poincaré sphere using the Hammer equal area projection. For more details, refer to Fig. 3.2.
3.4. Results and discussion of individual pulsars

Figure 3.68: PSR J1136 + 1551. Left: Fluctuation analysis of the pulse-stack using 1,280 of the 1,302 pulses (5 blocks with FFT size 256). For details, refer to Fig. 3.3. Right: Small section of the pulse-stack containing 100 individual pulses.

et al. 2006, 2007). Weltevrede et al. (2006) measured $P_3 = (33 \pm 3)P$. Our fluctuation analysis (see left-hand side of Fig. 3.68) resulted in featureless spectra, hence no drifting subpulses were confirmed. It is possible that we were not able to detect drifting subpulses for the pulsar because of our relatively short observation compared to Weltevrede et al. (2006).

**PSR J1731−4744/B1727−47**

PSR J1731−4744 (B1727−47) was observed in one session for 1,091 rotations. It has a triple component intensity profile (see left-hand side of Fig. 3.69) with low linear polarisation and almost no circular polarisation. $L$ is especially low starting from pulse longitude $231^\circ$. The PA curve (second panel) is non-RVM like, including a discontinuity at pulse longitude $231^\circ$.

The PA distribution (fourth panel) indicates that there is mixture of polarisation modes for most of the on-pulse region. The $\chi$ distribution (bottom panel) is broad and centred at zero ellipticity. A Poincaré sphere for a longitude where OPM mixture is seen (right hand side of Fig. 3.69) confirms the existence of
Figure 3.69: Polarimetric properties of PSR J1731−4744. *Left:* Integrated polarisation profile. For details of individual panels, refer to Fig. 3.1. *Right:* Distribution of polarisation orientations for pulse longitude 230°, where we see a mixture of OPM dominating, on a Poincaré sphere using the Hammer equal area projection. A offset of 45° in PA was applied for display purposes. For more details, refer to Fig. 3.2.
two clear and distinct OPMs, both almost entirely linearly polarised. This agrees with Mitra et al. (2016), who also identified a mixture of OPMs at 333 MHz and 618 MHz.

Looking at the fluctuation analysis (see left-hand side of Fig. 3.70) or the pulse-stack (left-hand and right-hand side of Fig. 3.70), no obvious subpulse drifting or other periodic modulation is identified. Basu et al. (2016), in their recent survey of the southern sky, did not find drifting for this pulsar at 333 MHz or at 618 MHz either. Without periodic modulation for PSR J1731 – 4744, no $p_3$-folding is possible, hence no further analysis was performed.

3.5 Discussion and Conclusions

In this Chapter we investigated, using a sample of 31 pulsars observed with the Parkes radio telescope, whether OPM switches synchronous with drifting subpulses are common. Before this study, there were four pulsars (PSRs B0809 + 74, B1237 + 25, B0320 + 39 and B0818 – 13) for which this phenomenon was known.
Figure 3.71: Pulse period $P$ and period derivative $\dot{P}$ diagram. The pulsars which showed OPM switches synchronous with drifting subpulses are represented with the red stars. The pulsar which showed OPM switches without an established connection with drifting subpulses is shown as the blue inverted triangle. Pulsars with drifting subpulses, but without OPM mixture are represented by black crosses, while the pulsars which showed OPM mixture but no intensity modulation are shown as the orange triangles. The pulsars which showed OPM mixture and non-random modulated intensity, and a connection between the two was established, are represented by green squares. The pulsar parameters were obtained from the ATNF pulsar database (Manchester et al., 2005), accessed February 2019, and the $P - \dot{P}$ diagram was created using the Python module PSRQPY, published by Pitkin (2018).
3.5. Discussion and Conclusions

to occur (Ramachandran et al., 2002; Rankin & Ramachandran, 2003; Edwards, 2004). In the previous Chapter (Chapter 2), an extensive study of PSR B0031−07 is presented and we established this phenomenon for both drift modes observable at 1369 MHz. Out of the 31 pulsars which were observed in this study, one was already known to show this phenomenon, and we discovered that seven more pulsars have OPM switches synchronous with their drifting subpulses (see Section 3.4.1). For the one pulsar for which the phenomenon was already known, PSR J0820−1350 (see Section 3.4.1), this is the first time this effect is observed at 1369 MHz, since the original detection was at a lower frequency of 328 MHz (Edwards, 2004).

Including PSR B0031−07, which was observed as part of the same survey, the population of pulsars showing this phenomenon has increased from four to twelve. There were two pulsars in the sample, PSRs J1932+1059 (see Section 3.4.2) and J2048−1616 (see Section 3.4.2, for which a mixture of OPMs and drifting subpulses were identified, however no synchronous modulation of the OPM switches could be established. The drifting subpulses are very complex for PSRs J1932+1059, with opposite drift rates being detected in the same part of the pulse profile. We established that this is due to two overlapping out-of-phase patterns which give rise to an apparent shorter period modulation, which is therefore not a separate drift mode. So that might have confused the picture since the complexity of the drift pattern could result in smearing in the $P_3$-fold, which makes it harder for weaker features to be observed. Although no connection between OPM switches and drifting subpulses were established, both the linear and circular polarisation were identified to be modulated with the periodicity of the drifting subpulses. A gradual decrease in fractional linear polarisation was seen in between intensity driftbands, indicating that the weaker OPM might preferentially occur in that region thereby causing depolarisation. Switches were seen in the $\chi P_3$-fold, consistent with a switch between the two OPMs of which one has been shown to have different ellipticity. Therefore, even in this case, a connection between polarisation and intensity modulation has been discovered. In the case of PSR J2048−1616, large variations occurred in the periodicity of drifting subpulses (between $2P$ and $3P$) and no clear OPM switches were seen synchronous with intensity variability. As for PSRs J1932+1059, a connection was established between linear polarisation and drifting subpulses.

There were two pulsars for which OPM mixture was identified, however drifting subpulses were not detected. These pulsars showed non-random, but not strictly periodic intensity modulation (see Section 3.4.3). In all these cases, a
connection between intensity and polarisation was established such that the polarisation properties of brighter pulses were different from weaker pulses. This therefore might relate to the same physics which causes the polarisation to change periodically for pulsars with drifting subpulses. For the rest of the pulsars in this survey, either only drifting subpulses were identified but no OPM mixture (see Section 3.4.4), or only OPM mixture was identified and only random intensity modulation (see Section 3.4.5).

Drifting subpulses were discovered for five pulsars in our survey (J1110–5637, J1453–6413, J1539–5626, J1605–5257 and J1651–5222), and amplitude modulation was discovered for three other pulsars (J1048–5832, J1745–3040 and J1817–3618). PSR J1932+1059 is a pulsar for which we observe emission from both magnetic poles (the MP and IP). By folding the pulse-stack of the MP based on the variable $P_3 = 10.1P$ periodicity observed in the IP, it was established that although the periodicity is variable, the modulation patterns of the MP and IP remain phase-locked. This implies there must be a connection between the MP and IP emission through which the modulation at both poles are regulated. This type of regulation is known only for few pulsars: PSR B1822–09 (Fowler & Wright, 1982), B1702–19 (Weltevrede et al., 2007) and B1055–52 (Weltevrede et al., 2012a). It is unclear how the connection can be established between the two poles, since these parts of the magnetosphere (open field line region) are not directly connected via field lines. An in depth discussion of the theoretical problems this “interpole communication” implies can be found in Weltevrede et al. (2012b).

For three pulsars (PSRs J1453–6413, J1921+2153 and J2048–1616) from our survey, small periodic shifts were seen in the PA $P_3$-folds at longitudes where only one OPM was seen dominating in the PA distributions. This suggests that this is not related to switches between polarisation modes, but that the PA of the mode is periodically changing. Clearer periodic shifts were seen in the $\chi P_3$-folds at these longitudes. This implies that a time dependent effect, such as Generalised Faraday rotation (Kennett & Melrose, 1998) in the pulsar magnetosphere, affects the polarisation properties of the pulsars. The study from this Chapter can be extended by looking for more subtle changes in PA rather than strictly the switches between two OPMs, by performing and analysis $P_3$-folds of PA and ellipticity angle for pulsars which show drifting subpulses/amplitude modulation regardless of whether OPM mixture was identified.

With a significant sample of pulsars for which periodic OPM switches have been established, their properties can be compared to the rest of the population of pulsars. The pulsars from the survey were indicated on a $P$-$\dot{P}$ diagram (see
Fig. 3.71, and see Section 1.1.4 for a general description of this type of diagram). The pulsars for which periodic intensity modulation was found to be linked to changing polarisation properties are represented with red stars, and the four pulsars (PSRs B0809+74, B1237+25, B0320+39 and B0818−13) for which this was already known from the literature as well as PSR B0031−07 were also included in the Figure represented with red stars. The other groups of pulsars discussed in this Chapter (e.g. pulsars which show OPM mixture and non-random intensity modulation) were also included in the $P$-$\dot{P}$ diagram, with different symbols, as indicated in the caption of Fig. 3.71. From Fig. 3.71, it is clear that synchronous OPM switches occurring are throughout the population of non-recycled pulsars, however they appear possibly to be confined to only the central part of the distribution of magnetic fields strengths (around $10^{12}$ Gauss). We investigated whether there is a difference between the distribution of magnetic field strengths of the pulsars which show modulated OPM switches and those of the population of normal pulsars and performed a Kolmogorov–Smirnov test (KS test) to assess the significance of the difference. This resulted in a test statistic of 0.3, which corresponds to a p-value of 0.16. Based on these values, there is no evidence for magnetic field strengths to be different. When synchronous OPM switching is established for a larger number of pulsars this correlation might become significant. It is important to note that when calculating the surface magnetic field, as plotted on the $P$-$\dot{P}$ diagram, several assumptions were made (see Section 1.1.2), including considering that $\alpha$ is $90^\circ$. Hence, one should potentially correct for this effect when expanding this analysis to a larger sample. The other classifications/groups of pulsars discussed in this Chapter also do not appear to have a preferred location in normal pulsar distribution in the $P$-$\dot{P}$ diagram.

Of the ten pulsars for which OPM mixture and drifting subpulses were identified, for eight (80%) we demonstrated a connection between the two. This suggests that, in general, OPM switches at a single pulse level are related to the variability seen in total intensity. Since it is thought the drifting subpulses can be traced back to changes in the acceleration region close to the neutron star surface where electron-positron pairs are formed (Ruderman & Sutherland, 1975), the polarisation variability should be linked to those changes as well. This could either be part of the emission mechanism itself, or caused by changes in the propagation effects in the magnetosphere triggered by the constantly changing properties reflecting changes in the pair creation sites (such as caused by $E \times B$ drift). Rankin & Ramachandran (2003) suggested that in order to explain these type of observations, the carousel model (Ruderman & Sutherland, 1975) should be extended. The authors suggested that the circulating system of sparks in the
acceleration region produces two images of the same carousel configuration, each image corresponding to one of the two OPMs. The two images should be offset in the azimuthal direction (with respect to the magnetic axis) as well as be magnified (away from the magnetic axis) differently to have different OPMs to be dominant in different parts of the profile, and for different OPMs to be dominant at different parts of the modulation cycle (see Section 1.7). A possible mechanism for generating the two images is birefringence in the pulsar magnetosphere (Rankin et al., 2006), where the OPMs correspond to the two plasma modes (the O and X modes) in the magnetised plasma. Only the O mode is thought to experience refraction in the magnetosphere, hence gets spatially separated from the X-mode image (see Section 2.4).

As discussed earlier in Chapter 2, also PSR B0031–07 shows synchronous OPM switches with the drifting subpulses and is a unique source as this phenomenon occurs for both drift modes observed at our frequency. The pulsar was also different, as it shows asymmetric evolution of the ellipticity angle during the modulation cycle. Furthermore, a puzzling discontinuity in the PA was discovered, such that in different halves of the on-pulse region a different OPM traces the driftband as seen in total intensity. All other four pulsars for which synchronous OPM switching was known before this study (PSRs B0809 + 74, B1237 + 25, B0320 + 39 and B0818 – 13) have a single OPM tracing the full total intensity driftbands and none of the pulsars in this chapter shows anything comparable to PSR B0031–07 either. None of the eight pulsars from Section 3.4.1 show asymmetric evolution of $\chi$ as a function of the modulation cycle. The results for PSR B0031 – 07 indicate that the double image model suggested by Rankin & Ramachandran (2003); Rankin et al. (2006) should be more complex than initially discussed (see Section 2.4). It should be noted that all of these eight pulsars show asymmetry in the polarisation $P_3$-folds with respect to the centre of the profile. This therefore suggests that if an inherently symmetrical carousel configuration is responsible for the periodicities observed, also for these pulsars the production of the images, i.e. the magnetospheric propagation, should be asymmetric.
Chapter 4

Evidence for magnetospheric effects on the radiation of radio pulsars

In this Chapter, we have conducted the largest investigation to date into the origin of phase resolved, apparent rotation measure (RM) variations in the polarised signals of radio pulsars. From a sample of 98 pulsars, based on observations at 1.4 GHz with the Parkes radio telescope, we carefully quantified systematic and statistical errors on the measured RM values. A total of 42 pulsars showed significant phase resolved RM variations. We show that both magnetospheric and scattering effects can cause these apparent variations. There is a clear correlation between complex profiles and the degree of RM variability, in addition to deviations from the Faraday law. Therefore, we conclude that scattering cannot be the only cause of RM variations, and show clear examples where magnetospheric effects dominate. It is likely that, given sufficient signal-to-noise, such effects will be present in all radio pulsars. These signatures provide a tool to probe the propagation of the radio emission through the magnetosphere.

4.1 Introduction

Polarised radiation from pulsars experiences Faraday rotation, as it propagates through the interstellar medium (ISM) (see Chapter 1.2.2). Generally, it is assumed that the radiation from the pulsar does not undergo changes as it traverses the magnetosphere, and therefore that the Faraday relation, shown in equation (1.22), represents the contribution to the frequency dependent rotation of the orientation of linear polarisation (APA) from the ISM alone. Using combined measurements of rotation measure (RM) and dispersion measure (DM) (see Section 1.2.2), the parallel component of the magnetic field along the line
Chapter 4. Evidence for magnetospheric effects on the radiation of pulsars

of sight can be estimated, and thus the structure of the Galactic magnetic field (e.g. Manchester, 1972, 1974; Thomson & Nelson, 1980; Lyne & Smith, 1989; Han et al., 1999; Mitra et al., 2003; Noutsos et al., 2008; Han et al., 2018), and it is therefore important to test the above assumption.

If Faraday rotation is the only source of frequency dependence of the PA, we expect the derived RM to be independent of the rotational phase of the pulsar. This can be tested using observations with high time resolution and signal-to-noise (S/N). The first authors to perform such an analysis were Ramachandran et al. (2004). They showed that the apparent RM of PSR B2016 + 28 varied by 30 rad m\(^{-2}\) as a function of pulse longitude. More recently, Dai et al. (2015) also saw apparent RM variations in a selection of millisecond pulsars. Ramachandran et al. (2004) investigated the origin of the frequency dependence of the PA for this pulsar using single pulse analysis and argued that it originated because of the incoherent addition of two non-orthogonal OPMs (quasi-OPMs) which had different spectral indices (see Section 1.7 for incoherent mode addition). The existence of OPMs with different spectral indices was later also observed by Karastergiou et al. (2005) and Smits et al. (2006). Noutsos et al. (2009) concluded that although this effect can explain the apparent RM variations across pulse phase in the case of some specific pulsars, it cannot be generalised to the entire pulsar population.

Ramachandran et al. (2004) argued that the observed apparent RM variations across pulse phase are not caused by Faraday rotation within the pulsar magnetosphere, since this would lead to significant depolarisation. Noutsos et al. (2009) investigated the possibility that a generalised Faraday effect could be the cause. Following work from Kennett & Melrose (1998), it was suggested that in this scenario the apparent RM variations should occur where the circular polarisation changes most rapidly with rotational phase. Although they did not find such correlation, generalised Faraday rotation was not dismissed completely, as the constraints on this theory are not well defined.

Interstellar scattering, which causes a shift of polarised radiation to a later rotational phase in a frequency dependent manner, will cause apparent phase resolved RM variations (see Section 1.2.2). Weisberg et al. (2010) observed, while studying a sample of 81 pulsars over a 4 year period, that interstellar variations can also cause changes in RM as a function of time. Karastergiou (2009) showed, using simulations, how even a small amount of scattering can affect the shape of the PA swing, most notably in the case of intrinsically steep PA swings. OPMs situated at phases close to where the PA swing is changing the fastest were also more likely to be affected by scattering. Noutsos et al. (2009) observed the largest
RM variations coinciding with the rotational phases where the PA was the steepest, and concluded that scattering was the dominant cause of apparent RM variations. More recently, Noutsos et al. (2015), using low frequency observations, concluded that the amplitude of the RM variations due to scattering should follow a $\lambda^{-2}$ law.

In this Chapter, we quantify and investigate the nature of the observed phase-resolved apparent RM variations, $\text{RM}(\phi)$, and whether interstellar scattering is the dominant mechanism responsible. We take a statistical approach, using a large sample of pulsars. It should be stressed that these apparent RM variations quantify changes in $\partial \text{PA}(\lambda, \phi) / \partial \lambda^2$. Hence, in the presence of other frequency dependent processes, the derived RM is not entirely a measure of the magneto-ionic properties of the ISM. From here onwards, unless otherwise stated, when we refer to RM, we refer to the RM defined in equation (1.22), rather than the RM from equation (1.23). The work presented in this Chapter has been published by Ilie et al. (2019).

In Section 4.2 we outline the details of our observations, while Section 4.3 describes the methodology used in this analysis. In Section 4.4, the results are presented and the pulsars which showed significant phase-resolved apparent RM variations are discussed on a case by case basis. The results related to the sample as a whole are discussed in Section 4.5 and a summary is given in Section 4.6.

### 4.2 Observations

A sample of the brightest pulsars from Johnston & Kerr (2018) ranked by S/N were selected for this analysis. The data were collected over the period of January 2016 to February 2017, using the Parkes radio telescope, at a frequency of 1.4 GHz and a bandwidth of 512 MHz, using the H-OH receiver. Individual observations of each pulsar were summed together in order to increase the S/N, and obtain integrated polarisation profiles (see Section 1.5). The available data were reduced to 32 frequency channels, by adding several frequency channels together. During this process, the RM of each pulsar was removed (using an RM value taken from the ATNF pulsar database (Manchester et al., 2005)), as detailed in Section 1.2.2. A test was performed on several pulsars, in order to investigate whether re-processing the data to include more frequency channels would improve our final result. No significant difference was observed, hence a decision was made to perform the analysis on the data with 32 frequency channels. Details of the observations and the calibration scheme used can be found in Johnston & Kerr (2018), and in Section 1.2.3.
4.3 Method

The method used to measure the RM is based on the most basic form of the RM synthesis technique (RMST), which was developed by Burn (1966) and later extended and implemented by Brentjens & de Bruyn (2005). The RMST is based on calculating the complex Faraday dispersion function, $\tilde{F}(RM)$, using a Discrete Fourier Transform (DFT) given by the equation

$$\tilde{F}(RM) = K \sum_{c=1}^{N} \tilde{P}_c e^{-2iRM(\lambda_c^2-\lambda_0^2)},$$

where $K$ is a normalisation constant, $c$ is the frequency channel index, $\tilde{P}_c$ is the observed linear polarisation expressed as a complex number, $Q + iU$, in terms of the Stokes parameters $Q$ and $U$, $\lambda_c$ is the wavelength of channel $c$ and $\lambda_0$ is a reference wavelength (see also Heald, 2009). The power spectrum of this function represents the RM spectrum, and $|\tilde{F}(RM)|^2$ will peak at the RM of the pulsar. Since we are only interested in the shape of $\tilde{F}(RM)$, we can set $\lambda_0$ to 0 and $K$ to 1, in equation (4.1). Effectively, this method consists of multiplying the complex polarisation vector of each individual frequency channel with a trial RM and $\lambda^2$ dependent complex exponential, therefore it de-Faraday rotates the linear polarisation before summing it over all frequencies. The RM spectrum is produced by taking the square of this function, which is effectively the degree of linear polarisation as a function of the trial RM. The peak of this function, i.e. when the linear polarisation is maximised, represents the optimum RM.

To obtain RM($\phi$), the calculation was performed for each pulse longitude bin ($\phi$) in a similar manner. The RMST algorithm has been included in the psrsalsa\(^{1}\) software package (Weltevrede, 2016), publicly available at the link provided.

An alternative method for measuring RMs, used by Noutsos et al. (2008, 2009), consists of performing a fit of the PA as a function of $\lambda^2$ to compute the RM. One has to be careful with this method concerning the non-Gaussianity of the uncertainties on the PA in the case of low linear polarisation signal, hence normally the PAs are computed only for bins where the linear polarisation exceeds a certain cut-off, therefore losing sensitivity (see Section 1.2.1). In the case of low linear polarisation, Noutsos et al. (2008, 2009) estimate the uncertainties on PAs from the distribution described in Naghizadeh-Khouei & Clarke (1993). In principle, the two methods mentioned are equivalent, however the RMST method, as implemented here, avoids the complexity of non-Gaussian error bars, as it does not require the determination of the PA with associated uncertainties.

\(^{1}\)https://github.com/weltevrede/psrsalsa
Although analytic errors can be determined on the RMs derived using RMST (Brentjens & de Bruyn, 2005), they rely on assumptions which are not necessarily correct. Here, we attributed a statistical uncertainty on each measured RM by adding random white noise with a standard deviation determined from the off-pulse region to the data of each frequency channel, and re-performing the analysis for a large number of iterations, i.e. bootstrapping. Thus, a distribution of RMs was obtained and the standard deviation was taken as the statistical uncertainty. This provides a robust error determination method. No a-priori assumptions have to be made about the underlying signal, and non-Gaussian errors will be properly taken into account. Assigning an analytic uncertainty on the derived RM is possible (Brentjens & de Bruyn, 2005), but requires assumptions about, for example, the shape of the band-pass (see also Schnitzeler & Lee, 2015). Furthermore, the spectral shape of the source and scintillation conditions will also affect the shape of the RM spectrum, complicating the determination of an accurate analytic uncertainty (see Section 1.2.2).

RM(\phi) curves with their associated statistical uncertainties were plotted for each pulsar and the results can be found in Appendix A, Fig. A.1–Fig. A.26. An example of a typical plot is shown in Fig. 4.1. In the top panel, the integrated pulse profile is displayed with the solid line denoting Stokes I, the dot-dashed line showing the linear polarisation, L, and the dotted line the circular polarisation, Stokes V. The second panel shows the frequency averaged PA (obtained as in Section 1.2.1) and in the third panel RM(\phi), along with associated uncertainties.

In order to assess deviations from Faraday law at a given pulse phase, the PA was computed at those frequencies where the linear polarisation exceeded 2\sigma. The \lambda^2 dependence was removed according to equation (1.22) using the determined RM(\phi), and the \chi^2, \chi^2_{PA}(\lambda^2, \phi), of the remaining variability was determined. This can be seen for all pulsars as shown in the case of an example pulsar displayed on the left-hand side bottom panel of Fig. 4.1. Note, that when deviations from the Faraday law are observed, the measured RM will not fully quantify Q and U as function of frequency. Nevertheless, since at least some of these deviations will be absorbed in the RM (as demonstrated by e.g. Noutsos et al. 2009 or Karastergiou 2009), variability in the RM(\phi) curves can be expected, hence it is a good indicator for additional frequency dependent effects.

RM values for the profiles (i.e. non-phase resolved), RM_{profile}, were also determined. The methodology was very similar to the one described above in the case of RM(\phi). A RM spectrum was computed using equation (4.1) for all pulse longitude bins in a selected on-pulse region. The RM power spectra were then summed and the RM determined. These values, as well as their corresponding
statistical uncertainties obtained from bootstrapping, are displayed in Table 4.1. A similar test to \( \chi^2_{PA(\lambda^2,\phi)} \) was performed. The data were de-Faraday rotated using the determined RM_{profile}, the frequency averaged PA was subtracted for each pulse longitude bin, before averaging the Stokes parameters in pulse longitude. A reduced \( \chi^2 \) was determined and the results are displayed in Table 4.1 as \( \chi^2_{PA(\lambda^2)} \).

Scattering will affect the measured RM_{profile}, but Noutsos et al. (2008) avoided this contamination by averaging the Stokes parameters over pulse longitude before measuring the RM. Since scattering does not affect the pulse longitude integrated Stokes parameters, the determined RM is unaffected (Karastergiou, 2009). We will refer to this RM as RM_{scatt}. Comparison of RM_{profile} and RM_{scatt} provides an indication if scattering affected the polarisation. The measurement of RM_{scatt} is less sensitive compared to that of RM_{profile}, as averaging Stokes parameters over pulse longitude leads to depolarisation depending on the steepness of the PA. Our measured values of RM_{scatt} can be found in Table 4.1.

We obtained the fractional circular polarisation change across the frequency band, \( \Delta(V/I) \), with associated statistical uncertainties, by performing a linear fit across the band, in a similar manner to what is presented in Noutsos et al. (2009), for each pulse longitude. The fractional change was calculated as the difference between the top and bottom of the frequency band based on the linear function fitted to \( V/I \). This is displayed in the fourth panel of the example plot shown on the left-hand side of Fig. 4.1. We also quantified the deviation from no variations as \( \chi^2_{V/I}(\lambda^2,\phi) \) (deviations from zero weighted by the statistical uncertainty), shown in the bottom panel of the plot, represented by red crosses.

Noutsos et al. (2009) argued that significant \( \Delta(V/I) \) variations can be taken as evidence for generalised Faraday rotation in the pulsar magnetosphere. If this is responsible for the observed RM(\( \phi \)) variations, then we expect the greatest variations to coincide in pulse longitude with the greatest change in \( \Delta(V/I) \). However, we here point out that interpreting \( \Delta(V/I) \) in terms of generalised Faraday rotation is complicated by the fact that scattering is also capable of creating \( \Delta(V/I) \) variations as a function of pulse longitude. We expect that if a pulsar is affected by interstellar scattering, then the greatest change in \( \Delta(V/I) \) coincides with that part of the profile where Stokes \( V \) is changing most rapidly as a function of pulse longitude (see below for a simulation). This is not necessarily where the largest RM(\( \phi \)) variations occur. This therefore potentially allows the distinction between which frequency dependent effect is responsible for the apparent RM variations.

To demonstrate the effect of scattering, a simulation was performed on a synthetic frequency resolved pulse with varying PA and Stokes \( V \) with pulse longitude, and an intrinsic RM of 100 rad m\(^{-2} \). Scattering was added to the profile
4.3. Method

with timescales, $\tau_{\text{scatt}}$, of 4 ms and 8 ms, for a pulse period of 1 sec. An exponential tail of the form $\exp(-t/\tau_{\text{scatt}})$, where $t$ represents time, was convolved with the Stokes parameters in the modified data in the Fourier domain, similar to the simulation done in Karastergiou (2009). We take $\tau_{\text{scatt}} \propto \nu^{-4}$ relative to a reference frequency of 1.4 GHz. A bandwidth of 512 MHz was assumed. The results are shown in Fig. 4.2. It is clear that scattering is capable of creating $\Delta(V/I)(\phi)$ variations and these coincide with where Stokes $V$ is changing rapidly. Note that scattering also produces RM variations in a region where the PA swing is steepest, as expected from Karastergiou (2009), as well as deviations from Faraday law, as observed in the bottom panel of Fig. 4.2. Note that the amplitude of variations is larger with larger amounts of scattering, consistent with the findings of Karastergiou (2009).

4.3.1 Systematic uncertainties

For pulsars with high S/N, the statistical uncertainties can be small enough that systematic effects will dominate. Some of these systematic effects could produce an additional frequency dependence of the polarisation, resulting in apparent phase-resolved RM variations. We attempted to determine and quantify a number of systematic effects.

Instrumental effects can produce a peak in the RM spectrum at a value of 0 rad m$^{-2}$, which could lead to erroneous estimates of the RM and its uncertainties (see e.g. Schnitzeler et al. 2015). All RM spectra were visually inspected for such peaks, and none were observed, hence these effects were not further considered.

An inaccurate DM value introduces a frequency dependent dispersive delay, which will affect the PA as a function of frequency, hence variations in RM($\phi$). We measured DMs using TEMPO2$^2$ (Hobbs et al., 2006) for each of the pulsars analysed. However, these measurements are affected by profile variations with frequency. Hence, in order to correct for such an effect further, we obtained RM($\phi$) after applying 20 trial offsets, DM$_{\text{offset}}$, around the determined value of DM, from $-0.5$ to 0.5 cm$^{-3}$pc in steps of 0.05 cm$^{-3}$pc. For each trial, we computed the RM($\phi$) and the weighted mean, $\langle \text{RM}(\phi) \rangle$, and obtained a reduced $\chi^2$, $\chi^2_{\text{RM}(\phi)}$, of the RM($\phi$) with respect $\langle \text{RM}(\phi) \rangle$. For each pulsar, the results for the DM$_{\text{offset}}$ which gave the lowest $\chi^2_{\text{RM}(\phi)}$ were displayed in Table 4.1. However, by minimising the variability in the RM($\phi$) curves, which could be caused by using

---

$^2$http://www.atnf.csiro.au/research/pulsar/tempo2/
Chapter 4. Evidence for magnetospheric effects on the radiation of pulsars

Figure 4.1: PSR J1703—3241. In the top panel the solid line denotes Stokes $I$, the dashed line shows the linear polarisation and the dotted line the circular polarisation. The second panel displays the frequency-averaged position angle of the linear polarisation. Position angles were only plotted when the linear polarisation exceeded 2 sigma. The third panel shows $\text{RM}(\phi)$ with associated statistical uncertainties represented by the errorbars. The green shaded region represents the $1\sigma$ systematic uncertainty contour region. The horizontal dotted line plotted is $\langle \text{RM}(\phi) \rangle$. The fourth panel shows the phase-resolved $\Delta(V/I)$ values with their associated statistical and systematic uncertainties. The bottom panel displays the $\chi^2_{PA(\lambda,\varphi)}$, represented by the black circles and $\chi^2_{V/I(\nu,\varphi)}$, represented by the red crosses. The horizontal dashed line corresponds to a reduced $\chi^2 = 1$. The plots for the 98 pulsars are in Appendix A, in Fig. A.1—Fig. A.26.
4.3. **Method**

![Graph showing simulations](image)

**Figure 4.2**: Simulations demonstrating the effect of scattering with a timescale of 4 ms (represented in black) and 8 ms (represented in red), for a pulse period of 1 sec. The curves without scattering were represented in grey. The reference frequency is 1.4 GHz and the bandwidth 512 MHz. The panels are as described in Fig. 4.1. In the second panel, a vertical shift of $10^\circ$ in PA is applied to help distinguishing between the simulations.
an incorrect DM ensures that, if variability is detected, it is not because of this systematic effect. This does not imply that this is the correct DM. As a consequence, the variations will be underestimated.

A possible systematic effect is the imperfect alignment of individual observations when creating the final datasets. The alignment is limited by the the time of arrival (ToA) uncertainties of each pulsar. We quantified this effect through simulations. The Stokes parameters of the pulsars were first averaged over frequency and duplicated to form 32 frequency channels. Prior to averaging over the frequency channels, the RM of the pulsar, from the ATNF pulsar catalogue (Manchester et al., 2005), was removed in the process of de-Faraday rotation (see Section 1.2.2). This ensured that all RM(\phi) variations were eliminated, while the shape of the average PA remained unaffected. Fifty such individual observations were created for each pulsar, with phase offsets sampled from a Gaussian distribution with a standard deviation equal to the respective ToA uncertainty. The ToA uncertainties were smaller than 0.01% of the pulse period. These individual observations were added together and RM(\phi) curves were obtained as described before. No significant variations were observed.

Another systematic effect which was quantified is the varying RM of the ionosphere, RM_{iono}, which can change depending on the time, day or season of observation. For our observations, we considered RM_{iono} to vary with ±3 rad m⁻² (Sotomayor-Beltran et al., 2013). If the alignment of individual observations were done perfectly, we would only expect a constant change in RM with pulse phase in each observation due to RM_{iono}. This would not create phase resolved RM variations. However, if the individual observations are not perfectly aligned when they are added together, the overall effect introduced by the RM of the ionosphere is no longer going to be a constant shift for all pulse longitude bins. In this case, we expect the effects of changing RM_{iono} to potetially introduce additional systematic phase resolved RM variations. In order to confirm this hypothesis, we expand on the simulation described earlier, by allowing the RM in each observation to randomly vary within the specified limits. This new simulation allows us to investigate the combined effects of varying RM_{iono} and adding mis-aligned observations. The only pulsar for which we observed this effect to create RM(\phi) variations is the Vela pulsar, J0835−4510. The results are displayed in Fig. 4.3. The contribution of this systematic effect appears to be less than 0.05%, much smaller than the next systematic to be discussed.

Polarisation imperfections in the H-OH receiver can be responsible for significant RM(\phi) variations compared to the statistical ones. Assuming the distortions to be linear, the transformation from un-calibrated Stokes parameters to intrinsic
4.3. Method

Stokes parameters can be determined by using a Mueller matrix, a $4 \times 4$ real matrix (e.g. Mueller, 1948; Heiles et al., 2001) (see Section 1.2.3). One of the seven independent parameters of this matrix is the overall gain and is not useful for the scope of this work. Two other parameters are the differential phase and gain. These were corrected for by performing a short pulse calibration observation, for each pulsar, which pointed slightly offset from the source right before the actual observation. The remaining four parameters, which are the ones we are interested in, are referred to as the leakage parameters. These correct for the effect where one of the dipoles records some signal that should have been detected by the other dipole.

We simulated artificial receiver imperfections, by randomising values for the four leakage parameters. For simplicity, it was assumed that they have a linear frequency dependence. When generating these artificial leakage parameters, it was ensured that no off-diagonal elements of the Mueller matrix exceeded 1.5\% conversion between Stokes parameters at any frequency channel, while reaching this maximum percentage in at least one frequency channel. This limit was chosen based on the following test. From our sample, we chose all pulsars which did not show any RM($\phi$) variations (e.g. J1048$-$5832 and J1709$-$4429). Our assumption was that the imperfections of the receiver could not generate more RM($\phi$) variations than were already observed. The limit was therefore chosen as the maximum value which did not create additional apparent variations in RM($\phi$).

---

**Figure 4.3:** PSR J0835$-$4510. The solid black triangles represent the observed RM($\phi$) values with the associated statistical uncertainties. The red circles represent the RM($\phi$) values obtained from simulating the effect of misaligned observations with varying RM$_{\text{iono}}$. The dashed horizontal line represents the mean of these values.
The systematic uncertainties because of receiver imperfections were quantified for each pulsar by randomly generating 100 receiver imperfections obeying the above description, which then were used to distort the pulsar signal in the process of polarisation calibration\(^3\). For each of these 100 different distortions, we calculated values for \(\text{RM}_{\text{profile}}\), \(\text{RM}_{\text{scatt}}\), \(\text{RM}(\phi)\) and \(\Delta(V/I)(\phi)\). The standard deviation of these values was quoted as the systematic uncertainty in Table 4.1. The systematic uncertainties determined for the \(\text{RM}(\phi)\) and \(\Delta(V/I)\) are displayed for each pulsar, for example in Fig. 4.1, in the third and fourth panels as a 1\(\sigma\) contour green shaded region over-plotted over the \(\text{RM}(\phi)\) values.

### 4.4 Results

Pulsars described in Sections 4.4.1 and 4.4.2 and in Table 4.1, for which the phase-resolved RM profile had never been investigated previously in the literature, are marked with an asterisk (*)

The plots for the 98 pulsars have been included in Fig. A.1–Fig. A.26 (in Appendix A), and an example is displayed in Fig. 4.1. All plots were aligned so that the total intensity peaked at pulse longitude 180°. For the six pulsars from the sample, which had both a main pulse (MP) and an interpulse (IP), we aligned the MP peak at pulse longitude 90° and hence, the IP peaked around pulse longitude 270° (see Section 1.5). The results from the analysis described in the Section 4.3 can be found in Table 4.1.

The resulting \(\text{RM}(\phi)\) profiles allowed us to classify the pulsars as follows. Pulsars which had \(\chi^2_{\text{RM}(\phi)}>2\) were classified as showing significant \(\text{RM}(\phi)\) variations and they are discussed in more detail, on a case to case basis, in Section 4.4.1. Six pulsars which were initially classified as showing significant \(\text{RM}(\phi)\) variations, were removed from this section based on their high systematic uncertainties. A total of 42 pulsars, out of our sample of 98, were classified as showing significant \(\text{RM}(\phi)\) variations.

For all cases where we saw \(\text{RM}(\phi)\) variations, we observed deviations from the expected \(\lambda^2\) dependence (as quantified by \(\chi^2_{\text{PA}(\lambda^2,\phi)}\), but also by inspecting \(\text{PA}\) versus \(\lambda^2\) directly), implying that Faraday law fails to describe the full frequency dependence of the PA, and there must be another frequency and pulse longitude dependent effect present. Therefore, the results obtained from the panel where \(\chi^2_{\text{PA}(\lambda^2,\phi)}\) is displayed, were not discussed on an individual basis.

---

\(^3\)Note that these variations are in general too small to result in a noticeable peak centred at \(\text{RM} = 0 \text{ rad m}^{-2}\) in the RM power spectrum.
4.4. Results

Unless otherwise stated in individual cases, $\text{RM}_{\text{profile}}$ and $\text{RM}_{\text{scatt}}$ were consistent, providing no indication whether the RM was affected by interstellar scattering or not.

4.4.1 Pulsars with significant RM variations

**PSR J0034−0721.** (Fig. A.1) The profile of this pulsar has a central peak and a long tail. $L$ is low ($< 20\%$), with two drops to zero at the longitudes where OPM jumps occur in the PA swing. Apparent $\text{RM}(\phi)$ variations occur after pulse longitude $175^\circ$, with the largest deviations at the second OPM jump, although Noutsos et al. (2015) observed no $\text{RM}(\phi)$ variations at 150 MHz. There are no significant $\Delta(V/I)$ variations observed. If scattering was responsible for the apparent RM variations, we would not necessarily expect to see large $\Delta(V/I)(\phi)$ variations, given Stokes $V$ is relatively constant as function of longitude. Furthermore, we would expect the largest RM variations at longitudes where the PA swing is steep or breaks occur, which is observed, indicating that the observed variations are consistent with scattering as being the cause. Nevertheless, the pulsar has a low DM of 10.922 pc cm$^{-3}$ (Stovall et al., 2015), indicating that the expected scattering timescale at our observing frequency is of the order of $\sim$ ns (Bhat et al., 2004), which is very small.

**PSR J0255−5304*.** (Fig. A.1) This pulsar has a two component profile, with low $L$ and a complex PA swing. There is an OPM jump at $\sim 179^\circ$. $\text{RM}(\phi)$ variations are as high as $\sim 90$ rad m$^{-2}$ but are sensitive to the choice of DM. The largest variations can be observed towards the centre of the profile although deviations can be seen at all pulse longitudes. We see significant variations in $\Delta(V/I)$ towards the centre of the profile. However, the largest variations occur towards the trailing part of the profile, where Stokes $V$ is changing strongly. This implies that scattering could be responsible for the observed RM variations. Nevertheless, the DM of this pulsar is 15.9 pc cm$^{-3}$ (Manchester et al., 1978), hence the expected scattering timescale at our observing frequency is around $\sim$ 4 ns (Bhat et al., 2004). This is low, making it unlikely that the observed variation were caused by interstellar scattering.

**PSR J0401−7608*.** (Fig. A.2) The profile of this pulsar has three blended components, with the central one being the strongest, and $L$ is moderately high, especially in the trailing component. The PA swing is flat, except in the central region of the profile, which is also where the deviations in $\text{RM}(\phi)$ occur ($\sim 20$ rad m$^{-2}$). The lack of significant deviations in $\Delta(V/I)$ indicates we cannot distinguish between scattering and magnetospheric effects being responsible for the
Chapter 4. Evidence for magnetospheric effects on the radiation of pulsars

apparent RM variations.

**PSR J0452–1759**. (Fig. A.2) This pulsar displays complex profile and polarisation frequency evolution. $L$ is low ($\sim 20\%$), with several OPM jumps present in the PA swing. The largest $\text{RM}(\phi)$ deviations ($\sim 80$ rad m$^{-2}$) occur at the pulse longitudes of the OPM jumps, and where the PA is the steepest, whereas between $184^\circ$ and $192^\circ$, the PA swing and $\text{RM}(\phi)$ are relatively flat. The values of $\text{RM}_{\text{profile}}$ and $\text{RM}_{\text{scatt}}$ are inconsistent, indicating that low-level scattering might affect the pulsar. Other authors (e.g. Krishnakumar et al., 2015; Lewandowski et al., 2015a; Pilia et al., 2016) indeed reported finding small amounts of scattering at lower frequencies. There are significant $\Delta(V/I) \phi$ variations across the whole profile, with the largest where the PA swing is the steepest and the $\text{RM}(\phi)$ curve is also changing the most. In this region, Stokes $V$ is also changing, as is expected for scattering. Therefore all indicators are consistent with interstellar scattering being the main mechanism responsible for the apparent RM variations.

**PSR J0536–7543**. (Fig. A.2) This pulsar has a high degree of linear polarisation and a steep ‘$S$’-shaped PA swing, except for the observed OPM break towards the trailing edge, around pulse longitude $185^\circ$. The $\text{RM}(\phi)$ curve is flat in the leading part of the profile, where the PA swing is also relatively flat. Deviations ($\sim 10$ rad m$^{-2}$) occur starting at longitude $\sim 170^\circ$, where the PA curve is steepest. Significant $\Delta(V/I) \phi$ variations can be seen in the same region, which is also where Stokes $V$ changes the most, hence we cannot distinguish which frequency dependent effect is responsible for the apparent RM variations (see Section 4.3).

**PSR J0738–4042**. (Fig. A.3) The PA swing of the pulsar reveals five OPM jumps (possibly six if we consider the steep transition at longitude $154^\circ$). At the pulse longitudes where these jumps occur, significant deviations can be seen in $\text{RM}(\phi)$. Towards the leading edge of the profile, $L$ is weak and the $\text{RM}(\phi)$ uncertainties are high, however a significant dip can be observed in $\text{RM}(\phi)$. Noutsos et al. (2009) classified this pulsar as having low apparent $\text{RM}(\phi)$ variations, since they only report a slow deviation in the centre of the profile, as we see between longitudes $\sim 170^\circ$ and $\sim 185^\circ$. However, we observe much larger deviations with a maximum amplitude of $\sim 35$ rad m$^{-2}$ where OPM jumps occur. Complex intensity and polarisation evolution with time and frequency has been reported for this pulsar (Karastergiou et al., 2011), explaining the difference in the shape of our profile compared to what was seen in 2004 and 2006. The greatest change in $\Delta(V/I) \phi$ occurs at pulse longitude $\sim 165^\circ$, coincident with the largest change in $\text{RM}(\phi)$, and with an OPM transition. However, this is not where Stokes $V$ changes most rapidly. This suggests that scattering may not be the dominant
4.4. Results

cause for the observed RM variations, and a magnetospheric effect is significant for this pulsar.

**PSR J0820−1350*. (Fig. A.4) The PA swing is very steep with several kinks around pulse longitudes 179° and 184°, however there are no OPM jumps. $L$ is low ($\sim 20\%$), and Stokes $V$ has comparable magnitude. RM($\phi$) variations are present across most pulse longitudes. The highest amplitude variations are located where the two kinks in the PA swing occur. The low degree of $L$ and the very steep PA swing means that $\text{RM}_{\text{scatt}}$ is not very significant, as reflected in the high systematic and statistical uncertainties. We see large changes in $\Delta(V/I)(\phi)$ up to pulse longitude 182°, coincident with several changes in Stokes $V$, as expected for scattering. It is however curious that the $\Delta(V/I)(\phi)$ variations occur only up to pulse longitude 182°, even if Stokes $V$ is slowly changing until pulse longitude 184°. There might be a direct correlation between the $\Delta(V/I)(\phi)$ and RM($\phi$) curves, if the RM($\phi$) is distorted downwards before pulse longitude 181°. There could be magnetospheric effects affecting the polarisation of this pulsar.

**PSR J0837−4135*. (Fig. A.5) This pulsar has a three component profile, with a bright central component and a weaker post and pre-cursor. $L$ is low ($\sim 20\%$) and is comparable with Stokes $V$. The shape of the PA swing is complex: up to pulse longitude 175° it is flat with a slight upwards gradient; in this region, the RM($\phi$) curve is flat. The highest amplitude apparent variations in RM($\phi$) are near the only OPM jump, at pulse longitude 175°. In the centre of the profile, there are several kinks in the PA swing. Where the most prominent kink occurs (at pulse longitude $\sim 180°$), we observe a significant dip in the shape of the RM($\phi$) values. Around pulse longitude 182° there is a steep PA gradient, coinciding with another region of high amplitude variations in RM($\phi$). The greatest $\Delta(V/I)$ variations occur in the central region, where Stokes $V$ is also changing rapidly. Considering that both RM($\phi$) and $\Delta(V/I)(\phi)$ variations happen where the PA and Stokes $V$ vary most rapidly, in addition to the correlation between the gradient of the PA swing and apparent RM variations suggest that scattering is the cause for RM variations. Scatter broadening has been previously reported at lower frequencies (e.g. Mitra & Ramachandran 2001).

**PSR J0907−5157*. (Fig. A.5) For this pulsar, $L$ is moderately strong, peaking towards the centre of the profile, and the PA swing is relatively flat with and OPM jump at pulse longitude 130°. This pulsar was classified by Noutsos et al. (2009) as showing no RM($\phi$) variations. In our observation, the RM($\phi$) curve remains generally consistent with $\langle\text{RM}($$\phi$$)\rangle$ in the second component, however at earlier pulse longitudes there are significant variations coinciding with variations in $\Delta(V/I)$. Stokes $V$ is smooth across the whole profile, hence if scattering
affected the pulsar, variations in $\Delta(V/I)$ would not be confined to the second component. This is therefore suggestive of magnetospheric effects as a primary cause for the apparent RM variations.

**PSR J0908–4913**. (Fig. A.5) This pulsar has a MP and an IP, both being completely linearly polarised. The PA swing is steep, without any OPM jumps. Kramer & Johnston (2008) determined the geometry of this pulsar at two frequencies, 1.4 GHz and 8.4 GHz, and concluded that this pulsar is an orthogonal rotator and the geometry is independent of frequency, if the effects of interstellar scattering were considered. The RM($\phi$) curve is flat for most pulse longitudes. The only observed apparent variations are in the MP, towards the trailing edge, where there is a significant upward deviation ($\sim 5$ rad m$^{-2}$), starting with pulse longitude $90^\circ$, coinciding with where the PA swing is the steepest. The IP appears to be similar to the MP (highly polarised, steep PA), but significant apparent RM($\phi$) variations are not observed. For the MP, $\Delta(V/I)$ variations occur at the same pulse longitudes as the RM($\phi$) variations. Stokes $V$ is low and not varying rapidly across the profile, hence scattering would not necessarily be able to create such variations in $\Delta(V/I)(\phi)$, and if it would, it should start earlier. It is possible that magnetospheric effects are the cause of the apparent RM variations.

<table>
<thead>
<tr>
<th>Pulsar name</th>
<th>DM (cm$^{-3}$pc)</th>
<th>DMoffset (cm$^{-3}$pc)</th>
<th>RMoffset (rad m$^{-2}$)</th>
<th>RMprofile (rad m$^{-2}$)</th>
<th>$\langle\text{RM(}\phi\rangle)$ (rad m$^{-2}$)</th>
<th>$\chi^2_{\text{RM(}\phi)}$</th>
<th>$\chi^2_{\text{PA(}\phi)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0034-0721</td>
<td>14.2 ± 0.1</td>
<td>-0.3</td>
<td>10.977 ± 0.004</td>
<td>8.1 ± 0.9</td>
<td>63.1 ± 5.7</td>
<td>27.4</td>
<td>7.6 ± 0.3</td>
</tr>
<tr>
<td>J0134-2937</td>
<td>21.792 ± 0.003</td>
<td>0.40</td>
<td>13 ± 2</td>
<td>15.9 ± 0.3</td>
<td>17.6 ± 0.3</td>
<td>0.4</td>
<td>15.7 ± 0.2</td>
</tr>
<tr>
<td>J0152-1637*</td>
<td>11.95 ± 0.04</td>
<td>0.30</td>
<td>6.6 ± 5.0</td>
<td>9.1 ± 3.5</td>
<td>8.5 ± 3.4</td>
<td>1.5</td>
<td>8.3 ± 0.7</td>
</tr>
<tr>
<td>J0255-5304*</td>
<td>17.879 ± 0.009</td>
<td>0.15</td>
<td>32 ± 3</td>
<td>22 ± 0.9</td>
<td>16.7 ± 2.9</td>
<td>9.6</td>
<td>21.9 ± 0.3</td>
</tr>
<tr>
<td>J0401-7608*</td>
<td>21.68 ± 0.02</td>
<td>0.05</td>
<td>19.0 ± 0.5</td>
<td>24.5 ± 0.4</td>
<td>26.1 ± 0.7</td>
<td>1.0</td>
<td>24.6 ± 0.2</td>
</tr>
<tr>
<td>J0452-1759*</td>
<td>39.76 ± 0.02</td>
<td>0.03</td>
<td>11.1 ± 0.3</td>
<td>13.6 ± 0.1</td>
<td>20.8 ± 0.1</td>
<td>1.2</td>
<td>13.6 ± 0.1</td>
</tr>
<tr>
<td>J0536-7543*</td>
<td>18.51 ± 0.03</td>
<td>-0.45</td>
<td>23.8 ± 0.9</td>
<td>25.4 ± 0.1</td>
<td>26.8 ± 0.2</td>
<td>1.2</td>
<td>25.4 ± 0.1</td>
</tr>
<tr>
<td>J0614+2229*</td>
<td>96.88 ± 0.01</td>
<td>0.25</td>
<td>66.0 ± 3.3</td>
<td>66.1 ± 0.2</td>
<td>66.7 ± 0.3</td>
<td>0.3</td>
<td>66.7 ± 0.2</td>
</tr>
<tr>
<td>J0630-2834*</td>
<td>35.08 ± 0.06</td>
<td>-0.40</td>
<td>46.53 ± 0.12</td>
<td>44.1 ± 0.1</td>
<td>44.1 ± 0.1</td>
<td>0.6</td>
<td>44.8 ± 0.1</td>
</tr>
<tr>
<td>J0729-1836*</td>
<td>61.26 ± 0.02</td>
<td>-0.05</td>
<td>51 ± 4</td>
<td>52.6 ± 0.8</td>
<td>54.7 ± 1.1</td>
<td>2.0</td>
<td>52.5 ± 0.3</td>
</tr>
<tr>
<td>J0738-4042</td>
<td>160.785 ± 0.003</td>
<td>0.00</td>
<td>121 ± 0.6</td>
<td>119.8 ± 0.02</td>
<td>10.32 ± 0.02</td>
<td>1.12</td>
<td>11.97 ± 0.04</td>
</tr>
<tr>
<td>J0742-2822</td>
<td>73.754 ± 0.003</td>
<td>0.00</td>
<td>149.95 ± 0.05</td>
<td>149.72 ± 0.03</td>
<td>149.72 ± 0.03</td>
<td>0.20</td>
<td>149.64 ± 0.06</td>
</tr>
<tr>
<td>J0745-5353*</td>
<td>121.88 ± 0.01</td>
<td>0.40</td>
<td>71 ± 4</td>
<td>75.6 ± 0.7</td>
<td>77.4 ± 1.0</td>
<td>1.5</td>
<td>75.7 ± 0.3</td>
</tr>
<tr>
<td>J0809-4753*</td>
<td>228.41 ± 0.02</td>
<td>0.50</td>
<td>105 ± 5</td>
<td>101.1 ± 0.9</td>
<td>104.3 ± 1.3</td>
<td>1.6</td>
<td>101.2 ± 0.3</td>
</tr>
<tr>
<td>J0820-1350*</td>
<td>40.93 ± 0.03</td>
<td>-0.05</td>
<td>1.2 ± 0.4</td>
<td>-3.1 ± 0.3</td>
<td>-10.6 ± 1.8</td>
<td>4.1</td>
<td>-3.1 ± 0.2</td>
</tr>
<tr>
<td>J0835-4510</td>
<td>67.894 ± 0.001</td>
<td>0.00</td>
<td>31.38 ± 0.01</td>
<td>39.3 ± 0.0</td>
<td>39.5 ± 0.0</td>
<td>0.4</td>
<td>39.3 ± 0.0</td>
</tr>
<tr>
<td>J0837-4135*</td>
<td>147.176 ± 0.003</td>
<td>0.10</td>
<td>145 ± 1</td>
<td>146.4 ± 0.1</td>
<td>146.4 ± 0.2</td>
<td>0.0</td>
<td>146.4 ± 0.09</td>
</tr>
<tr>
<td>J0907-5157</td>
<td>103.659 ± 0.007</td>
<td>-0.05</td>
<td>23.3 ± 1.0</td>
<td>-25.7 ± 0.1</td>
<td>-26.5 ± 0.2</td>
<td>0.6</td>
<td>-25.9 ± 0.1</td>
</tr>
<tr>
<td>J0908-4913* (MP)</td>
<td>180.2062 ± 0.0008</td>
<td>0.00</td>
<td>10.0 ± 1.6</td>
<td>14.85 ± 0.03</td>
<td>15.2 ± 0.04</td>
<td>0.30</td>
<td>14.85 ± 0.07</td>
</tr>
<tr>
<td>J0908-4913* (IP)</td>
<td>180.2062 ± 0.0008</td>
<td>0.00</td>
<td>10.0 ± 1.6</td>
<td>14.3 ± 0.1</td>
<td>14.3 ± 0.1</td>
<td>0.3</td>
<td>14.3 ± 0.1</td>
</tr>
<tr>
<td>J0942-5552</td>
<td>180.24 ± 0.02</td>
<td>0.25</td>
<td>-61.9 ± 0.21</td>
<td>-64.8 ± 0.3</td>
<td>-68.4 ± 0.4</td>
<td>1.2</td>
<td>-64.8 ± 0.2</td>
</tr>
<tr>
<td>J1001-5507*</td>
<td>130.246 ± 0.008</td>
<td>0.05</td>
<td>297 ± 18</td>
<td>270.9 ± 0.4</td>
<td>286.7 ± 1.5</td>
<td>2.9</td>
<td>270.8 ± 0.3</td>
</tr>
<tr>
<td>J1043-6116*</td>
<td>449.02 ± 0.01</td>
<td>-0.40</td>
<td>257 ± 23</td>
<td>189.6 ± 2.9</td>
<td>189.0 ± 2.9</td>
<td>0.6</td>
<td>188.2 ± 0.6</td>
</tr>
<tr>
<td>J1047-6709*</td>
<td>116.269 ± 0.007</td>
<td>0.40</td>
<td>-79.3 ± 2.0</td>
<td>-79.4 ± 0.3</td>
<td>-81.5 ± 0.3</td>
<td>0.5</td>
<td>-79.5 ± 0.2</td>
</tr>
</tbody>
</table>
### Table 4.1: Continued

<table>
<thead>
<tr>
<th>Pulsar name</th>
<th>DM (cm⁻¹pc)</th>
<th>DM_offset (cm⁻¹pc)</th>
<th>RMcat (rad m⁻²)</th>
<th>RM_profile (rad m⁻²)</th>
<th>RM_cat (rad m⁻²)</th>
<th>Χ²RM_cat</th>
<th>Χ²PA(λ²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1048−5832⁺</td>
<td>128.72 ± 0.006</td>
<td>-0.10</td>
<td>-1.55 ± 5°</td>
<td>154.1 ± 0.1</td>
<td>-150.7 ± 0.1</td>
<td>-151.3 ± 0.09</td>
<td>0.9</td>
</tr>
<tr>
<td>J1056−6258</td>
<td>320.64 ± 0.01</td>
<td>0.45</td>
<td>4.2 ± 1.2</td>
<td>6.5 ± 0.1</td>
<td>8.1 ± 0.1</td>
<td>6.5 ± 0.1</td>
<td>1.7</td>
</tr>
<tr>
<td>J1057−5226(MP)</td>
<td>29.71 ± 0.003</td>
<td>0.25</td>
<td>47.2 ± 0.8</td>
<td>46.56 ± 0.1</td>
<td>47.02 ± 0.2</td>
<td>46.56 ± 0.04</td>
<td>10.9</td>
</tr>
<tr>
<td>J1057−5226⁺(IP)</td>
<td>29.71 ± 0.003</td>
<td>0.45</td>
<td>47.2 ± 0.8</td>
<td>45.39 ± 0.04</td>
<td>45.39 ± 0.05</td>
<td>27.3</td>
<td>1.1</td>
</tr>
<tr>
<td>J1136−5525⁺</td>
<td>85.41 ± 0.02</td>
<td>0.30</td>
<td>28 ± 5°</td>
<td>27.3 ± 2.0</td>
<td>32.9 ± 7.1</td>
<td>27.2 ± 0.5</td>
<td>1.1</td>
</tr>
<tr>
<td>J1146−6030⁺</td>
<td>111.67 ± 0.01</td>
<td>-0.05</td>
<td>5 ± 4²</td>
<td>2.6 ± 0.5</td>
<td>1.5 ± 1.0</td>
<td>2.5 ± 0.3</td>
<td>0.7</td>
</tr>
<tr>
<td>J1157−6224</td>
<td>324.32 ± 0.02</td>
<td>-0.20</td>
<td>508.2 ± 0.5</td>
<td>507.2 ± 0.3</td>
<td>507.1 ± 0.4</td>
<td>507.4 ± 0.2</td>
<td>11.2</td>
</tr>
<tr>
<td>J1234−6243</td>
<td>297.04 ± 0.002</td>
<td>0.10</td>
<td>157.8 ± 0.4</td>
<td>161.9 ± 0.1</td>
<td>161.7 ± 0.2</td>
<td>161.93 ± 0.1</td>
<td>87.3</td>
</tr>
<tr>
<td>J1306−6617⁺</td>
<td>437.09 ± 0.03</td>
<td>0.45</td>
<td>396 ± 4²</td>
<td>393.9 ± 0.7</td>
<td>390.8 ± 1.6</td>
<td>393.7 ± 0.3</td>
<td>1.6</td>
</tr>
<tr>
<td>J1326−5859</td>
<td>287.25 ± 0.006</td>
<td>-0.50</td>
<td>-579.6 ± 0.9</td>
<td>-578.1 ± 0.1</td>
<td>-581.4 ± 0.1</td>
<td>-578.1 ± 0.1</td>
<td>124.6</td>
</tr>
<tr>
<td>J1326−6408⁺</td>
<td>502.61 ± 0.031</td>
<td>-0.50</td>
<td>226.4 ± 3.8²</td>
<td>235.5 ± 1.9</td>
<td>231.7 ± 3.2</td>
<td>235.8 ± 0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>J1326−6700⁺</td>
<td>209.17 ± 0.03</td>
<td>0.15</td>
<td>-47 ± 1²</td>
<td>-51.5 ± 0.2</td>
<td>-58.3 ± 0.3</td>
<td>-51.5 ± 0.1</td>
<td>1.4</td>
</tr>
<tr>
<td>J1327−6222⁺</td>
<td>318.43 ± 0.01</td>
<td>-0.50</td>
<td>-306 ± 8²</td>
<td>-316.0 ± 0.3</td>
<td>-318.8 ± 0.7</td>
<td>-316.1 ± 0.2</td>
<td>1.9</td>
</tr>
<tr>
<td>J1328−4357⁺</td>
<td>41.58 ± 0.02</td>
<td>0.00</td>
<td>-22.9 ± 0.9³</td>
<td>-34.8 ± 0.2</td>
<td>-31.1 ± 0.4</td>
<td>-34.8 ± 0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>J1357−62⁺</td>
<td>416.47 ± 0.03</td>
<td>-0.45</td>
<td>-586 ± 5²</td>
<td>-585.4 ± 0.4</td>
<td>-594.0 ± 1.3</td>
<td>-586.6 ± 0.2</td>
<td>2.0</td>
</tr>
<tr>
<td>J1357−6038</td>
<td>293.73 ± 0.004</td>
<td>0.50</td>
<td>33 ± 5²</td>
<td>38.5 ± 0.3</td>
<td>36.5 ± 0.1</td>
<td>38.5 ± 0.1</td>
<td>3.4</td>
</tr>
<tr>
<td>J1401−6357⁺</td>
<td>97.76 ± 0.01</td>
<td>-0.35</td>
<td>62 ± 4²</td>
<td>52.0 ± 0.2</td>
<td>53.1 ± 0.3</td>
<td>52.0 ± 0.2</td>
<td>4.3</td>
</tr>
<tr>
<td>J1428−5530⁺</td>
<td>82.19 ± 0.02</td>
<td>-0.20</td>
<td>4 ± 3²</td>
<td>10.8 ± 1.4</td>
<td>4.4 ± 2.0</td>
<td>-9.6 ± 0.4</td>
<td>2.1</td>
</tr>
<tr>
<td>J1430−6623⁺</td>
<td>65.13 ± 0.01</td>
<td>0.10</td>
<td>-19.2 ± 0.3³</td>
<td>-22.2 ± 0.3</td>
<td>-26.5 ± 2.5</td>
<td>-22.2 ± 0.2</td>
<td>3.7</td>
</tr>
<tr>
<td>J1453−6413</td>
<td>71.25 ± 0.006</td>
<td>0.00</td>
<td>-18.6 ± 0.2³</td>
<td>-22.6 ± 0.1</td>
<td>-41.9 ± 0.3</td>
<td>-22.6 ± 0.1</td>
<td>5.2</td>
</tr>
<tr>
<td>J1456−6843⁺</td>
<td>8.720 ± 0.007</td>
<td>-0.15</td>
<td>-4.0 ± 0.3</td>
<td>-0.9 ± 0.1</td>
<td>1.8 ± 0.1</td>
<td>-0.9 ± 0.1</td>
<td>54.1</td>
</tr>
<tr>
<td>J1512−5759⁺</td>
<td>627.353 ± 0.045</td>
<td>-0.35</td>
<td>510.0 ± 0.7³</td>
<td>511.7 ± 1.1</td>
<td>500.7 ± 5.6</td>
<td>511.9 ± 0.3</td>
<td>2.0</td>
</tr>
<tr>
<td>J1522−5829</td>
<td>199.83 ± 0.02</td>
<td>0.15</td>
<td>-24.2 ± 2.0³</td>
<td>-24.3 ± 0.4</td>
<td>-55.6 ± 4.2</td>
<td>-24.2 ± 0.2</td>
<td>1.4</td>
</tr>
<tr>
<td>J1534−5334⁺</td>
<td>25.39 ± 0.02</td>
<td>-0.05</td>
<td>-46.1 ± 1.7³</td>
<td>21.9 ± 0.8</td>
<td>17.9 ± 1.2</td>
<td>21.7 ± 0.3</td>
<td>2.0</td>
</tr>
<tr>
<td>J1539−5626⁺</td>
<td>175.90 ± 0.01</td>
<td>0.1</td>
<td>-18.0 ± 2.0³</td>
<td>-14.4 ± 0.5</td>
<td>-167 ± 0.7</td>
<td>-14.6 ± 0.2</td>
<td>1.1</td>
</tr>
<tr>
<td>J1544−5308⁺</td>
<td>35.214 ± 0.007</td>
<td>-0.20</td>
<td>-29 ± 7²</td>
<td>-41.9 ± 1.0</td>
<td>-37.7 ± 1.2</td>
<td>-41.5 ± 0.4</td>
<td>1.0</td>
</tr>
<tr>
<td>J1555−3134</td>
<td>73.01 ± 0.02</td>
<td>0.25</td>
<td>-49 ± 6¹⁰</td>
<td>-52.4 ± 2.0</td>
<td>-82.3 ± 4.9</td>
<td>-52.3 ± 0.4</td>
<td>1.0</td>
</tr>
<tr>
<td>J1557−4258⁺</td>
<td>144.43 ± 0.01</td>
<td>-0.10</td>
<td>-41.9 ± 2.0³</td>
<td>-37.2 ± 0.7</td>
<td>-40.0 ± 1.2</td>
<td>-37.5 ± 0.3</td>
<td>0.9</td>
</tr>
<tr>
<td>J1559−4438⁺</td>
<td>55.87 ± 0.01</td>
<td>-0.20</td>
<td>-5.0 ± 0.6³</td>
<td>-2.9 ± 0.1</td>
<td>-7.4 ± 0.1</td>
<td>-2.9 ± 0.1</td>
<td>39</td>
</tr>
<tr>
<td>J1602−5100⁺</td>
<td>170.921 ± 0.008</td>
<td>0.10</td>
<td>71.5 ± 1.1¹¹</td>
<td>84.8 ± 0.5</td>
<td>80.1 ± 0.9</td>
<td>84.7 ± 0.3</td>
<td>4.1</td>
</tr>
<tr>
<td>J1604−4909⁺</td>
<td>140.730 ± 0.007</td>
<td>0.10</td>
<td>34 ± 1³</td>
<td>13.4 ± 1.0</td>
<td>30.8 ± 3.1</td>
<td>13.8 ± 0.4</td>
<td>3.9</td>
</tr>
</tbody>
</table>
481.74 ± 0.04
178.84 ± 0.03
206.83 ± 0.01
301.1 ± 0.2

J1817−3618*
J1820−0427*
J1822−2256*

J1745−3040
J1751−4657*
J1752−2806*
J1807−0847

J1739−2903* (MP)
J1739−2903* (IP)
J1740−3015*
J1741−3927*

J1722−3207*
J1722−3712* (MP)
J1722−3712* (IP)
J1731−4744*

J1709−1640*
J1709−4429*
J1717−3425*
J1721−3532*

J1703−3241*
J1705−1906 (MP)
J1705−1906* (IP)
J1705−3423*

± 0.02
± 0.01
± 0.01
± 0.01
138.58 ± 0.01
138.58 ± 0.01
151.82 ± 0.01
158.52 ± 0.02
88.074 ± 0.008
20.61 ± 0.01
50.302 ± 0.003
112.344 ± 0.003
94.29 ± 0.02
84.48 ± 0.02
120.9 ± 0.1

126.11
99.47
99.47
122.87

24.95 ± 0.01
75.645 ± 0.005
585.20 ± 0.14
496.046 ± 0.016

110.01 ± 0.03
22.906 ± 0.007
22.906 ± 0.007
146.34 ± 0.01

474.022 ± 0.025
399.04 ± 0.01
478.6673 ± 0.0071
42.18 ± 0.07

J1651−4246*
J1651−5222*
J1653−3838*
J1701−3726*

J1633−4453*
J1633−5015*
J1644−4559
J1646−6831*

35.03 ± 0.04

(cm−3 pc)

DM

J1605−5257*

Pulsar name

−167.4± 1.17
−38± 52
−82± 34
−605.9± 2.04
−21.7± 0.510
−19.2± 1.04
−19.2± 1.04
−44± 89
−1.3± 0.310
0.70 ± 0.078
−191 ± 149
159 ± 44
70.4 ± 0.53
104 ± 32
104 ± 32
−429.1± 0.511
−236± 189
−236± 189
−168.0± 0.74
204 ± 69
101 ± 710
19 ± 12
96 ± 210
166 ± 910
66 ± 45
69.2 ± 0.28
124 ± 34

159.0 ± 0.64
406.1 ± 2.04
−626.9 ± 0.87
105 ± 35

−0.45
−0.35
−0.5
−0.50
0.50
−0.35
−0.15
−0.50
0.20
0.10
0.45
0.25
0.40
−0.30
−0.05
0.40
0.00
−0.50
−0.25
−0.05
0.05
0.45
0.50
−0.50
−0.20
−0.10
0.00
0.25
0.45
−0.35
−0.40

(rad m−2 )

1.0 ± 2.04

RMcat

0.20

(cm−3 pc)

DMoffset
(rad m−2 )

(rad m−2 )

153.7 ± 1.7 ± 1.1
407.4 ± 0.4 ± 0.3
−621.4 ± 0.1 ± 0.2
99.5 ± 0.5 ± 0.4

−170.0 ± 0.3 ± 9.2
−41.1 ± 2.7 ± 2.1
−82.3 ± 0.7 ± 0.8
−632.4 ± 2.7 ± 0.7
−22.4 ± 0.5 ± 1.6
−19.9 ± 0.2 ± 0.5
−21.1 ± 0.3 ± 0.3
−44.1 ± 1.4 ± 2.0
−1.5 ± 0.4 ± 2.0
−1.3 ± 0.1 ± 0.3
−192.7 ± 2.5 ± 0.9
170.1 ± 1.0 ± 1.2
63.9 ± 1.3 ± 2.3
110.6 ± 0.7 ± 0.6
111.5 ± 2.2 ± 0.3
−445.5 ± 0.2 ± 0.3
−301.6± 4.7 ± 0.8
−298.9 ± 2.2 ± 0.5
−156.9 ± 0.1 ± 0.2
213.5 ± 2.4 ± 1.6
94.7 ± 0.2 ± 0.7
27.7 ± 0.9 ± 2.8
78.4 ± 0.6 ± 7.1
168.7 ± 0.8 ± 2.2
60.6 ± 2.6 ± 3.4
59.8 ± 0.3 ± 1.6
133.5 ± 0.9 ± 0.7

−166.9 ± 0.1 ± 2.5
−47.8 ± 1.1 ± 0.5
−81.2 ± 0.7 ± 0.7
−607.4 ± 0.6 ± 0.3
−22.6 ± 0.1 ± 0.7
−21.1 ± 0.2 ± 1.5
−20.8 ± 0.4 ± 0.3
−43.9 ± 1.1 ± 1.8
−6.3 ± 0.4 ± 1.5
−1.7 ± 0.1 ± 0.4
−192.1 ± 2.0 ± 0.7
169.3 ± 0.9 ± 0.7
67.8 ± 0.5 ± 0.4
108.2 ± 0.5 ± 0.5
111.1 ± 2.4 ± 0.3
−445.9 ± 0.1 ± 0.3
−301.0 ± 4.8 ± 0.7
−303.3 ± 1.7 ± 1.8
−158.4 ± 0.1 ± 0.3
211.2 ± 0.7 ± 0.4
96.0 ± 0.2 ± 0.4
17.1 ± 0.3 ± 1.0
87.1 ± 0.3 ± 2.8
163.3 ± 0.2 ± 0.3
66.0 ± 1.1 ± 0.8
62.5 ± 0.2 ± 1.2
134.0 ± 0.8 ± 0.6

4.8 ± 0.5 ± 0.9

RMscatt

157.4 ± 1.8 ± 1.0
406.8 ± 0.3 ± 0.3
−623.3 ± 0.1 ± 0.2
100.1 ± 0.4 ± 0.3

3.7 ± 0.2 ± 0.3

RMprofile

Table 4.1: Continued

−166.9 ± 0.1
−48.6 ± 0.4
−81.1 ± 0.4
−607.6 ± 0.3
−22.6 ± 0.2
20.8 ± 0.2
−20.8 ± 0.3
−44.2 ± 0.3
−5.9 ± 0.2
−2.0 ± 0.1
−192.4 ± 0.6
169.5 ± 0.4
67.6 ± 0.23
108.2 ± 0.3
111.4 ± 0.7
−445.9 ± 0.1
−300.5 ± 0.7
−303.4 ± 0.5
−158.4 ± 0.1
210.8 ± 0.3
96.0 ± 0.1
17.3 ± 0.3
86.6 ± 0.2
163.3 ± 0.1
65.5 ± 0.4
62.4 ± 0.2
133.6 ± 0.3

156.5 ± 0.5
406.7 ± 0.2
−623.4 ± 0.1
100.0 ± 0.2

3.76 ± 0.14

(rad m−2 )

⟨RM(ϕ)⟩

2.6
7.3
0.7

2.5
7.5
72
2.0

0.8
0.8
2.7
1.7

3.0
0.9
0.4
10.5

4.4
0.7
1.3
1.2

2.7
2.7
1.3
0.8

1.4
3.8
0.8
5.0

1.0
1.8
404
1.3

1.8

χ2RM(ϕ)

0.9
1.4
2.8

1.8
1.7
6.0
4.5

1.5
1.0
9.5
1.2

0.9
1.3
1.3
14.3

4.0
3.2
1.9
2.9

1.2
2.6
0.8
1.0

1.1
1.1
1.9
1.8

2.0
5.7
2200
1.4

1.8

χ2PA(λ2 )

4.4. Results
183


Table 4.1: Continued

<table>
<thead>
<tr>
<th>Pulsar name</th>
<th>DM</th>
<th>DM\text{offset}</th>
<th>RM\text{cat}</th>
<th>RM\text{profile}</th>
<th>RM\text{scatter}</th>
<th>1000 \text{RM}(\phi)</th>
<th>\chi^2_{\text{RM}(\phi)}</th>
<th>\chi^2_{\text{PA}(\lambda^2)}</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1823–3106*</td>
<td>50.275 ± 0.006</td>
<td>0.50</td>
<td>95 ± 5$^\circ$</td>
<td>89.2 ± 0.2 ± 0.5</td>
<td>91.9 ± 0.2 ± 0.7</td>
<td>89.1 ± 0.2</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>J1824–1945*</td>
<td>224.31 ± 0.02</td>
<td>-0.25</td>
<td>-302.2 ± 0.7$^3$</td>
<td>-297.1 ± 0.3 ± 0.7</td>
<td>-296.6 ± 0.9 ± 1.1</td>
<td>-297.1 ± 0.2</td>
<td>9.5</td>
<td>1.0</td>
</tr>
<tr>
<td>J1825–0935* (MP)</td>
<td>19.62 ± 0.03</td>
<td>-0.50</td>
<td>65.2 ± 0.2$^{10}$</td>
<td>68.3 ± 0.7 ± 1.2</td>
<td>69.1 ± 0.8 ± 1.3</td>
<td>68.4 ± 0.3</td>
<td>1.3</td>
<td>2.0</td>
</tr>
<tr>
<td>J1825–0935* (IP)</td>
<td>19.62 ± 0.03</td>
<td>0.35</td>
<td>65.2 ± 0.2$^{10}$</td>
<td>51.1 ± 10.6 ± 2.0</td>
<td>59.1 ± 9.7 ± 3.0</td>
<td>58.5 ± 1.18</td>
<td>0.8</td>
<td>3.9</td>
</tr>
<tr>
<td>J1829–1751*</td>
<td>216.79 ± 0.01</td>
<td>0.00</td>
<td>304.7 ± 0.4$^3$</td>
<td>303.1 ± 0.2 ± 0.2</td>
<td>300.1 ± 1.0 ± 1.3</td>
<td>303.1 ± 0.2</td>
<td>1.0</td>
<td>0.8</td>
</tr>
<tr>
<td>J1830–1059*</td>
<td>159.71 ± 0.02</td>
<td>0.30</td>
<td>47 ± 5$^3$</td>
<td>44.6 ± 0.5 ± 0.4</td>
<td>45.9 ± 0.6 ± 0.4</td>
<td>44.4 ± 0.3</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>J1832–0827*</td>
<td>301.01 ± 0.02</td>
<td>-0.45</td>
<td>39 ± 7$^3$</td>
<td>17.8 ± 0.8 ± 0.4</td>
<td>16.6 ± 1.7 ± 1.4</td>
<td>17.7 ± 0.4</td>
<td>0.7</td>
<td>1.0</td>
</tr>
<tr>
<td>J1845–0743*</td>
<td>280.99 ± 0.01</td>
<td>-0.20</td>
<td>448.4 ± 1.8$^3$</td>
<td>449.5 ± 0.8 ± 0.3</td>
<td>436.5 ± 8.0 ± 2.8</td>
<td>449.4 ± 0.3</td>
<td>0.7</td>
<td>1.0</td>
</tr>
<tr>
<td>J1847–0402*</td>
<td>141.42 ± 0.03</td>
<td>-0.15</td>
<td>117 ± 8$^{10}$</td>
<td>106.9 ± 0.9 ± 0.3</td>
<td>113.9 ± 1.6 ± 1.7</td>
<td>106.9 ± 0.3</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>J1848–0123*</td>
<td>159.88 ± 0.02</td>
<td>0.25</td>
<td>580 ± 30$^{11}$</td>
<td>513.6 ± 0.5 ± 0.2</td>
<td>521.0 ± 1.3 ± 0.9</td>
<td>513.9 ± 0.2</td>
<td>3.5</td>
<td>2.0</td>
</tr>
<tr>
<td>J1852–0635*</td>
<td>173.14 ± 0.03</td>
<td>0.45</td>
<td>414.5 ± 0.7$^7$</td>
<td>413.6 ± 0.3 ± 0.3</td>
<td>414.9 ± 0.4 ± 0.3</td>
<td>413.6 ± 0.1</td>
<td>0.9</td>
<td>2.0</td>
</tr>
<tr>
<td>J1900–2600*</td>
<td>38.22 ± 0.03</td>
<td>-0.50</td>
<td>-9.3 ± 2$^2$</td>
<td>-5.9 ± 0.2 ± 0.3</td>
<td>-13 ± 0.3 ± 0.6</td>
<td>-5.9 ± 0.1</td>
<td>5.8</td>
<td>0.9</td>
</tr>
<tr>
<td>J1913–0440*</td>
<td>89.49 ± 0.02</td>
<td>-0.20</td>
<td>3.98 ± 0.05$^5$</td>
<td>4.6 ± 0.5 ± 1.1</td>
<td>0.0 ± 1.5 ± 4.6</td>
<td>4.7 ± 0.3</td>
<td>5.6</td>
<td>1.0</td>
</tr>
<tr>
<td>J1941–2602*</td>
<td>50.12 ± 0.01</td>
<td>0.00</td>
<td>-33.5 ± 0.8$^8$</td>
<td>-33.9 ± 0.3 ± 0.3</td>
<td>-34.0 ± 0.3 ± 0.3</td>
<td>-33.7 ± 0.2</td>
<td>0.7</td>
<td>2.0</td>
</tr>
<tr>
<td>J2048–1616</td>
<td>11.86 ± 0.01</td>
<td>-0.50</td>
<td>-10.0 ± 0.3$^6$</td>
<td>-10.5 ± 0.1 ± 0.4</td>
<td>-11.0 ± 0.1 ± 0.7</td>
<td>-10.5 ± 0.1</td>
<td>12.7</td>
<td>22.8</td>
</tr>
<tr>
<td>J2330–2005*</td>
<td>8.81 ± 0.09</td>
<td>0.25</td>
<td>9.2 ± 0.8$^4$</td>
<td>8.7 ± 1.3 ± 0.6</td>
<td>9.0 ± 1.8 ± 2.1</td>
<td>7.6 ± 0.5</td>
<td>0.8</td>
<td>1.0</td>
</tr>
<tr>
<td>J2346–0609*</td>
<td>22.73 ± 0.03</td>
<td>0.50</td>
<td>-5 ± 1$^2$</td>
<td>-6.3 ± 0.6 ± 0.3</td>
<td>-12.1 ± 3.6 ± 1.5</td>
<td>-6.6 ± 0.2</td>
<td>1.0</td>
<td>1.1</td>
</tr>
</tbody>
</table>
**PSR J0942–5552.** (Fig. A.6) The profile of this pulsar has three components: a strong central one and two weaker outliers. $L$ is moderately high and the PA swing is relatively flat, broken by one OPM jump at pulse longitude $172^\circ$. Around longitude $187^\circ$, a dip can be seen in the PA swing. Noutsos et al. (2009) observed a varying RM($\phi$) curve, by as much as 20 rad m$^{-2}$ in the trailing component, as well as a change in the leading component, but not the dip because of the lack of S/N. We observe similar trends in the leading component, near the OPM jump, of the order $\sim 15$ rad m$^{-2}$ and towards the centre of the profile in a shape of a downward gradient of few rad m$^{-2}$, however we do not observe any significant apparent RM($\phi$) variations in the trailing component. The statistical uncertainties on RM($\phi$) are relatively large, hence the significance of the variations is moderate. There are no significant variations observed in the $\Delta(V/I)$. If scattering was responsible for the apparent RM variations, we expect $\Delta(V/I)(\phi)$ variations towards the centre of the profile, where Stokes $V$ is changing. Given the large observed uncertainties on $\Delta(V/I)(\phi)$, this is difficult to verify. As Mitra & Ramachandran (2001) measured a low level of scatter broadening at lower frequencies, it is possible that the observed RM variations were caused by low level scattering.

**PSR J1001–5507*.** (Fig. A.6) This pulsar has a three component profile, with a strong central component and two weaker components. $L$ is very low as is Stokes $V$, which displays the common sign reversal towards the centre of the profile. The PA swing has a complex shape. The highest apparent RM($\phi$) variations coincide with the first OPM jump and with where the PA gradient is steep. The values of RM$_{\text{profile}}$ and RM$_{\text{scatt}}$ suggest that interstellar scattering could affect the RM measurements. Scatter broadening has been previously reported at lower frequencies, as this pulsar is located in the direction of the Gum nebula (e.g. Mitra & Ramachandran 2001). We see marginally significant variations in $\Delta(V/I)$ towards the trailing half of the profile, where Stokes $V$ is changing, as expected if scattering was responsible for the apparent RM variations. Since this coincides with where the RM($\phi$) curve is changing most, it is difficult to distinguish between scattering and a magnetospheric effect as the dominant effect (see Section 4.3).

**PSR J1057–5226.** (Fig. A.7) This pulsar has a completely polarised four component MP, with a smooth PA swing. There is also a three component IP, with a similar flux density to the MP at several observing frequencies (Weltevrede & Wright, 2009). The first component of the IP is highly polarised, however $L$ decreases significantly towards the trailing edge. The shape of the PA swing of the IP is peculiar, as towards the centre of the profile there is a sharp gradient
change in the PA sweep, accompanied by a drop in $L$, which is hard to fit with the RVM model (e.g. Rookyard et al. 2015). Noutsos et al. (2009) only analysed the MP and did not find $\text{RM}(\phi)$ variations. From our observations with better S/N, both the MP and IP show significant deviations in $\text{RM}(\phi)$. The amplitude of the observed variations in the MP are $\sim 3 \text{ rad m}^{-2}$ and appear as a shallow gradient in $\text{RM}(\phi)$. The observed variations in the IP are much larger ($\sim 30 \text{ rad m}^{-2}$) and coincide with the peculiar change of gradient of the PA swing. An extreme scattering event with a duration of $\sim 3$ years, was reported in the direction of this pulsar (Kerr et al., 2018). Hence, it is very likely that during the time of our observations, the radiation was affected by a low amount of scattering. For the MP, there are significant $\Delta(V/I)$ variations around longitudes $110^\circ$ and possibly $90^\circ$, where Stokes $V$ is changing, which is what we expect if scattering was the effect responsible for the apparent RM variations. Since this is where the largest $\text{RM}(\phi)$ variations occur, we cannot dismiss magnetospheric effects as a possible cause (see Section 4.3). For the IP, there are $\Delta(V/I)(\phi)$ and $\text{RM}(\phi)$ variations only up to pulse longitude $270^\circ$, where Stokes $V$ is changing the most. Evidence points towards low level of interstellar scattering as the reason for the observed RM variations, however we cannot dismiss magnetospheric effects.

**PSR J1243–6423.** (Fig. A.8) For this pulsar, $L$ is low ($\sim 20\%$), with significant depolarisation observed starting from pulse longitude $180^\circ$. The PA swing is complex, with flat regions and a very steep region in the centre of the profile. The observed $\text{RM}(\phi)$ variations have a similar shape to that reported by Noutsos et al. (2009). One discrepancy is the amplitude of variations: in our observation it is $\sim 20 \text{ rad m}^{-2}$, while in Noutsos et al. (2009) it is $\sim 60 \text{ rad m}^{-2}$. The largest variations in $\text{RM}(\phi)$ occur at a similar pulse phase where there is a kink in the PA swing. At higher frequencies, an OPM is seen at the location of this kink (Karastergiou & Johnston, 2006). The values of $\text{RM}_{\text{profile}}$ and $\text{RM}_{\text{scatt}}$ indicate that the pulsar might be affected by scattering. The pulsar appears to be located behind an HII region, however a scattering deficit is reported by Cordes et al. (2016). If scattering affected the pulsar, we would expect to see significant variations in $\Delta(V/I)(\phi)$ around pulse longitudes $179^\circ$, where Stokes $V$ is changing most rapidly, as observed. However, despite Stokes $V$ being less variable, the largest $\text{RM}(\phi)$ variations occur where the greatest $\Delta(V/I)(\phi)$ changes occur. This indicates that the observed RM variations are caused by a mixture of scattering and magnetospheric effects.

**PSR J1326–5859.** (Fig. A.9) The profile of this pulsar has three components: one bright central one and two weak outriders. Using multi-frequency observations, Lewandowski et al. (2015a) estimated the scattering timescale for this
4.4. Results

A pulsar at 1 GHz to be 9.47 ms. $\text{RM}_{\text{profile}}$ and $\text{RM}_{\text{scatt}}$ are inconsistent with each other, indicating that this pulsar may indeed be significantly affected by scattering. The pulsar has a moderately high $L$ and a complex PA swing. There is an OPM jump towards the leading edge of the profile, around pulse longitude $173^\circ$, in a region where the PA swing is flat and there is a drop in the amount of $L$. In this region, there are large $\text{RM}(\phi)$ variations, similar to the ones presented in Noutsos et al. (2009). $\Delta(V/I)(\phi)$ varies where Stokes $V$ is most changing as function of pulse longitude. This starts before the largest RM variations. So far, this is consistent with scattering. However, the largest $\text{RM}(\phi)$ variations do not coincide with where the PA is the steepest, suggesting that they could have been caused by a mixture of scattering and magnetospheric effects.

**PSR J1357−62*.** (Fig. A.10) For this pulsar, the PA swing is generally flat, with the exception of longitude $175^\circ$, where a very steep swing can be seen. In this region, two OPM jumps occur where $L$ is low. The first OPM is in the leading part of the profile, while the second one coincides with the bridge between the second and third profile components. The $\text{RM}(\phi)$ curve is flat, except where the PA swing is steep and where the second OPM jump occurs. The peak-to-peak amplitude of these apparent variations is $\sim 60 \text{ rad m}^{-2}$. We also see variations in $\Delta(V/I)$ where Stokes $V$ is changing the most, coinciding also with the largest amplitude variations in $\text{RM}(\phi)$. Comparing the values of $\text{RM}_{\text{profile}}$ and $\text{RM}_{\text{scatt}}$, we see that they are inconsistent with each other, therefore all indicators suggest that scattering is likely the reason for the apparent RM variations, however we cannot dismiss magnetospheric effects (see Section 4.3).

**PSR J1359−6038.** (Fig. A.10) The pulsar has a single component profile and a high degree of $L$. It was classified by Noutsos et al. (2009) as having small variations in $\text{RM}(\phi)$ towards the trailing edge of the profile, with an amplitude of $\sim 40 \text{ rad m}^{-2}$. In our observation, we see a similar behaviour, however the overall amplitude of the apparent variations is around $\sim 10 \text{ rad m}^{-2}$. $\text{RM}_{\text{profile}}$ and $\text{RM}_{\text{scatt}}$ are inconsistent, indicating that this pulsar could be affected by scattering. Lewandowski et al. (2015a) estimated a scattering timescale of 1 ms at 1 GHz. If scattering was responsible for the observed RM variations, $\Delta(V/I)(\phi)$ variations should occur where Stokes $V$ is changing most rapidly, around pulse longitudes $180^\circ$ and $185^\circ$. $\Delta(V/I)(\phi)$ variations are only observed around pulse longitude $185^\circ$, where the greatest $\text{RM}(\phi)$ variations occur. This points towards magnetospheric effects playing a role in producing the observed RM variations.

**PSR J1401−6357*.** (Fig. A.11) The profile of this pulsar consists of one weak leading component and several other blended components. $L$ is very weak in the leading part of the profile. After pulse longitude $178^\circ$, where an OPM jump
occurs in the PA swing, the degree of $L$ is relatively high. Moderately significant variations in the RM($\phi$) curve coincide with the OPM jump. The degree of Stokes $V$ is very low and we do not see significant $\Delta(V/I)(\phi)$ variations, preventing us saying more about the origin of the apparent RM($\phi$) variations.

**PSR J1428–5530*. (Fig. A.11) Both the degree of $L$ and Stokes $V$ of this pulsar are low ($\sim 10\%$). The PA swing is relatively flat with several kinks. Where $L$ drops to zero, apparent variations can be seen in RM($\phi$) ($\sim 50$ rad m$^{-2}$). The statistical uncertainties on RM($\phi$) are large, hence this is only moderately significant. There are no significant $\Delta(V/I)(\phi)$ variations to help comment on the origin of the apparent RM($\phi$) variations.

**PSR J1453–6413.** (Fig. A.11) This pulsar has a profile with one strong component, one weak pre-cursor and an extended tail. $L$ is moderately high, with a drop to zero coinciding with the OPM jump in the PA swing at pulse longitude $177^\circ$. In the extended tail of this pulsar, $L$ is weak and the PA swing becomes very steep around longitude $188^\circ$. The observed RM($\phi$) variations have a similar shape to the ones presented in Noutsos et al. (2009). The largest RM($\phi$) variations are where the OPM jump is and where the PA swing is the steepest. The values of RM$_{\text{profile}}$ and RM$_{\text{scatt}}$ are inconsistent with each other, indicating that this pulsar may well be affected by scattering. Hence, the largest $\Delta(V/I)(\phi)$ variations should be in the central region of the profile, where Stokes $V$ displays several steep sign reversals. This is the case. Interestingly, at pulse longitude $185^\circ$, where there is a kink in the PA swing, there is a peak in the RM($\phi$) curve and a significant dip in the $\Delta(V/I)(\phi)$ curve. At this pulse longitude, Stokes $V$ is relatively smooth, indicating at least some of the observed RM variations are caused by magnetospheric effects.

**PSR J1456–6843*. (Fig. A.12) For this pulsar, $L$ is low, with one drop to nearly zero at pulse longitude $182^\circ$, coincident with a dip in the PA swing. The shape of the PA sweep is complex, with one OPM jump around pulse longitude $158^\circ$. The RM($\phi$) variations display one of the most complex shapes in our sample, with the largest variations ($\sim 20$ rad m$^{-2}$) near where the PA gradient is the steepest. There are $\Delta(V/I)(\phi)$ variations across the entire profile, however they do not coincide with longitudes where Stokes $V$ is changing the most. The largest $\Delta(V/I)(\phi)$ variations occur around longitude $168^\circ$, coincident with significant RM($\phi$) variations, but Stokes $V$ is relatively constant. This suggests that the effect responsible is of magnetospheric origin.

**J1512–5759*. (Fig. A.12) This pulsar has a single peaked profile with a long tail. $L$ is low ($\sim 10\%$), and it vanishes at higher frequencies (Karastergiou et al., 2005). At pulse longitude $172^\circ$, $L$ drops to zero, coincident with an OPM
jump in the PA swing. At pulse longitude $179^\circ$, the PA swing is steep and some depolarisation can be observed. Here, deviations of $\sim 80$ rad m$^{-2}$ in RM($\phi$) occur. More deviations occur towards the trailing edge, coincident with a wiggle in the PA swing. The $\Delta(V/I)$ variations are seen where Stokes $V$ is changing the most, indicating that the possible cause for the observed RM($\phi$) variations is scattering.

**PSR J1534–5334*.** (Fig. A.12) The profile of this pulsar has three components: a strong leading one, which peaks at the same pulse longitude as Stokes $V$; and two weaker and wider trailing components. $L$ is low, hence the statistical uncertainty on RM($\phi$) is high, especially in the trailing part of the profile. Nevertheless, there is a region between pulse longitudes $178^\circ$ and $185^\circ$ where there are significant RM($\phi$) variations with an amplitude of $\sim 10$ rad m$^{-2}$, coincident with the wiggle in the PA swing. Where Stokes $V$ is changing sharply, there are moderately significant $\Delta(V/I)(\phi)$ variations, indicating that scattering could well be the cause for the apparent RM variations.

**PSR J1559–4438*.** (Fig. A.14) The profile of this pulsar consists of a strong central component and weaker pre- and post-cursors. $L$ is moderately high with two drops to zero, which coincide with the OPM jumps in the PA swing. In the centre of the profile, the PA swing shows a dip close to where Stokes $V$ changes sign. RM($\phi$) varies significantly where the PA gradient is steep, with the largest deviations coincident with the dip in the PA swing. Significant $\Delta(V/I)(\phi)$ variations occur at longitudes where Stokes $V$ is changing the most, as expected for scattering. The measured values of RM$_{\text{profile}}$ and RM$_{\text{scatt}}$ indicate that our observation might be affected by interstellar scattering. Johnston et al. (2008) found that at low frequencies, scatter broadening can be seen in the profile of this pulsar, hence all indicators are suggestive of scattering being the primary cause for the observed RM($\phi$) variations.

**PSR J1604–4909*.** (Fig. A.14) The profile of this pulsar consists of multiple components. $L$ is generally weak, with the exception of the central region of the profile. Here, the PA swing is steep with several kinks. Across most of the profile, the statistical uncertainty on RM($\phi$) points is high. Nevertheless, significant apparent RM($\phi$) variations ($\sim 15$ rad m$^{-2}$) occur where the PA gradient is steep. There are significant $\Delta(V/I)(\phi)$ variations in the central region of the profile, where Stokes $V$ is changing rapidly, as expected if scattering affected the pulsar. This is not where the RM($\phi$) curve is changing the most, pointing to scattering as the main cause. RM$_{\text{profile}}$ and RM$_{\text{scatt}}$ are inconsistent (10$\sigma$ deviation), indicating that the RM measurements could be indeed affected by scattering. Krishnakumar et al. (2017) estimated that the scattering timescale at 1GHz is 0.02 ms, which is small. RM$_{\text{scatt}}$ is consistent with the similarly derived value by Johnston et al.
Chapter 4. Evidence for magnetospheric effects on the radiation of pulsars (2007).

**PSR J1644–4559.** (Fig. A.15) The profile of this pulsar has an scatter extended tail and a very weak pre-cursor. $L$ is weak and the PA swing is relatively shallow with several bumps and an OPM transition at pulse longitude $172^\circ$. The $\text{RM}(\phi)$ curve displays variations ($\sim 20$ rad m$^{-2}$) across the whole profile and has a similar shape to what Noutsos et al. (2009) presented, with the largest variations coincident with the bump in the PA swing at longitude $\sim 186^\circ$. The pulsar is highly scattered at lower frequencies (e.g Rickett et al., 2009). $\text{RM}_{\text{profile}}$ and $\text{RM}_{\text{scatt}}$ are inconsistent, indicating that the pulsar is indeed affected by scattering. Where Stokes $V$ changes most rapidly, $\Delta(V/I)(\phi)$ variations are seen, as expected from scattering. Since $\text{RM}(\phi)$ and $\Delta(V/I)(\phi)$ variations coincide, magnetospheric effects cannot be entirely dismissed, but it is clear scattering contributes significantly to the observed $\text{RM}(\phi)$.

**PSR J1651–5222*.** (Fig. A.16) This pulsar has a profile consisting of several components blended into one feature. $L$ is low ($\sim 20\%$) and the PA swing is relatively flat up to pulse longitude $176^\circ$. The $\text{RM}(\phi)$ curve in this part of the profile has a U-shaped structure and is higher compared to $\langle \text{RM}(\phi) \rangle$. After longitude $176^\circ$, the PA swing is steeper and there are some $\text{RM}(\phi)$ variations. The highest amplitude variations ($\sim 40$ rad m$^{-2}$) occur around the notch in the PA curve where the gradient changes. Krishnakumar et al. (2017) measured scatter broadening at lower frequencies, however the scattering should be small above 600 MHz. There are some moderately significant $\Delta(V/I)(\phi)$ variations between longitudes $177^\circ$ and $180^\circ$, in a region where Stokes $V$ is changing most rapidly. However, this region is also where $\text{RM}(\phi)$ is varying and we cannot indicate which effect was responsible for the $\text{RM}$ variations (see Section 4.3).

**PSR J1701–3726*.** (Fig. A.16) This pulsar has a complex profile. $L$ is moderately high and Stokes $V$ has a comparable magnitude with regions where it exceeds $L$. The PA swing is steep in the central region of the profile and displays several kinks. The largest $\text{RM}(\phi)$ variations ($\sim 30$ rad m$^{-2}$) occur in the shape of a dip where the PA swing is the steepest. $\text{RM}_{\text{profile}}$ and $\text{RM}_{\text{scatt}}$ are inconsistent, indicating that scattering could be responsible. Significant $\Delta(V/I)(\phi)$ variations appear towards the centre of the profile, with the largest variations around longitude $\sim 184^\circ$, where Stokes $V$ is changing rapidly. The steepest variations in $\text{RM}(\phi)$ occur at an earlier longitude, suggesting that scattering is the main cause for the observed $\text{RM}$ variations.

**PSR J1703–3241*.** (Fig. A.17) For this pulsar, $L$ is moderately high and the PA has a smooth and steep swing, without any OPM jumps. There are two wiggles in the PA swing towards the trailing edge of the profile, and this region
is where significant RM(\(\phi\)) variations (\(\sim 5 \text{ rad m}^{-2}\)) occur. Krishnakumar et al. (2017) estimated a scattering timescale of 0.13 ms at 1GHz, which is low. If the observed RM variations were caused by scattering, \(\Delta(V/I)(\phi)\) variations would be expected at most longitudes, as Stokes \(V\) is steeply changing across the entire profile. However, \(\Delta(V/I)\) only varies towards the trailing half of the profile, where RM(\(\phi\)) is changing the most. This suggests that the observed variations are caused by a magnetospheric origin effect.

**PSR J1722−3207*. (Fig. A.19) The profile of this pulsar has two components: a strong leading one and a weaker and wider trailing one. \(L\) is relatively low, peaking in the leading edge of the profile. The PA swing and RM(\(\phi\)) curve remain flat until pulse longitude 181°. After this longitude, the PA gradient becomes steep and a dip in the shape of the apparent RM(\(\phi\)) variations can be seen, followed by an upward deviation. The amplitude of the overall variations is \(\sim 40 \text{ rad m}^{-2}\). The \(\Delta(V/I)(\phi)\) variations do not coincide with where the largest RM(\(\phi\)) variations occur. The only significant deviations can be seen around longitude 186°, where Stokes \(V\) is changing the most, indicating that scattering is the likely cause for the apparent RM variations. Krishnakumar et al. (2017) estimated a scattering timescale of 0.3 ms at 1 GHz.

**PSR J1731−4744*. (Fig. A.19) This pulsar has a complex profile, with the central component being the weakest. \(L\) is generally low (\(\sim 20\%\)) and the PA swing has a complex shape: it is flat until pulse longitude 182°, followed by a steep region and several kinks and a dip around longitude 187°. The RM(\(\phi\)) curve shows significant variations across the whole profile, with the highest apparent variations (\(\sim 20 \text{ rad m}^{-2}\)) occurring coincident with the dip in the PA curve. There are no significant \(\Delta(V/I)(\phi)\) variations across the profile, since Stokes \(V\) is very low, hence the origin of the RM variations cannot be determined.

**PSR J1745−3040.** (Fig. A.21) This pulsar has a three component profile with a moderately high \(L\). The PA swing is relatively flat and it is broken by two OPM jumps, at pulse longitudes 168° and 187°, and has a bump towards the centre of the profile. Noutsos et al. (2009) classified this pulsar as showing high RM(\(\phi\)) variations, with a downwards gradient change in the central region of the profile of the order \(\sim 20 \text{ rad m}^{-2}\), and no apparent variations in the leading component of the pulse. In our observation, the RM(\(\phi\)) curve is very different. In the leading part of the profile, the statistical uncertainties on the RM values are high, consistent with \(\langle \text{RM(\(\phi\))} \rangle\). Towards the centre of the profile, we see two bumps in the RM(\(\phi\)) curve, right before and after the bump in the PA swing. There is no obvious gradient. This suggests the RM(\(\phi\)) curve is potentially time variable. Krishnakumar et al. (2017) observed scatter broadening at lower frequencies for
this pulsar and estimated a timescale of 0.06 ms at 1 GHz, which is relatively low. The largest $\Delta(V/I)(\phi)$ variations occur at longitude $\sim 173^\circ$, which is not where $V$ changes most rapidly, suggesting a magnetospheric origin for the $\text{RM}(\phi)$ variations. If magnetospheric effects are the cause of the time variability, one might expect the profiles to change as well (a similar argument applies to changes in scattering). This is not obvious from the observations. It should be noted that a change in frequency dependence (causing $\text{RM}(\phi)$ variations) does not imply a noticeable change in frequency average (profile shape).

**PSR J1751–4657*. (Fig. A.21) This pulsar has a double component profile, with a stronger leading component. $L$ is low ($\sim 20\%$) and Stokes $V$ is most intense in the leading peak of the profile. The PA swing is relatively steep across the entire profile with a kink, which coincides with the peak in Stokes $V$, and the minimum in $L$. This is also where the highest variations in $\text{RM}(\phi)$ occur ($\sim 20 \text{ rad m}^{-2}$). At all other longitudes, the $\text{RM}(\phi)$ curve remains flat. The large systematic uncertainties indicate that the $\text{RM}(\phi)$ variations are only moderately significant. If the pulsar was affected by scattering, $\Delta(V/I)(\phi)$ variations are expected to occur in the centre of the profile, where Stokes $V$ is changing, especially around longitude $\sim 178^\circ$, where the most rapid changes happen. Moderately significant $\Delta(V/I)(\phi)$ variations are observed between pulse longitudes $180^\circ$ and $183^\circ$. It is unclear as to the origin of the $\text{RM}$ variations.

**PSR J1752–2806*. This pulsar has very low $L$ and a PA swing which is relatively shallow, but with an OPM jump at pulse longitude $178^\circ$ and several steep kinks in the central part of the profile. Significant $\text{RM}(\phi)$ variations can be seen before the OPM jump. In the centre of the profile, the systematic uncertainties on $\text{RM}(\phi)$ are higher making these variations only moderately significant ($\sim 80 \text{ rad m}^{-2}$). The largest $\Delta(V/I)(\phi)$ variations coincide with where Stokes $V$ changes most rapidly, but do not occur where the largest $\text{RM}(\phi)$ variations are seen. This suggests that the $\text{RM}$ variations are caused scattering.

**PSR J1807–0847*. (Fig. A.21) The profile of this pulsar has several components, with the central one the strongest. $L$ is low ($\sim 20\%$) and there are two longitudes where it is minimal, coincident with the OPM jumps in the PA curve. The PA swing is shallow except for several kinks under the central component. This pulsar was classified by Noutsos et al. (2009) as a low varying $\text{RM}(\phi)$ pulsar with similar looking $\text{RM}(\phi)$ curve to ours. Most apparent variations can be seen where the PA swing displays wiggles starting at longitude $\sim 178^\circ$. The statistical uncertainties on $\text{RM}(\phi)$ are large, hence these apparent variations are only moderately significant. Krishnakumar et al. (2017) estimated a scattering timescale of 0.3 ms at 1 GHz, which is small. Large $\Delta(V/I)(\phi)$ variations occur across the
whole profile, and they do not all coincide with Stokes $V$ changing steeply. This indicates that the RM variations are unlikely to be entirely because of scattering.

**PSR J1817–3618**. (Fig. A.22) The pulsar has two components, as well as a long tail. $L$ is relatively low, with a drop to zero at the OPM jump in the PA swing. The PA gradient becomes steep after the OPM jump, and this is where an upward deviation of the RM($\phi$) curve occurs ($\sim 10$ rad m$^{-2}$). If the pulsar was affected by scattering, the largest $\Delta(V/I)(\phi)$ variations should be in the centre of the profile, where Stokes $V$ is changing most. No significant variations are detected, so without detailed modelling we cannot comment further on the origin of the RM variations.

**PSR J1820–0427**. (Fig. A.22) The profile consists of multiple blended components, with the central one having the highest amplitude. As discussed by Johnston et al. (2007), at lower frequencies an OPM jump can be seen in the PA swing towards the leading edge of the profile around pulse longitude 178°, however at our observing frequency the jump is less than 90° and $L$ does not completely disappear. At this longitude we see the highest variations in RM($\phi$) (20 rad m$^{-2}$), in the shape of a dip. This coincides with the largest $\Delta(V/I)(\phi)$ variations, and where Stokes $V$ is changing the most. For this pulsar, everything is consistent with scattering being the cause. However, since the rapid Stokes $V$ and PA changes coincide, magnetospheric effects cannot be ruled out (see Section 4.3).

**PSR J1824–1945**. (Fig. A.23) The profile of this pulsar has a strong central component and a weaker leading component. The PA swing is relatively flat and it is broken by two OPM jumps at pulse longitudes 177° and 180°, which is where the largest RM($\phi$) variations occur, with the largest variations at the second OPM jump ($\sim 35$ rad m$^{-2}$). At the pulse longitudes where significant $\Delta(V/I)(\phi)$ variations occur, Stokes $V$ changes steeply. This suggests that scattering could be the cause for the observed variations. Several authors (e.g. Löhmer et al. 2004; Weltevrede et al. 2007) indeed reported finding scatter broadening at lower frequencies for this pulsar.

**PSR J1848–0123**. (Fig. A.25) The profile of this pulsar consists of multiple components. $L$ is very low, and rapid steep changes are observed in the shape of the PA swing. RM$_{\text{profile}}$ and RM$_{\text{scatt}}$ are inconsistent, indicating that this pulsar could have been affected by interstellar scattering. Lewandowski et al. (2015a) did not detect any scatter broadening at higher frequencies, hence could not predict a scattering timescale at 1 GHz. The statistical uncertainties on the RM($\phi$) values are high, especially towards the trailing part of the profile. The RM($\phi$) curve is flat, with the exception of some significant deviations around the OPM
jumps and near a very steep part of the PA swing (∼ 40 rad m⁻²). At a pulse longitude of 179° the largest Δ(V/I)(φ) variations occur, coincident with the largest changes in Stokes V. Since this coincides with where the RM(φ) variations are observed, we cannot distinguish the effect responsible for the RM variations (see Section 4.3).

**PSR J1900–2600**. (Fig. A.25) This pulsar has a multi-component profile with moderately high L and Stokes V. The PA swing is steep and it is broken by a jump around pulse longitude 171°. This jump is less than 90° and L does not completely disappear. After the jump, the slope of the PA swing changes sign, which is different from a typical OPM jump where the slope is conserved. The largest variations in RM(φ) occur at the quasi-OPM jump in the shape of a peak in RM(φ) of ∼ 30 rad m⁻². At a similar longitude the largest Δ(V/I)(φ) variations occur, and the Stokes V is steeply changing. Hence, we cannot distinguish which effect was responsible for the apparent RM variations (see Section 4.3). RM_profile and RM_scatt are inconsistent, indicating that this pulsar could be affected by interstellar scattering. This would confirm findings from other authors (e.g. Pilia et al. 2016; Yao et al. 2017), who found scattering at lower frequencies. Our measurements are consistent with scattering being the dominant cause of RM variations, but magnetospheric effects are also possible.

**PSR J1913–0440**. (Fig. A.25) This pulsar has a profile consisting of three overlapping components. L is low (∼15%) at all observed frequencies (Johnston et al., 2008). The PA swing is steep, with several kinks and one OPM jump situated at a pulse longitude 176°. The RM(φ) curve is generally flat, except a ∼ 30 rad m⁻² deviation where the PA swing is the steepest (∼ 181°). The largest Δ(V/I)(φ) variations occur at an earlier (∼ 178°) and later (∼ 182°) longitude, where Stokes V is changing most rapidly. This suggest that scattering is the reason for the apparent RM variations. Several authors (e.g. Lewandowski et al. 2015b; Noutsos et al. 2015) observed this pulsar to be scattered at low frequencies. Hence it is possible that the observed RM variations were caused by low level scattering.

**PSR J2048–1616**. (Fig. A.26) The profile of this pulsar has three components, with the trailing one being the strongest. The PA swing has an ‘S’-shape and can be fit with the RVM model at multiple frequencies (Johnston et al., 2007). The shape of the apparent variations in RM(φ) is similar to those of the observations from Noutsos et al. (2009). The RM(φ) curve has a dip at pulse longitude 176° of around ∼ 5 rad m⁻², coincident with the steepest region of the PA swing. We see the largest Δ(V/I)(φ) variations where Stokes V changes most rapidly. This indicates that the possible dominant cause for the observed RM variations is interstellar scattering.
4.4.2 Pulsars without significant RM variations

The remaining pulsars, for which $\chi^2_{\text{RM}(\phi)} < 2$, were classified as not showing any significant RM variations. A list is given in Table 4.2. One of these pulsars, PSR J1056–6258 (see Fig. A.7), was classified by Noutsos et al. (2009) as having high RM($\phi$) variations of ~ 100 rad m$^{-2}$, especially away from the centre of the profile. In our observation, the RM($\phi$) curve is relatively flat across the whole profile. There appears to be a small upwards gradient of the entire curve, however given the size of the systematic uncertainty, this effect is not significant. PSR J0134–2937 (Fig. A.1) has a shallow PA swing with two OPM jumps and shows no apparent RM($\phi$) variations. However, around pulse longitude 175°, there are significant $\Delta(V/I)(\phi)$ variations where Stokes $V$ is changing most rapidly. This indicates that the pulsar may be affected by interstellar scattering, but not at a level which is enough to produce RM($\phi$) variations, which is not surprising considering the flat PA swing.

The Vela pulsar, PSR J0835–4510 (Fig. A.4), is very bright, has high $L$ and a steep ‘S’-shaped PA swing without OPM jumps. Noutsos et al. (2009) observed RM($\phi$) variations of ~ 13 rad m$^{-2}$ in their 2004 observation and ~ 6 rad m$^{-2}$ in their 2006 observation. In addition, the authors did not find any non-Faraday behaviour affecting the PA. Although we see statistically significant RM($\phi$) variations, the systematic effects are large and completely dominate the results. There are deviations from the expected $\lambda^2$ dependence of the PA as a function of frequency at all pulse longitudes, but again these are introduced by the large systematic errors. In the centre of the profile the deviations are so large, that the

Table 4.2: A list of pulsars which show no significant phase-resolved RM variations. Pulsars for which the phase-resolved RM profiles have not previously been investigated are marked with an asterisk (*).

<table>
<thead>
<tr>
<th>Pulsar</th>
<th>Pulsar</th>
<th>Pulsar</th>
<th>Pulsar</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0134–2937</td>
<td>J0152–1637*</td>
<td>J0614+2229*</td>
<td>J0630–2834*</td>
</tr>
<tr>
<td>J0729–1836*</td>
<td>J0742–2822</td>
<td>J0745–5353*</td>
<td>J0809–4753*</td>
</tr>
<tr>
<td>J1328–4357*</td>
<td>J1430–6623*</td>
<td>J1522–5829*</td>
<td>J1539–5626*</td>
</tr>
<tr>
<td>J1544–5308*</td>
<td>J1555–3134*</td>
<td>J1557–4258*</td>
<td>J1602–5100*</td>
</tr>
<tr>
<td>J1651–4246*</td>
<td>J1653–3838*</td>
<td>J1705–1906*</td>
<td>J1705–3423*</td>
</tr>
<tr>
<td>J1709–1640*</td>
<td>J1709–4429*</td>
<td>J1717–3425*</td>
<td>J1721–3532*</td>
</tr>
<tr>
<td>J1722–3712*</td>
<td>J1739–2903*</td>
<td>J1740–3015*</td>
<td>J1741–3927*</td>
</tr>
<tr>
<td>J1822–2256*</td>
<td>J1823–3106*</td>
<td>J1825–0935*</td>
<td>J1829–1751*</td>
</tr>
<tr>
<td>J1830–1059*</td>
<td>J1832–0827*</td>
<td>J1845–0743*</td>
<td>J1847–0402*</td>
</tr>
</tbody>
</table>

Notable pulsars include:

- **J0134–2937**: Shallow PA swing with two OPM jumps.
- **J0835–4510**: High RM($\phi$) variations of ~ 100 rad m$^{-2}$.
- **J1056–6258**: High RM($\phi$) variations as classified by Noutsos et al. (2009).
- **J0152–1637**: Significant $\Delta(V/I)(\phi)$ variations.
- **J1306–6617**: Significant $\Delta(V/I)(\phi)$ variations.
- **J1544–5308**: Significant $\Delta(V/I)(\phi)$ variations.
- **J1605–5257**: Significant $\Delta(V/I)(\phi)$ variations.
- **J1651–4246**: Significant $\Delta(V/I)(\phi)$ variations.
- **J1709–1640**: Significant $\Delta(V/I)(\phi)$ variations.
- **J1722–3712**: Significant $\Delta(V/I)(\phi)$ variations.
- **J1822–2256**: Significant $\Delta(V/I)(\phi)$ variations.
values of $\chi^2_{PA(\lambda^2, \phi)}$ greatly exceed few hundreds, and are not displayed in Fig. A.4. Ultimately, the systematic effects prevent us from seeing any significant RM($\phi$) variations.

There are a few other pulsars which do not show RM($\phi$) variations, however significant $\Delta (V/I)(\phi)$ variations occur coincident with the most rapid changes in Stokes $V$, indicating that it is possible that low level scattering is affecting them. These pulsars are PSRs J0630$-$2834 (Fig. A.3), J1157$-$6224 (Fig. A.8), J1602$-$5100 (Fig. A.14), J1605$-$5257 (Fig. A.14) and J2330$-$2005 (Fig. A.26). In addition, for PSR J1741$-$3927 (Fig. A.20), we also see tentative evidence for RM($\phi$) variations where the PA swing is steep. This strongly suggests that our ability to detect RM($\phi$) is S/N limited.

4.5 Discussion

From our sample of 98 pulsars, 78 pulsars had their RM($\phi$) curves determined for the first time. Of the 98 pulsars, 42 showed significant RM($\phi$) variations. This is a similar fraction (9/19) from the much smaller sample of Noutsos et al. (2009). Currently, for the majority of our sample, the statistical errors dominate over the systematic errors. We provided evidence that with increased S/N more examples of pulsars with RM($\phi$) variations would be detected. Noutsos et al. (2009) concluded that interstellar scattering is the dominant cause of the RM($\phi$) variations they observed. We re-examine this conclusion below.

From the results, it is clear that scattering alone is not enough to explain the apparent RM variations. We have identified some clear examples of pulsars for which the RM($\phi$) and $\Delta (V/I)(\phi)$ curves were not consistent with scattering as the cause of the observed apparent RM variations. In the case of the interpulse pulsar, PSR J0908$-$4913 (Fig. A.5), for the MP, we observe that the greatest apparent RM variations occur towards the trailing part of pulse where the PA gradient is the steepest. This is consistent with a picture where scattering is the cause for the observed variations. However, for the IP, in the region where the PA swing is steeper than in the MP, the RM($\phi$) curve is flat. This is inconsistent with scattering. We also expect that if the linear polarisation and Stokes $V$ are affected by scattering, the largest $\Delta (V/I)(\phi)$ variations should occur where Stokes $V$ is changing the most. For the MP, we instead see the largest $\Delta (V/I)(\phi)$ variations coincident with the greatest change in RM($\phi$) rather than Stokes $V$, which varies more at earlier pulse longitudes. This points towards magnetospheric effects as a cause for the apparent RM variations of this pulsar.
4.5. Discussion

Table 4.3: Table summarising the observational results. The classification of whether a pulsar showed significant phase-resolved RM variations or not is displayed in columns 2 and 7, as discussed in Section 4.4. In columns 3 and 8, the number of identified profile components is displayed. The classification of whether the PA swing of a pulsar was steep or shallow is shown in columns 4 and 9. For the 42 pulsars with significant RM($\phi$) variations, columns 5 and 10 display whether the observed variations can be explained by scattering alone, or whether magnetospheric effects play an important role. For the pulsars marked with an asterisk (*), we concluded that it is likely that scattering plays a role in the observed RM($\phi$) variations, besides magnetospheric effects.

<table>
<thead>
<tr>
<th>PSR name</th>
<th>RM var</th>
<th>No$_c$</th>
<th>PA swing</th>
<th>Scatt. enough?</th>
<th>PSR name</th>
<th>RM var</th>
<th>No$_c$</th>
<th>PA swing</th>
<th>Scatt. enough?</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0034-0721</td>
<td>Yes</td>
<td>1</td>
<td>Steep</td>
<td>Ambiguous</td>
<td>J1557-4258</td>
<td>No</td>
<td>3</td>
<td>Steep</td>
<td></td>
</tr>
<tr>
<td>J0134-2937</td>
<td>No</td>
<td>2</td>
<td>Shallow</td>
<td></td>
<td>J1559-4438</td>
<td>Yes</td>
<td>3</td>
<td>Steep</td>
<td>Yes</td>
</tr>
<tr>
<td>J0152-1637</td>
<td>No</td>
<td>2</td>
<td>Shallow</td>
<td></td>
<td>J1602-5100</td>
<td>No</td>
<td>5</td>
<td>Steep</td>
<td></td>
</tr>
<tr>
<td>J0255-5304</td>
<td>Yes</td>
<td>2</td>
<td>Steep</td>
<td>Yes</td>
<td>J1604-4909</td>
<td>Yes</td>
<td>4</td>
<td>Steep</td>
<td>Yes</td>
</tr>
<tr>
<td>J0401-7608</td>
<td>Yes</td>
<td>3</td>
<td>Steep</td>
<td>Ambiguous</td>
<td>J1605-5257</td>
<td>No</td>
<td>5</td>
<td>Steep</td>
<td></td>
</tr>
<tr>
<td>J0452-1759</td>
<td>Yes</td>
<td>3</td>
<td>Steep</td>
<td>Ambiguous</td>
<td>J1633-4453</td>
<td>No</td>
<td>2</td>
<td>Shallow</td>
<td></td>
</tr>
<tr>
<td>J0536-7543</td>
<td>Yes</td>
<td>3</td>
<td>Steep</td>
<td>Ambiguous</td>
<td>J1633-5015</td>
<td>No</td>
<td>3</td>
<td>Shallow</td>
<td></td>
</tr>
<tr>
<td>J0614+2229</td>
<td>No</td>
<td>1</td>
<td>Steep</td>
<td></td>
<td>J1644-4559</td>
<td>Yes</td>
<td>3</td>
<td>Shallow</td>
<td>Ambiguous</td>
</tr>
<tr>
<td>J0630-2834</td>
<td>No</td>
<td>2</td>
<td>Steep</td>
<td></td>
<td>J1646-6831</td>
<td>No</td>
<td>4</td>
<td>Steep</td>
<td></td>
</tr>
<tr>
<td>J0729-1836</td>
<td>No</td>
<td>2</td>
<td>Steep</td>
<td></td>
<td>J1651-4246</td>
<td>No</td>
<td>2</td>
<td>Steep</td>
<td></td>
</tr>
<tr>
<td>J0738-4042</td>
<td>Yes</td>
<td>3</td>
<td>Steep</td>
<td>No</td>
<td>J1651-5222</td>
<td>Yes</td>
<td>3</td>
<td>Steep</td>
<td>Ambiguous</td>
</tr>
<tr>
<td>J0742-2822</td>
<td>No</td>
<td>4</td>
<td>Steep</td>
<td></td>
<td>J1653-3838</td>
<td>No</td>
<td>2</td>
<td>Shallow</td>
<td></td>
</tr>
<tr>
<td>J0745-5353</td>
<td>No</td>
<td>1</td>
<td>Steep</td>
<td></td>
<td>J1701-3726</td>
<td>Yes</td>
<td>3</td>
<td>Steep</td>
<td>Yes</td>
</tr>
<tr>
<td>J0809-4753</td>
<td>No</td>
<td>3</td>
<td>Steep</td>
<td></td>
<td>J1703-3241</td>
<td>Yes</td>
<td>2</td>
<td>Steep</td>
<td>No</td>
</tr>
<tr>
<td>J0820-1350</td>
<td>Yes</td>
<td>2</td>
<td>Steep</td>
<td>No</td>
<td>J1705-1906</td>
<td>No</td>
<td>5</td>
<td>Steep</td>
<td></td>
</tr>
<tr>
<td>J0835-4510</td>
<td>No</td>
<td>3</td>
<td>Steep</td>
<td></td>
<td>J1705-3423</td>
<td>No</td>
<td>1</td>
<td>Shallow</td>
<td></td>
</tr>
<tr>
<td>J0837-4135</td>
<td>Yes</td>
<td>3</td>
<td>Steep</td>
<td>Yes</td>
<td>J1709-1640</td>
<td>No</td>
<td>1</td>
<td>Steep</td>
<td></td>
</tr>
<tr>
<td>J0907-5157</td>
<td>Yes</td>
<td>3</td>
<td>Shallow</td>
<td>No</td>
<td>J1709-4429</td>
<td>No</td>
<td>1</td>
<td>Steep</td>
<td></td>
</tr>
<tr>
<td>J0908-4913</td>
<td>Yes</td>
<td>2</td>
<td>Steep</td>
<td>No</td>
<td>J1717-3425</td>
<td>No</td>
<td>1</td>
<td>Shallow</td>
<td></td>
</tr>
<tr>
<td>J0942-5552</td>
<td>Yes</td>
<td>3</td>
<td>Shallow</td>
<td>Ambiguous</td>
<td>J1721-3532</td>
<td>No</td>
<td>1</td>
<td>Steep</td>
<td></td>
</tr>
<tr>
<td>J1001-5507</td>
<td>Yes</td>
<td>3</td>
<td>Steep</td>
<td>Ambiguous</td>
<td>J1722-3207</td>
<td>Yes</td>
<td>2</td>
<td>Steep</td>
<td>Yes</td>
</tr>
<tr>
<td>PSR name</td>
<td>RM var</td>
<td>No.</td>
<td>PA swing</td>
<td>Scatt. enough?</td>
<td>PSR name</td>
<td>RM var</td>
<td>No.</td>
<td>PA swing</td>
<td>Scatt. enough?</td>
</tr>
<tr>
<td>----------</td>
<td>--------</td>
<td>-----</td>
<td>----------</td>
<td>---------------</td>
<td>----------</td>
<td>--------</td>
<td>-----</td>
<td>----------</td>
<td>---------------</td>
</tr>
<tr>
<td>J1043–6116</td>
<td>No</td>
<td>3</td>
<td>Shallow</td>
<td>J1722–3712</td>
<td>No</td>
<td>2</td>
<td>Steep</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1047–6709</td>
<td>No</td>
<td>2</td>
<td>Shallow</td>
<td>J1731–4744</td>
<td>Yes</td>
<td>4</td>
<td>Steep</td>
<td>Ambiguous</td>
<td></td>
</tr>
<tr>
<td>J1048–5832</td>
<td>No</td>
<td>3</td>
<td>Steep</td>
<td>J1739–2903</td>
<td>No</td>
<td>2</td>
<td>Shallow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1056–6258</td>
<td>No</td>
<td>3</td>
<td>Steep</td>
<td>J1740–3015</td>
<td>No</td>
<td>2</td>
<td>Steep</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1057–5226</td>
<td>Yes</td>
<td>5</td>
<td>Steep</td>
<td>J1741–3927</td>
<td>No</td>
<td>3</td>
<td>Steep</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1136–5525</td>
<td>No</td>
<td>4</td>
<td>Shallow</td>
<td>J1745–3040</td>
<td>Yes</td>
<td>3</td>
<td>Shallow</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>J1146–6030</td>
<td>No</td>
<td>4</td>
<td>Steep</td>
<td>J1751–4657</td>
<td>Yes</td>
<td>2</td>
<td>Steep</td>
<td>Ambiguous</td>
<td></td>
</tr>
<tr>
<td>J1157–6224</td>
<td>No</td>
<td>3</td>
<td>Shallow</td>
<td>J1752–2806</td>
<td>Yes</td>
<td>2</td>
<td>Steep</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>J1243–6423*</td>
<td>Yes</td>
<td>2</td>
<td>Steep</td>
<td>J1807–0847</td>
<td>Yes</td>
<td>4</td>
<td>Shallow</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>J1306–6617</td>
<td>No</td>
<td>2</td>
<td>Steep</td>
<td>J1817–3618</td>
<td>Yes</td>
<td>3</td>
<td>Steep</td>
<td>Ambiguous</td>
<td></td>
</tr>
<tr>
<td>J1326–5859*</td>
<td>Yes</td>
<td>3</td>
<td>Steep</td>
<td>J1820–0427</td>
<td>Yes</td>
<td>3</td>
<td>Steep</td>
<td>Ambiguous</td>
<td></td>
</tr>
<tr>
<td>J1326–6408</td>
<td>No</td>
<td>3</td>
<td>Shallow</td>
<td>J1822–2256</td>
<td>No</td>
<td>1</td>
<td>Shallow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1326–6700</td>
<td>No</td>
<td>3</td>
<td>Steep</td>
<td>J1823–3106</td>
<td>No</td>
<td>1</td>
<td>Steep</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1327–6222</td>
<td>No</td>
<td>2</td>
<td>Steep</td>
<td>J1824–1945</td>
<td>Yes</td>
<td>2</td>
<td>Shallow</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>J1328–4357</td>
<td>No</td>
<td>2</td>
<td>Steep</td>
<td>J1825–0935</td>
<td>No</td>
<td>2</td>
<td>Shallow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1357–62</td>
<td>Yes</td>
<td>3</td>
<td>Steep</td>
<td>J1829–1751</td>
<td>No</td>
<td>3</td>
<td>Shallow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1359–6038</td>
<td>Yes</td>
<td>1</td>
<td>Shallow</td>
<td>J1830–1059</td>
<td>No</td>
<td>2</td>
<td>Shallow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1401–6357</td>
<td>Yes</td>
<td>3</td>
<td>Steep</td>
<td>J1832–0827</td>
<td>No</td>
<td>2</td>
<td>Steep</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1428–5530</td>
<td>Yes</td>
<td>2</td>
<td>Shallow</td>
<td>J1845–0743</td>
<td>No</td>
<td>3</td>
<td>Shallow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1430–6623</td>
<td>No</td>
<td>3</td>
<td>Steep</td>
<td>J1847–0402</td>
<td>No</td>
<td>5</td>
<td>Steep</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1453–6413</td>
<td>Yes</td>
<td>3</td>
<td>Steep</td>
<td>J1848–0123</td>
<td>Yes</td>
<td>3</td>
<td>Steep</td>
<td>Ambiguous</td>
<td></td>
</tr>
<tr>
<td>J1456–6843</td>
<td>Yes</td>
<td>5</td>
<td>Steep</td>
<td>J1852–0635</td>
<td>No</td>
<td>3</td>
<td>Steep</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1512–5759</td>
<td>Yes</td>
<td>1</td>
<td>Steep</td>
<td>J1900–2600</td>
<td>Yes</td>
<td>4</td>
<td>Steep</td>
<td>Ambiguous</td>
<td></td>
</tr>
<tr>
<td>J1522–5829</td>
<td>No</td>
<td>3</td>
<td>Shallow</td>
<td>J1913–0440</td>
<td>Yes</td>
<td>3</td>
<td>Steep</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>J1534–5334</td>
<td>Yes</td>
<td>3</td>
<td>Steep</td>
<td>J1941–2602</td>
<td>No</td>
<td>2</td>
<td>Shallow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1539–5626</td>
<td>No</td>
<td>2</td>
<td>Shallow</td>
<td>J2048–1616</td>
<td>Yes</td>
<td>3</td>
<td>Steep</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>
**Table 4.3: Continued**

<table>
<thead>
<tr>
<th>PSR name</th>
<th>RM var</th>
<th>No.</th>
<th>PA swing</th>
<th>Scatt. enough?</th>
<th>PSR name</th>
<th>RM var</th>
<th>No.</th>
<th>PA swing</th>
<th>Scatt. enough?</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1544–5308</td>
<td>No</td>
<td>3</td>
<td>Shallow</td>
<td></td>
<td>J2330–2005</td>
<td>No</td>
<td>2</td>
<td>Steep</td>
<td></td>
</tr>
<tr>
<td>J1555–3134</td>
<td>No</td>
<td>4</td>
<td>Shallow</td>
<td></td>
<td>J2346–0609</td>
<td>No</td>
<td>2</td>
<td>Steep</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4.4: A list of pulsars for which we discovered that magnetospheric effects were the cause for the observed apparent phase resolved RM variations.

<table>
<thead>
<tr>
<th>J0738-4042</th>
<th>J1359-6038</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0820-1350</td>
<td>J1453-6413</td>
</tr>
<tr>
<td>J0907-5157</td>
<td>J1456-6843</td>
</tr>
<tr>
<td>J1243-6423</td>
<td>J1745-3040</td>
</tr>
<tr>
<td>J1326-5859</td>
<td>J1807-0847</td>
</tr>
</tbody>
</table>

Another good example is PSR J1703–3241 (Fig. A.17). For this pulsar, Stokes $V$ is changing throughout the profile and is sharply varying in the central region. If scattering was the dominant cause for the apparent RM variations, $\Delta (V/I)(\phi)$ variations should occur at almost all pulse longitudes equally. However, large $\Delta (V/I)(\phi)$ variations only occur coincident with the greatest gradient in the RM$(\phi)$ curve. Using similar arguments we also identified magnetospheric effects as a cause for apparent RM variations for twelve pulsars out of 42 pulsars with RM$(\phi)$ variations (see Table 4.4 for a list and Section 4.4.1 for more details). The variations in twelve other pulsars were caused by scattering, with the results for the final 18 pulsars being ambiguous (see Table 4.3).

Noutsos et al. (2009) considered two intrinsic effects of magnetospheric origin which could cause RM$(\phi)$ variations. The first is the superposition of two quasi-orthogonal OPMs with different spectral indices. The authors assumed completely linearly polarised OPMs with a spectral index of $\sim -0.5$, as derived by Smits et al. (2006). Using simulations, Noutsos et al. (2009) concluded that in order to create apparent RM variations of the observed amplitudes, the fractional linear polarisation should remain under 10%, which occurs only rarely in either their sample or ours. Hence, it was deemed unlikely that this effect could produce apparent RM variations on a large scale.

The second intrinsic effect considered is generalised Faraday rotation. Based on theory discussed in Kennett & Melrose (1998), both linear and circular polarisation are expected to be frequency dependent. Hence, one can take a correlation between the RM$(\phi)$ and $\Delta (V/I)(\phi)$ curves as evidence for generalised Faraday rotation. Noutsos et al. (2009) did not observe, based on a limited sample of five pulsars, any obvious correlations and concluded that this effect is not able to produce the observed RM variations on a large scale. However, in our sample these correlations appear to be observed for many of our pulsars (based on inspecting the curves, see Section 4.4.1), hence the lack of correlation appears as an exception from the general rule. One of these pulsars is J1243–6423, for which Noutsos et al. (2009) did not find a correlation, yet in our data clearly reveals a correlation between the region of greatest RM$(\phi)$ change and greatest
4.5. Discussion

$\Delta(V/I)(\phi)$ change, but it occurs at a pulse longitude where Noutsos et al. (2009) did not have significant data points (see Section 4.4.1 and Fig. A.8). Although these correlations are common, we note that this does not imply generalised Faraday rotation must be operating in the magnetosphere of pulsars. This is because also the presence of scattering will introduce a frequency dependence in both linear and circular polarisation, and as a consequence, for both generalised Faraday rotation and scattering one expects a correlation between the $\text{RM}(\phi)$ and $\Delta(V/I)(\phi)$ curves.

Although there is now good evidence that scattering is not the only effect causing apparent RM variations, we note that without detailed simulations for each pulsar, one cannot be sure on a case by case basis which effect is dominant. However, additional evidence for the importance of magnetospheric effects can be found by using results drawn from the sample as a whole.

Noutsos et al. (2009) supported the idea that the $\text{RM}(\phi)$ variations we observe are caused by interstellar scattering, given that they observed the largest RM variations coincident with the steepest gradients of the PA swing. Dai et al. (2015) also noted this coincidence in their millisecond pulsar sample. We tried to verify whether a similar trends exists in our sample. By inspection, we classified a PA swing as steep if we identified a region of the swing which had a gradient larger than $\sim 4$ deg/deg$^4$. This classification can be found in Table 4.3. The trend was confirmed, considering that out of the 42 pulsars which were classified as showing phase-resolved RM variations, 34 of these have a steep PA curve and only 8 of the pulsars display a shallow PA curve. In contrast, for the 56 pulsars classified as not showing apparent RM(\phi) variations, 33 had a steep PA swing and 23 had a shallow PA swing. However, it is not correct that this implies that scattering is the primary cause for RM variations. If effects intrinsic to the pulsar magnetosphere distort the PA as function of both frequency and pulse longitude, then we would also expect the greatest variations in RM to occur near the steepest part of the PA swing.

If scattering was the dominant cause for most cases of RM(\phi) variations, we expect that the pulsars which show apparent RM variations to be high-DM pulsars. This is because pulsars with higher DM are more affected by interstellar scattering (e.g. Bhat et al. 2004; Geyer et al. 2017) (see Section 1.2.2). Noutsos et al. (2009) observed a weak correlation, since the two strongest RM varying pulsars from their sample were also the highest DM pulsars. In Fig. 4.4, a DM histogram is displayed for pulsars showing (42 pulsars) and not showing RM variations (56 pulsars).

---

$^4$Scattering will flatten the observed PA curve (e.g. Karastergiou, 2009). However, since most pulsars from our sample are not heavily scattered, this effect will be small.
Figure 4.4: DM distributions. The pulsars with apparent RM variations are represented with the clear hatched distribution, while the pulsars without apparent RM variations are represented in grey.

pulsars. A Kolmogorov–Smirnov (KS) test shows the DM distributions are very similar, pointing to magnetospheric effects being important.

Similar to Fig. 9 in Noutsos et al. (2009), the amount of observed RM(ϕ) variations of the 42 pulsars as a function of the DM of the pulsar is shown in the top panel of Fig. 4.5. The peak-to-peak amplitude of the apparent RM variations, ΔRM, was obtained by only considering RM(ϕ) values which were situated more than 3σ away from \langle RM(ϕ) \rangle. For the 56 pulsars with no significantly varying RM(ϕ) curves, ΔRM was set to zero. The uncertainties on the ΔRM values were obtained by combining the statistical uncertainties of the two RM(ϕ) values in quadrature. For all pulsars with non-zero measurements of ΔRM, the statistical uncertainties dominated over the expected systematics. The S/N of each pulsar was also represented in the plot, by displaying a symbol with a size proportional to the log_{10}(S_{1400}), where $S_{1400}$ is the mean flux density at 1.4 GHz taken from Johnston & Kerr (2018) in Fig. 4.5.

From the top plot in Fig. 4.5, there is no correlation between the DM of a pulsar and ΔRM. There are several low-DM pulsars which display comparable magnitude apparent RM variations to the high-DM pulsars. Regardless of including the pulsars with lower flux densities, for which the detection of phase-resolved apparent RM variations is more difficult, we do not observe a correlation. Pulsars for which the variations were caused by magnetospheric effects (blue circles in Fig. 4.5) appear to have in general smaller RM(ϕ) variations compared to the
ones for which scattering was identified as the dominant effect. This suggests that magnetospheric effects are most evident in cases of pulsars with low levels of scattering. If both effects are present, scattering potentially masks the other effect.

The absence of a correlation between DM and the magnitude of the detected apparent RM variations is surprising, given that scattering should theoretically have an effect. We therefore simulate what level of correlation could be expected assuming scattering is the main reason for the apparent RM variations. We used a distribution between measured scattering timescales, $\tau_{\text{scatt}}$, and DM. Measurements from Bhat et al. (2004) were supplemented by more recent measurements, in order to quantify the range of expected scattering timescales for a certain DM. The obtained distribution of $\tau_{\text{scatt}}$ versus DM, scaled at a frequency of 1.4 GHz, is shown in Fig. 4.6. Most of the points with a DM $< 200$ pc cm$^{-3}$ were derived from measured values of scintillation bandwidths, $\nu_d$. These correspond to scattering timescales of $C/2\pi\nu_d$, with C being a constant with values between 0.6 and 1.5 (Lambert & Rickett, 1999). These values depend on various assumptions about the spectrum or geometry of the electron density variations. We assume $C = 1$.

Before simulating the expected effects of interstellar scattering on our pulsars, the profile in each frequency channel was replaced by the frequency-averaged profile. This ensured that all RM($\phi$) variations were eliminated, while the shape of the average PA swing remained unaffected. We randomly selected three possible scattering timescales for each DM of every pulsar using the distribution from Fig. 4.6. Scattering was added, as described in the Method section, Section 4.3. Each of the three different scattered versions of each pulsar was analysed as previously described, and the plot of $\Delta$RM versus DM is displayed as the bottom panel of Fig. 4.5.

It is clear from this panel that the expected RM($\phi$) variations are too low compared to what is observed for low, DM $< 200$ pc cm$^{-3}$ pulsars. Furthermore, we were also not able to reproduce the observed amplitude of RM variations for the highest-DM pulsar of our sample (PSR J1512–5759 with DM = 627.47 pc cm$^{-3}$). This was because the expected $\tau_{\text{scatt}}$ for this pulsar was large enough to completely flatten the PA swing and not produce any apparent RM variations, suggesting that this pulsar has an unusually low scatter timescale for its DM. The fact that scattering alone cannot reproduce the amount of apparent RM variations found at the low DM end of the distribution supports the conclusion that additional magnetospheric effects are important, especially for pulsars that have low levels of scattering.

The magnetospheric effects that can cause the PA to be distorted in a frequency
Figure 4.5: The amplitude of phase-resolved apparent RM variations, $\Delta RM$, as a function of their DM. The radius of the symbols is proportional to the $\log_{10}(S_{1400})$ of each pulsar. **Top**: The measured $\Delta RM$ values for the observed 98 pulsars. The red triangles and blue filled circles are pulsars for which scattering or magnetospheric effects are responsible for the RM variations. For the pulsars indicated by the green open circles it could not be distinguished which effect was responsible. **Bottom**: The expected $\Delta RM$ values for the pulsars based on simulations including only the effects of scattering.
4.5. Discussion

Figure 4.6: Measured scattering timescales, $\tau_s$, scaled to 1.4 GHz, as a function of DM. The blue circles are measurements from Bhat et al. (2004), orange circles from Geyer et al. (2017), green circles from Krishnakumar et al. (2017), pink circles from Lewandowski et al. (2015a), grey circles from Nice et al. (2013) and the light green circles from Lyne et al. (2017). Most of the points with a DM < 200 pc cm$^{-3}$ were derived from measured values of scintillation bandwidths. The purple points were taken from Johnston et al. (1998), the red points from Levin et al. (2016) and the brown circles from Keith et al. (2013).

dependent way might well be most prominent in pulsars which show evidence for other complex emission properties. Motivated by this we made a distribution (Fig. 4.7) of the number of profile components of pulsar which show, or not show, significant apparent RM variations (Table 4.3). We counted the number of profile components by visual inspection. It is clear from Fig. 4.7 that pulsars which show RM($\phi$) variations tend to have more complex profiles. Pulsars with single-peaked or double-peaked profiles tend to not display RM variations, suggesting that profile shape complexity and apparent RM variations are related. For scattering to cause apparent RM variations only requires a complex or steep PA-swing. So unless complex profiles have complex PA-swings, scattering alone cannot explain Fig. 4.7. Fig. 4.8 shows a histogram of the classification of a PA swing as either steep or shallow as a function of the number of profile components. There is no evidence for such a correlation, indicating interstellar scattering is not enough to explain the observed apparent RM variations.

In all cases where we observed RM($\phi$) variations, there are significant deviations from the Faraday law expected $\lambda^2$ dependence of the PA as a function of frequency (as shown in the panels where $\lambda_{PA}(\lambda^2,\phi)$ is displayed). This implies that another frequency and pulse longitude dependent effect is present. Furthermore, as expected, we also observe large deviations from a $\lambda^2$ dependence for pulsars
Figure 4.7: A histogram of the number of profile components for pulsars with apparent RM variations (dashed line) and without apparent RM variations (solid black line).

Figure 4.8: A histogram of the number of profile components for pulsars with a shallow PA swing (dashed line) and pulsars with a steep PA swing (solid black line).
with large systematic uncertainties on their RM(\(\phi\)) values (e.g. J0742−2822 and J0835−4510). These findings are different from Noutsos et al. (2009), who did not find any evidence for non-Faraday components, at least for the two pulse longitudes they investigated for PSRs J0835−4510 and J1243−6423. Since our PA uncertainties are an order of magnitude smaller compared to the measurements presented by Noutsos et al. (2009), it is maybe not surprising a different conclusion is reached. We observe similar deviations in the lowest panels of Fig. A.1–Fig. A.26, in Appendix A, for \(\lambda^2_{V/I,\phi}\) in regions where \(\Delta(V/I)(\phi)\) is deviating from zero, indicating that both linear and circular polarisation are often both affected. These findings are as expected, considering that for both scattering (see Fig. 4.9 for an example) and magnetospheric effects, there is no reason to expect a \(\lambda^2\) relation to describe their induced frequency dependence of the PA.

### 4.6 Summary and Conclusions

A large sample of pulsars was analysed for phase-resolved apparent RM variations, RM(\(\phi\)). We used a basic version of the Rotation Measure Synthesis Technique and quantified both statistical uncertainties, using bootstrapping, as well as systematic uncertainties. The way we computed the statistical uncertainties avoided making a-priori assumptions about the underlying signal. The dominant source of systematic uncertainties was identified to be due to the impurities of the
receiver. The RM(ϕ) curves of 78 pulsars which have never been published before are presented in this analysis and 42 pulsars out of our sample of 98 showed significant phase-resolved RM variations. Given sufficient S/N, this fraction will increase, but will ultimately be limited by the systematic uncertainties.

It has been suggested in the literature, that if the largest changes in circular polarisation across the frequency band, Δ(V/I)(ϕ), coincide with RM(ϕ) variations, this can be taken as evidence for generalised Faraday rotation in the pulsar magnetosphere. However, we have argued that scattering is also capable of producing such changes, complicating distinguishing between magnetospheric effects and scattering as the main reason for apparent RM(ϕ) variations. However, we were able in some individual cases to make this distinction. This is different to Noutsos et al. (2009), who concluded based on a smaller sample that all apparent RM variations are consistent with interstellar scattering. We identified magnetospheric effects as a cause for apparent RM(ϕ) variations for a total of 12 out of 42 pulsars with RM(ϕ) variations (see Table 4.4). The variations in 12 pulsars were consistent with scattering, while the results for the final 18 pulsars were ambiguous.

If scattering, which is most prominent in high-DM pulsars, was the dominant cause for phase-resolved apparent RM variations, then the amplitude of apparent RM variations should be correlated with DM. This is not observed. A simulation revealed that if scattering was the dominant cause for apparent RM(ϕ) variations, then these variations should be significantly lower for pulsars with DM ≤ 200 pc cm⁻³. This confirms the conclusion that magnetospheric effects are important, especially for pulsars that have low levels of scattering.

We have pointed out that significant deviations from the expected λ² dependence of the PA as a function of frequency are expected both for interstellar scattering and magnetospheric effects. Although Noutsos et al. (2009) concluded that scattering was the main cause for the observed RM(ϕ) variations, they did not find any evidence for non-Faraday components. We found clear evidence for these expected deviations in our higher S/N data.

We found a correlation between complexity of profiles and whether the pulsars showed RM variations or not, which cannot be explained if scattering is the only cause of the apparent RM variations, considering that in that case only the shape of the PA-swing is important. Pulsars with multiple profile components potentially have more complex emission properties and hence the magnetospheric effects could cause the PA to be distorted with frequency. It has been confirmed that RM(ϕ) variations are associated with complex and steep dependencies of PA
4.6. Summary and Conclusions

with pulse longitude. We found that in general both linear and circular polarisation as a function of frequency are affected by the effect responsible for the RM(\(\phi\)) variations.

All this evidence strongly points towards magnetospheric effects, such as generalised Faraday rotation, as a reason for apparent RM(\(\phi\)) variations in many pulsars. In most cases, the amplitude of these variations is relatively small, with the exception of a few pulsars. PSR J1512\(–\)5759, for which RM(\(\phi\)) variations are \(\sim 80\) rad m\(^{-2}\), has one of the largest amplitude variations from the sample. Even then the impact on the phase-averaged RM is only modest. Therefore, apparent RM(\(\phi\)) variations will not have a great impact on, for example, the strength of the Galactic magnetic field as derived from RM, especially when compared with the other uncertainties involved. Our results imply that the frequency dependence of PA gives a way to probe what is happening to the radiation in the pulsar magnetosphere.
Chapter 5

Polarisation properties of new discoveries from the GMRT High Resolution Southern Sky Survey for pulsars and transients

In this Chapter, we performed an investigation into the average polarisation properties and pulse profile evolution at a wide range of radio frequencies of three out of the ten pulsar discoveries from the GMRT High Resolution Southern Sky Survey: PSRs J0418−4154, J0514−4408 and J2144−5237. The polarisation properties of these pulsars were observed with the Parkes radio telescope, Australia, at a centre frequency of 1369 MHz. Lower frequency total intensity observations were obtained with the GMRT. Analysis of the polarisation properties and profile evolution of these pulsars allowed us to impose constraints on the geometry of the pulsars, as well as to provide measurements of the rotation measure. PSR J0418−4154 was found to be un-polarised at our observing frequency. PSR J2144−5237 is a millisecond pulsar with a wide profile which shows an evolution with observing frequency. It appears to be highly linearly polarised with a position angle curve which has a complex shape. The most interesting pulsar from the sample is PSR J0514−4407, a young pulsar which is detected γ-ray detected and we inferred that the pulsar is an orthogonal rotator. This conclusion was based on the fact that the relative position of the interpulse, separated roughly half a turn from the main pulse in the pulse profile, remains constant as a function of frequency. The alternative explanation for the origin of the main and interpulse would be that it corresponds to two sides of an emission cone for a roughly aligned rotator. The latter would be inconsistent with predictions from
\(\gamma\)-ray models, thereby providing further evidence that this pulsar is an orthogonal rotator. We predict a half-beam opening angle of \(\sim 25^\circ\) is required to explain the observations.

5.1 Introduction

The aim of this Chapter was to investigate the polarisation properties for three out of ten new pulsar discoveries, first presented by Bhattacharyya et al. (2016), from a survey performed with the Giant Metrewave Radio Telescope (GMRT). The GMRT consists of an array of thirty radio antennas, and each of these antennas has a diameter of 45 m. The telescope is spread out over a total area with a diameter of 25 km, making it the largest telescope array at its wavelength. The survey, referred to as the GMRT High Resolution Southern Sky Survey (GHRSS), is a 322 MHz off-Galactic plane survey and it covers the declination range of \(-40^\circ\) to \(-52^\circ\). The first publication from GHRSS, Bhattacharyya et al. (2016), provided details of the survey and reported the first ten pulsars discovered. The work described in this Chapter is also presented as part of the second publication from GHRSS, Bhattacharyya et al. (2019), in which the discovery of three additional new pulsars is reported, PSRs J1239–48, J1516–43 and J1726–52, as well as timing solutions for some of the pulsars from Bhattacharyya et al. (2016): PSRs J0514–4408, J1516–43 and J2144–5237. Timing solutions are models obtained based on monitoring the times of arrival (ToAs) from pulsars for a long period of time, which can be used to predict the arrival times of pulses in the future. These models describe the rotational evolution of the star. Using the timing model obtained from radio observations for PSR J0514–4408 to analyse the Fermi Large Area Telescope (LAT) data, Bhattacharyya et al. (2019) were able to detect \(\gamma\)-ray pulsations from this pulsar. The Fermi Gamma-ray Space Telescope, previously known as GLAST, was launched on the 11th of June 2008 (Abdo et al., 2010, 2013), and is sensitive to \(\gamma\)-ray photons with energies between 20 MeV and 300 GeV.

Unlike radio emission, which is thought to be generated close to the neutron star surface (see Section 1.4), the \(\gamma\)-ray emission is believed to originate from higher altitudes, near the light-cylinder. The two most well known \(\gamma\)-ray models are the ‘outer gap model’ (e.g. Cheng et al. 1986; Romani & Yadigaroglu 1995; Romani 1996; Cheng et al. 2000) or the ‘two pole caustic model’ (e.g. Dyks & Rudak 2003). The latter is a geometrical realisation of the slot-gap model (Muslimov & Harding, 2003). A principle difference between the two classes of
models is that in the outer gap models, the $\gamma$-rays are produced above the null-charge surface or null line $\Omega \cdot B = 0$ (Goldreich & Julian 1969, see Section 1.1). On either side of the null-charge surface, the sign of the net charge density of the relativistic plasma in the magnetosphere will be opposite, and at the null line the net charge density is zero (see Section 1.4). In the outer gap model, the emission originates between the null-charge surface and the light-cylinder (grey shaded region in Fig. 5.1). In the two pole caustic model, the emission is confined to a region indicated by the two dashed lines (hatched region in Fig. 5.1). Modelling of the $\gamma$-ray emission (Watters et al., 2009; Romani & Watters, 2010) revealed that both models can reproduce observed $\gamma$-ray profiles and they suggest that many $\gamma$-ray emitters should be orthogonal rotators (the angle between the rotation axis and the magnetic axis, $\alpha$, is close to 90°).

The polarisation observations for the three pulsars discussed here were performed with the Parkes radio telescope at 1369 MHz, as it is known for the excellent performance in pulsar polarisation studies (e.g. Weltevrede & Johnston 2008; Rookyard et al. 2015) and because it is the only other telescope, apart from the GMRT, which covers the declination range of the survey. Investigating the polarisation properties of these pulsars allows us to impose constrains on the geometry of the pulsars, as well as to provide measurements of the Rotation
5.1. Introduction

Figure 5.2: Pulse profiles for PSRs J0418–4154 (left), J0514–4408 (middle) and J2144–5237 (right). On the top of each plot, the integrated profile of each pulsar is shown twice. On the bottom panels, the pulsar signal is shown over time as a function of pulse phase. Where a white box appears, the data has been ignored due to being affected by radio frequency interference (RFI). Images from Bhattacharyya et al. (2016).

Measure (RM) (see Section 1.2.2 and Chapter 4) for these pulsars.

A proposal was submitted to the Parkes radio telescope to observe the three brightest pulsars from Bhattacharyya et al. (2016), J0418–4154, J0514–4408 and J0702–4956, as well as the millisecond pulsar (MSP) J2144–5237, which is the only MSP discovered in GHRSS. However, due to technical difficulties during the observation, only three pulsars were observed, and hence investigated in this Chapter: PSRs J0418–4154, J0514–4408 and J2144–5237. A summary of their basic properties, as determined using data from GHRSS, can be found in Table 5.1. As seen in the left-hand panel of Fig 5.2, which shows the discovery profile at 322 MHz of PSRs J0418–4154, the pulsar has a profile with a single bright component. Investigating the polarisation properties of this pulsar could reveal information about the geometry of the emitting region. As shown in the middle plot of Fig 5.2, PSR J0514–4408 has a double peaked profile at 322 MHz with a peak-to-peak separation which is more than 180°, indicating that the two peaks might not be the Main Pulse (MP) and Interpulse (IP), in the sense that it is an orthogonal rotator where each peak originates from a different magnetic pole. Rather, the peaks might originate from a single wide beam from an almost aligned rotator with a small $\alpha$. As discussed earlier, Bhattacharyya et al. (2019) were able to detect that this young pulsar (large $\dot{P}$, see Section 1.1.4) emits in $\gamma$-rays as well as in radio. If the pulsar had a low inclination angle $\alpha$ (i.e. the two
observed profile peaks originated from the edges of a wide beam of emission), it would be surprising, since models predict that more orthogonal rotators should be easier to detect in $\gamma$-rays (Watters et al., 2009). Looking at at the profile evolution at higher frequencies, as well as the polarimetric profile, allows us to put more constrains on the geometry of this pulsar, and to establish the geometry is not inconsistent with $\gamma$-ray models. PSR J2144–5237 is a MSP with a wide profile with multiple components at 322 MHz, extending over the entire pulse phase (right-hand plot of Fig. 5.2), which is situated in a binary system with another object which has an upper-limit on the mass of $0.18M_\odot$ ($M_\odot$ represents the mass of the Sun). The period in which the binary system completes one revolution is 10.5 days. If the PA swing of this MSP would be RVM-like (see Section 1.6), studying the polarisation curve of such a wide profile would allow us to infer more about its geometry. In a study of the polarimetry of 24 MSPs at 1.4 GHz, Xilouris et al. (1998) concluded that the PA swings of MSPs are generally flatter compared to those of normal non-recycled pulsars. However, in a recent study by Dai et al. (2015), the polarisation properties of 24 MSPs were investigated at 730, 1400 and 3100 MHz and the authors reported that the PA swings of several MSPs had very complex non-RVM like swings. Nevertheless, Dai et al. (2015) observed that at higher frequencies the PA swings of MSPs are typically more RVM like compared to lower frequencies.

### 5.2 The geometry of radio beams

As discussed in more detail in Section 1.6, the observed PA of linear polarisation is closely related to the orientation of the magnetic field relative to the observer and is described by the RVM model (Radhakrishnan & Cooke, 1969; Komesaroff, 1970). The radio emission is thought to originate from a beam centred on the magnetic axis, defined by the last open magnetic field lines (see Fig. 1.1), at a certain emission height $h_{em}$ above the neutron star surface. A schematic diagram of a pulsar with its beam of emission is shown in the top panel of Fig 5.3. Several

<table>
<thead>
<tr>
<th>PSR name</th>
<th>Period (sec)</th>
<th>DM (pc cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0418–4154</td>
<td>0.75711887132(6)$^1$</td>
<td>24.54(8)$^1$</td>
</tr>
<tr>
<td>J0514–4408</td>
<td>0.320270822408985(4)$^2$</td>
<td>15.122(6)$^2$</td>
</tr>
<tr>
<td>J2144–5237</td>
<td>0.00504145377851813(2)$^2$</td>
<td>19.5465(2)$^2$</td>
</tr>
</tbody>
</table>

**Table 5.1:** A table summarising the parameters of three newly discovered pulsars from GHRSS. **References:** (1) Bhattacharyya et al. (2016); (2) Bhattacharyya et al. (2019).
5.2. The geometry of radio beams

Figure 5.3: Schematic diagrams showing the geometry of the radio beam of a pulsar.
important angles when defining the geometry of a pulsar are shown: the angle between the rotation axis and the magnetic axis $\alpha$, also referred to as the magnetic inclination angle; the impact parameter $\beta$, which is the angle between the magnetic axis and the line of sight at closest approach; and the half-opening angle of the radio beam $\rho$. Since the radio emission is produced on open magnetic field lines, the observed radio beam is confined by tangential surface to the last open field lines at the height where emission originates, $h_{\text{em}}$. Thus, for a dipolar magnetic field,

$$\rho = \theta_{\text{em}} + \arctan\left(\frac{\tan(\theta_{\text{em}})}{2}\right),$$  \hspace{1cm} (5.1)

where $\theta_{\text{em}}$ is the polar angle (relative to the magnetic axis) of a point on the last open field line at the emission height (e.g. Gangadhara & Gupta 2001). A schematic diagram which displays the difference between $\theta_{\text{em}}$ and $\rho$ is shown on the bottom of Fig. 5.3. $\theta_{\text{em}}$ can be expressed as

$$\theta_{\text{em}} = \arcsin\left(\sqrt{\frac{2\pi h_{\text{em}}}{Pc}}\right),$$  \hspace{1cm} (5.2)

where $P$ is the period of the pulsar and $c$ is the speed of light (Gangadhara & Gupta 2001). As shown in the top plot of Fig 5.3, if a pulsar is observed from Earth our line of sight (LOS) will cut through the radio beam of the pulsar at a certain angle with respect to the centre of the beam i.e. the magnetic axis (the impact angle $\beta$). Generally, $\beta$ is defined to be positive if the LOS cuts the beam (the cut through the beam line of sight and the rotation axis are on either side of the magnetic axis $B$ when the pulsar beam points to Earth), as shown in Fig 5.3 (Lyne & Manchester, 1988). The observed width of the pulse $W$, measured in rotational phase, (see Section 1.5) is related to $\rho$ and the geometry of the pulsar as

$$\sin(W/4)^2 = \frac{\sin(\rho/2)^2 - \sin(\beta/2)^2}{\sin(\alpha)\sin(\alpha + \beta)},$$  \hspace{1cm} (5.3)

(e.g. Gil et al. 1984; Kramer et al. 1998). It is important to note that $W$ can be larger than the expected $2\rho$, because of the curved path of the LOS through the beam.

Due to the wide variety of integrated pulse profiles observed (see Section 1.5), Komesaroff (1970) were the first to propose that the radio beam is not fully illuminated and has a shape of a hollow cone. Backer (1976) extended this model by suggesting the beam also has a central emitting component, later referred to as a core component by Rankin (1983). Rankin (1983) defined two types of
profile components: the core components, originating in the central beam component, and cone component which arise from the hollow cone (core-cone emission model). Other authors (e.g. Oster & Sieber 1976; Rankin 1993; Gil et al. 1993) extended this model further, for example suggesting a nested hollow cone model (Rankin, 1993). Lyne & Manchester (1988) suggested an alternative model to the core-cone model, in which discrete emission regions are randomly distributed across the radio beam, and other authors supported this idea (e.g. Han & Manchester 2001). A variety of other beam shapes have also been suggested (e.g. Weisberg & Taylor 2002; Dyks & Harding 2004; Karastergiou & Johnston 2007), including the fan-beam model (Dyks et al., 2010; Wang et al., 2014; Teixeira et al., 2016). In this model, the radio emission is concentrated in fan-beam like structures across the radio beam.

5.3 Observations

The polarimetric observations of the newly discovered GHRSS pulsars were performed on the 10th of September 2017 with the Parkes radio telescope. We used the central beam of the multibeam receiver (Staveley-Smith et al., 1996) and the PDFB4 back-end at a central frequency of 1369 MHz and a bandwidth of 256 MHz. More details about the receiver and the back-end used in this observation can be found in Manchester et al. (2013). The receiver (a linear feed) consists of two linear, perpendicular dipoles which receive the orthogonal components of the incoming electric field. These two fields were correlated to produce the four Stokes parameters. The receiver is equipped with a noise diode which injects a pulsed polarised signal at a 45° angle between the two dipoles, allowing us to calibrate the differential phase and the gain (see Section 1.2.3 for more details). In order to calibrate for the leakage between the dipoles, a polarimetric calibration model (van Straten, 2004) has been applied to the data, as derived for the Parkes Pulsar Timing Array project (Manchester et al., 2013). For additional details about the methodology we refer to Weltevrede & Johnston (2008) and Section 1.2.

PSR J0418+4154 was observed for 3599 sec, PSR J0514+4408 for 13499 sec and PSR J2144+5237 for 12240 sec. For each pulsar, the observation was written out in continuous stretches of data (sub-integrations) which were obtained by adding together (folded) individual pulses to increase the S/N. The length of a sub-integration was 30 sec. The second half of each observation was obtained after rotating the feed by 90°, allowing any asymmetries in the performance of each dipole to effectively cancel out. An 120 sec calibration observation with the
noise diode enabled was performed before the first half and after the second half of the observation. Each half was calibrated using its corresponding polarisation calibration observation. The two halves were averaged over the sub-integrations and then added together to form the final integrated polarised profiles. The tools which were used to calibrate the observations are part PSrchive\(^1\) library and for more details of how these were used, refer back to Section 1.2. In order to produce the polarisation plots in this Chapter we used tool which are part of the PSRSalsa\(^2\) software package (Weltevrede, 2016).

### 5.4 Analysis and discussion of individual pulsars

In this section, we present the polarimetric analysis for each pulsar, as well as discuss potential geometries which can be inferred from the observations.

#### 5.4.1 PSR J0418–4154

The polarised integrated pulse profile of PSR J0418–4154 is displayed in the top left of Fig. 5.4. This single component pulse profile appears to be un-polarised at our observing frequency (as the linear and circular polarisation are consistent with zero). A search for a rotation measure (RM) was performed over an RM range between \(-1,500 \text{ rad m}^{-2}\) and \(1,500 \text{ rad m}^{-2}\) using a method based on the RM synthesis technique, described in more detail by Ilie et al. (2019), and in Chapter 4, however no significant RM was detected, suggesting the lack of linear polarisation is intrinsic rather than because of Faraday rotation. Due to the fact that no significant polarisation was detected for this pulsar, no geometry could be derived.

#### 5.4.2 PSR J0514–4407

For PSR J0514–4407, we measure the RM to be \((17.3 \pm 5.9) \text{ rad m}^{-2}\). For the method we refer to Chapter 4 and Ilie et al. (2019). We can infer some geometrical information about this pulsar by looking at the frequency evolution of the intensity profile, displayed in Fig. 5.5. The profiles at 322, 650 and 1369 MHz were aligned using the leftmost component of the MP, so that this feature was always at 0.2 phase. The observations at 322 and 650 MHz were taken with the GMRT telescope and the observation at 1369 MHz was obtained with the Parkes

\(^1\)https://http://psrchive.sourceforge.net/
\(^2\)https://github.com/weltevrede/psrsalsa
5.4. Analysis and discussion of individual pulsars

Figure 5.4: Integrated pulse profiles of PSRs J0418–4154 (top left), J0514–4407 (top right) and J2144–5237 (bottom). In the top panel, the black solid line represents Stokes $I$, the red line represents the linear polarisation while the green line represents the circular polarisation. The second panel shows only significant detections of the average position angle (PA) if the linear polarisation (linear polarisation exceeds 2σ).
telescope, as described in Section 5.3. More details on how the GMRT data was acquired can be found in Bhattacharyya et al. (2019). Note there is notch on the left-hand side of the first component of the pulse profile at phase 0.17, which can be seen at all frequencies at the same pulse phase. This indicates that we correctly identified and aligned the same components in the plots.

It is generally assumed that if we observe a MP and an IP separated by half a phase, the pulsar is an orthogonal rotator (the two magnetic poles are on the rotational equator), with the line of sight crossing both poles and what we observe is radiation coming from both magnetic poles. Note that the peak-to-peak separation between the MP and IP at 322 MHz is more than 0.5 phase. Thus, it could be the two sides of a wide beam centred on a magnetic axis situated at a low inclination angle $\alpha$ relative to the rotation axis. The strong indicator of it being an orthogonal rotator, however, is that the separation between the two peaks remains constant as a function of frequency. In general, the emission height is thought to be a function of frequency, which should change the separation between components observed from the same pole (radio-to-frequency mapping RFM; Cordes 1978) (see also equation (5.1) and equation (5.2)). Here we see significant evolution of the shape of the pulse with frequency, suggestive of possible changes in emission height, but the MP-IP separation is unaffected. Another indication of it being an orthogonal rotator would be the absence of significant bridge emission in between the MP and IP at any frequencies. If the MP and IP originated from two sides of the same beam, we would expect to observe some emission in between them, as the line of sight traverses the beam. We do not see any signs of bridge emission present in the top and bottom panels (322 and 1369 MHz), however we do see a bump in between the MP and IP in profile at 650 MHz. However, this observation was severely affected by RFI and the baseline of the profile displayed significant time variation, and therefore cannot be taken as evidence of bridge emission.

As seen in Section 5.2, the observed pulse profile depends on how the line of sight of the observer intersects the emission beam, as well as the structure of the beam. If the emission beam is fully illuminated such that all open field lines generate an equal amount of radio emission, then the line of sight approaches the magnetic axis closest in the middle of the profile. At that pulse longitude the line of sight and the rotation axis lie in a plane referred to as the fiducial plane, which also contains the magnetic axis. The MP of this pulsar looks like a single peaked component at 322 MHz (bottom plot in Fig. 5.5) with weak structure on the trailing edge of the pulse. From Fig. 5.5, we can see that with increasing frequency the structure evolves into two peaks, and hence the beam might be
5.4. Analysis and discussion of individual pulsars

Figure 5.5: The normalised intensity profile of PSR J0514–4407 at various frequencies. The profiles at 322 and 650 MHz were observed with the GMRT, while the profile at 1369 MHz was observed with the Parkes telescope.

wider than initially inferred from the 322 MHz profile and thus the centre of the beam might not correspond to where the first component peaks. This indicates that the fiducial plane crossing could be at a later pulse phase than the peak of the primary component. Furthermore, by looking at the IP we see that the profile is asymmetrical at all observed frequencies, as the leading edge has a slower rise compared to the trailing edge. This might indicate that the fiducial plane crossing is at an earlier pulse phase compared to where the IP peaks, where the centre of the profile is. This would explain the deviation from 0.5 phase difference between the MP and IP when looking at the 322 MHz profile, as should be the case if we see opposite poles of the neutron star.

Therefore, from our multi-frequency observations of this pulsar, displayed in Fig. 5.5, we infer that J0514–4407 is most likely an orthogonal rotator, which is consistent with the fact that γ-rays are observed, since γ-rays are easier to detect for orthogonal rotators (e.g. Watters et al. 2009). Rookyard et al. (2015) obtained a distribution of magnetic inclination angles for 28 γ-ray loud pulsars, and observed an unexpected skewness towards low values of α. This would invalidate the conclusion that γ-ray pulsars have large inclination angles. Despite this skew, a number of high α pulsars are present in their sample, for example PSRs J0908–4913 and J1057–5226, which both have an interpulse. The conclusion that PSR J0514–4407 is an orthogonal rotator is therefore also not at odds with Rookyard et al. (2015).

The integrated polarimetric pulse profile is displayed in Fig. 5.4 (top right). The MP, which peaks at pulse phase 0.2, appears to be completely linearly polarised, with no significant circular polarisation, while the IP is un-polarised. The position angle (PA) swing of the MP is relatively shallow and smooth, without
orthogonal polarisation mode (OPM) jumps. We can measure the steepest gradient of the PA swing by fitting a straight line, and we obtain \((-1.1 \pm 0.1) \text{ deg/deg}\). If PSR 0514–4407 is an orthogonal rotator, as we argue, the closest approach of the line of sight to the magnetic axis should occur somewhere within the MP, and the steepest region of the PA swing (inflection point) should occur in this region as well, as predicted by the RVM (see Section 1.6). Our determined value for the gradient should be considered to be a lower limit, as the steepest part of the PA swing could occur at a later pulse longitude compared to the centre of the intensity profile, potentially beyond the MP thereby making the steepest gradient unobserved. Such a delay could arise if first order relativistic effects are considered, as derived by Blaskiewicz et al. (1991). The authors extended the RVM model by considering the velocity of the relativistic plasma in the region where emission originates. They do not neglect the local co-rotating velocity component resulting in small corrections to where the steepest gradient of the PA swing occurs.

The gradient of the steepest part of the PA-swing, as predicted by the RVM, is 
\[
\sin(\alpha) / \sin(\beta) = (-1.1 \pm 0.1) \quad (\text{Komesaroff, 1970})
\]
In the multi-frequency analysis previously described, we argued that the pulsar is most likely an orthogonal rotator, hence we consider \(\alpha \sim 90^\circ\). Thus, \(\sin(\alpha) \) is close to 1. Furthermore, as discussed before, the value of the steepest gradient is actually a lower limit, i.e it could be a more negative number, thus the equation for the steepest gradient can be written as \(1 / \sin(\beta) < (-1.1 \pm 0.1)\). From this, we can infer that \(\beta > -65^{+9}_{-25} \text{ deg}\).

Since \(\beta\) is the angle between the magnetic axis and the line of sight at closest approach, the beam diameter should be at least twice as big as \(\beta\). Such a large value of \(\beta\) implies that the emission beams of both poles should be very wide (>\(130^{+50}_{-18}\) deg). If we assume the beams to be fully illuminated, it is very hard to explain how a line of sight traversing two very wide emission beams (from both magnetic poles) create such narrow MP and IP. From Fig. 5.5, we can estimate the 10%-pulse widths of the MP and IP as \(W_{\text{MP}} \sim 25^\circ\) and \(W_{\text{IP}} \sim 50^\circ\) (the 10%-pulse width is measured at the point of which the intensity has dropped to 10%). Hence, the beams should be narrower in order to explain the observed pulse widths. If \(\rho\) is smaller, then \(\beta\) should be smaller as well (see Fig. 5.3) and thus the value of the steepest gradient, as predicted by the RVM, should be higher than what appears in the observable part of the PA-swing, which is confined to where there is emission. As stated before, this could be the case if the steepest part of the predicted PA-swing occurs at a later pulse phase compared to the fiducial plane crossing, somewhere outside the observed MP, with a delay of at least 0.05
in rotational phase. A delay between the fiducial plane and the steepest part of the PA swing, $\Delta \phi$, measured in radians, is predicted to be

$$\Delta \phi = \frac{8\pi h_{\text{em}}}{Pc},$$  (5.4)

(Blaskiewicz et al., 1991). This prediction is based on first order relativistic corrections applied to the RVM. In their model, Blaskiewicz et al. (1991) assumed that the magnetic field of the pulsar was dipolar, and that in the closed magnetic field region there was force-free plasma (see Section 1.4). Using the required lower limit on the rotational phase delay in Equation 5.4, gives a lower limit on the emission height as $h_{\text{em}} \sim 1130$ km, which is relatively high compared to other $\gamma$-loud pulsars (Rookyard et al., 2015). From the sample of pulsars presented by Rookyard et al. (2015), only PSR J0659+1414 had a higher emission height compared to our lower limit, indicating that the actual value of $h_{\text{em}}$ is unlikely to be much larger than the limit.

Using our predicted lower limit on $h_{\text{em}}$ in Equation 5.2, and substituting the resulting value of $\theta_{\text{em}}$ in Equation 5.1, we infer a lower limit on the half-opening angle of the beam of $\rho \sim 25^\circ$. This implies that the two emission beams could be at least $50^\circ$ wide, which, in the lower limit, could explain the observed narrow MP and IP. Given the two radio beams of this pulsar are still relatively wide, $\alpha$ must be smaller than $90^\circ$ in order to explain the observed pulse widths.

A possible extension of this project, would be to re-observe this pulsar for a longer period of time, in order to increase the S/N in the integrated pulse profile. This could be interesting because in Fig. 5.4, we see a hint of linear polarisation in the IP (two significant PA points). With increased S/N, we could establish the shape of the PA swing, and measure the gradient of the PA swing for both the MP and the IP. From RVM theory (see Section 1.6), we know that the gradients of the MP and IP are not independent of each other, hence we would be able to put more severe constrains on the geometry of the pulsar.

### 5.4.3 PSR J2144–5237

The integrated polarisation pulse profile of PSR J2144–5237 is displayed in Fig. 5.4 (bottom plot). The profile appears to span across the full rotation and consists of at least five clearly distinguishable components. Such a wide multi-component profile is typically observed for MSPs (e.g. Kramer et al. 1998; Yan et al. 2011; Dai et al. 2015).
The degree of linear polarisation is relatively high for all components, except for the second component, at rotational phase 0.2, which appears to be largely un-polarised. The RM value measured for this pulsar is \((25 \pm 2) \text{ rad m}^{-2}\). The PA swing has a complex behaviour with different gradients and slope signs for different components, making it impossible to fit with the RVM. In the RVM (Section 1.6), the PA swing is determined by the geometry of the pulsar, and the sign of the steepest gradient is determined by the sign of \(\beta\), hence one would not expect to see several different gradients with different signs for each component of the pulse profile. Attempts to fit the RVM model, which included an OPM jump between the third and fourth profile components, were unsuccessful. However, there are no observed OPM jumps visible in the shape of the PA curve. Although in general the polarisation properties of MSPs are similar to those of normal pulsar: high degree of linear polarisation, OPM transitions etc., the PA curves of MSPs are generally shallower compared to normal pulsars and do not fit the RVM very well (e.g. Manchester & Han 2004; Ord et al. 2004; Yan et al. 2011). Dai et al. (2015) managed to fit the RVM model for only some MSPs in their sample using their higher frequency observations. The authors noted that more deviations from the RVM were seen at lower frequencies compared to our observation, and suggested that a reason for this could be that lower frequencies are generated further away from the neutron star surface (RFM). Because of their very small periods the light-cylinder radius of MSPs, \(R_{\text{LC}} = cP/2\pi\) (see Section 1.1) is also very small compared to normal pulsars. This implies that the co-rotating magnetosphere of MSPs are compact, hence the lower frequencies are probably generated close to the light-cylinder where the magnetic field deviates from a dipolar field.

The intensity profile of PSR J2144–5237 at three different frequencies (322, 650 and 1369 MHz) is displayed in Fig. 5.6. The profiles were aligned based on the first (at pulse phase 0.1) and fourth (at pulse phase 0.7) components, which could be clearly identified at all frequencies and their separation did not change as a function of frequency. A slower evolution (compared to normal slower spinning pulsars) of the pulse profile with frequency, especially component separation, is observed in several MSPs, potentially due to their very compact magnetosphere (small light-cylinder radius, see Section 1.1), which implies that the range of emission heights must be smaller. In Fig. 5.6, the most striking evolution with frequency can be seen for the second component, situated at pulse phase 0.2.
5.5 Summary and Conclusions

In this Chapter, we presented the polarisation properties at 1369 MHz of three out of the ten new pulsar discoveries from GHRSS (Bhattacharyya et al., 2016). These results are included in Bhattacharyya et al. (2019).

PSR J0418–4154 is a bright pulsar which was found to be un-polarised at our observing frequency and therefore no RM could be determined.

PSR J0514–4407 is a young pulsar which was found to emit $\gamma$-rays (Bhattacharyya et al., 2019). Based on the 322 MHz observation from GHRSS, it was initially thought to be an aligned rotator, because the separation between the two profile peaks was more than 180°. Using additional 610 MHz observations from GHRSS and the 1369 MHz polarisation observation, we were able to infer that the pulsar is in fact an orthogonal rotator. This conclusion was based on the fact that the separation between the two profile peaks remained constant as a function of frequency (according to RFM, this separation should change if the peaks originate from the same emission beam). The pulsar being an orthogonal rotator is not at odds with the classical $\gamma$-ray models (e.g. Watters et al. 2009), which predict that more orthogonal rotators are easier to detect. Using the polarimetry profile, we were able to find a geometry for the pulsar starting from the assumption of an orthogonal rotator, in which the half-beam opening angle is $\sim 25^\circ$. With such wide beams, the pulsar geometry does not necessarily have to be exactly orthogonal.

PSR J2144–5237 is an MSP with a wide profile. We observe a slow evolution with observing frequency, with the exception of the second profile component, situated at pulse phase 0.2 in Fig. 5.6, which almost disappears at 1369 MHz.
This is the only component which is not polarised in the polarimetry profile from Fig. 5.4. The PA swing shows a complex profile with various slopes, which was not possible to fit with the RVM.
Chapter 6

Conclusions

In this thesis, we have explored many aspects of the polarisation properties of radio pulsars and the connection with propagation effects in the pulsar magnetosphere. Here we present the concluding remarks, including some suggested directions for potential future analysis.

In Chapters 2 and 3, a sample of 32 radio pulsars was studied with the aim to investigate if it is common for orthogonal polarisation modes (OPMs) to switch synchronously with the drifting subpulses observed in total intensity. Prior to this thesis work, there were four pulsars for which this phenomenon was known to occur (Ramachandran et al., 2002; Rankin & Ramachandran, 2003; Edwards, 2004). In Chapter 2, we demonstrated using the $P_3$-folding technique, that for PSR B0031–07 the OPM switching at a single pulse level is synchronous with the drifting subpulses. This is observed for both drift modes (out of a total of three) which are present at our observing frequency of 1369 MHz. PSR B0031–07 is the only pulsar in this group of pulsars which shows drift-mode changes, making it a unique source to study.

An additional 31 pulsars were analysed and discussed in Chapter 3. We found that ten pulsars showed both OPM switching as well as periodic intensity variability. We discovered that eight of these pulsars showed OPM switches synchronously modulated with drifting subpulses. For one of these eight pulsars, PSR J0820–1350, this phenomenon was only known at a lower observing frequency (Edwards, 2004). The remaining two pulsars, PSRs J1932+1059 and J2048–1616, did not show a clear connection between OPM switches and drifting subpulses. Nevertheless, a connection was still established between both the linear and circular polarisation and the periodicity of drifting subpulses. For these two pulsars, a decrease in the fractional linear polarisation was observed in between intensity driftbands, suggestive of depolarisation caused by the less common OPM preferentially occurring in that part of the modulation cycle. The
results from Chapters 2 and 3 therefore suggest that somewhere between $\sim 80\%$ and 100% of all pulsars which show OPM switches and drifting subpulses have a demonstrable connection between the two phenomena. Hence, despite this phenomenon being known for only a handful of sources, the connection between PA switches and drifting subpulses appears to be very common.

For $\sim 20\%$ of the pulsars no connection was established, despite both OPM switches and drifting subpulses were present. Additional analysis techniques might be required to reveal the connection. In the present analysis, the Stokes parameters were $P_3$-folded before the PA was computed in order to have sensitivity for weak polarisation. However, if one of the OPMs is very rare, it is likely to not show up after $P_3$-folding since it will not dominate at any point during the modulation cycle. In those cases folding the Stokes data before computing the PA might in fact be undesirable.

There were two pulsars in our sample which showed OPM mixture, however no drifting subpulses were detected. Nonetheless, these pulsars show non-random, although not periodic, intensity modulation. Even without strictly periodic modulation present, we establish a link between intensity variability and changes in the polarisation. Since drifting subpulses result in intensity variations as well, the same physics might explain the connection between synchronously modulated polarisation and intensity.

From Chapters 2 and 3 it is now firmly established that the connection between OPM switches at a single pulse level and organised variability seen in total intensity is a common phenomenon. This could either be part of the emission mechanism itself such that different OPMs are periodically generated, but more likely propagation effects in the magnetosphere with constantly changing properties play a role. Periodic changes in the magnetospheric properties can be expected if there is a rotating carousel with pair creation sites present in the magnetosphere (Ruderman & Sutherland, 1975). Rankin & Ramachandran (2003) suggested the carousel model can be extended in order to accommodate these observations. In the extension of the model, the circulating system of sparks in the acceleration region produces radiation in both OPMs. Propagation effects cause a spatial separation between the two polarisation modes such that two images of the same carousel configuration are produced, each image corresponding to one of the two OPMs. The two images should be offset in the azimuthal direction, as well as be magnified differently away from the magnetic axis, in order to have different OPMs dominating in different parts in the profile and at different parts of the modulation cycle. A likely mechanism for generating the two images is birefringence in the pulsar magnetosphere (Rankin et al., 2006), where the
OPMs correspond to the two plasma modes (the O and X modes) in the magnetised plasma. Only the O mode is thought to experience refraction, hence it gets spatially separated from the X-mode image.

In Chapter 2, we show that the above picture must be more complicated for PSR B0031–07. This pulsar is different from the rest of the sample, as the drift-bands observed in total intensity are dominated by different OPMs in different halves of the profile. This is accompanied by a slight change of the slope of the intensity driftband in the middle of the profile. This suggests that if an inherently symmetrical carousel configuration is responsible for the observed periodicities, the magnetospheric propagation effects should be asymmetric. It also suggests that mode-conversion between the O and X-mode might play an important role in this pulsar.

Furthermore, for PSR B0031–07 it was found that the ellipticity evolves asymmetrically with time during the modulation cycle, such that the ellipticity is monotonically changing from pulse to pulse across driftbands. This points again towards some form of symmetry breaking. Moreover, it suggests that the linear polarisation modes are coupled to circular polarisation. One way to couple linear and circular polarisation would be via Generalised Faraday rotation (Kennett & Melrose, 1998), which can be invoked to explain more results in this thesis as mentioned below.

None of the other pulsars in Chapter 3 show asymmetric evolution of $\chi$ as a function of the modulation cycle or a similar inversion in the PA of single pulses as for PSR B0031–07. However, it should be noted that all pulsars which showed OPM switches synchronous with drifting subpulses also show asymmetric polarisation features in the $P_3$-folds with respect to the centre of the profile. So some source of asymmetry is in general required to explain the results.

For two pulsars from the survey (PSRs J1453–6413 and J1921+2153), the PA of the OPM itself appears to be changing periodically. Moreover, in these cases clearer periodic changes were observed in ellipticity. Both a rotation in PA and a change in circular polarisation could be the result of Generalised Faraday rotation. So although our study focused on discrete switches in OPMs which are linked to drifting subpulses, it has become evident that the link between polarisation and drifting subpulses can be more subtle, and that circular polarisation is involved in many cases. There is therefore scope to survey a sample for pulsars to quantify these effects in more detail, some of which can be done with the available data. The sample studied could also be more unbiased in the sense that the pulsars do not have to be selected based on evidence being present for OPM switches.
In the process of analysing the pulsars in Chapter 3, we discovered drifting sub-pulses for five pulsars (J1110–5637, J1453–6413, J1539–5626, J1605–5257 and J1651–5222), and periodic amplitude modulation was discovered for three other pulsars (J1048–5832, J1745–3040 and J1817–3618). Furthermore, we discovered interpole communication for PSR J1932+1059, which shows drifting subpulses with periodicities which are evidently regulated by a single physical source for both magnetic poles at opposite sides of the star.

The results from Chapters 2 and 3 illustrate that magnetospheric effects have an important impact on the observed single pulse polarisation properties. Chapter 4 demonstrates there are also frequency dependent signatures in the polarised radiation because of magnetospheric propagation effects. When polarised pulsar radiation propagates through the cold magnetised interstellar medium, it is affected by Faraday rotation. This results in a rotation of the position angle (PA) of linear polarisation as a function of frequency, with the constant of proportionality known as the rotation measure (RM). If Faraday rotation is the only source of frequency dependence of the PA, we expect the derived RM to be independent of the rotational phase of the pulsar. Ramachandran et al. (2004) were the first to observe variations in RM of around 30 rad m$^{-2}$ as a function of pulse longitude. Using a sample of 19 pulsars, Noutsos et al. (2009) observed that the largest phase resolved apparent RM variations coincide with the rotational phases where the PA was the steepest, and concluded that interstellar scattering was the dominant cause of apparent RM variations.

In Chapter 4, we performed the largest investigation to date into the origin of phase resolved apparent RM variations in the polarised signals of radio pulsars. This analysis is also presented in Ilie et al. (2019). A large sample of 98 pulsars was analysed at 1.4 GHz with the Parkes radio telescope. Both statistical and systematic uncertainties arising from imperfect polarisation calibration were considered in our RM measurements. The phase resolved RM curves of 78 pulsars which have never been published before are presented in this analysis and 42 pulsars out of our sample of 98 showed significant phase-resolved RM variations.

In the analysis, we showed that both magnetospheric and scattering effects are responsible for the observed apparent RM variations. No correlation was found between the amplitude of apparent RM variations and scatter timescale, and this correlation is not expected to exist if magnetospheric effects are the cause of at least some of the apparent RM variations. A clear correlation between the complexity of the pulse profiles shape and the degree of RM variability is found. This again suggest a magnetospheric process is involved, rather than scattering in the interstellar medium is the only cause of RM variability. In addition to
statistical evidence, we show in Chapter 4 clear examples of individual pulsar observations where magnetospheric effects play an important role in explaining the apparent RM variability.

In Chapter 5, we presented the polarisation properties at 1369 MHz and the frequency dependent profile evolution of three out of the ten new pulsar discoveries from GMRT High Resolution Southern Sky Survey (GHRSS) (Bhattacharyya et al., 2016). These results are published as part of Bhattacharyya et al. (2019). The pulsars analysed were PSRs J0418—4154, J0514—4407 and J2144—5237. The most interesting pulsar from this sample is PSR J0514—4407, a young pulsar which was found to emit $\gamma$-rays (Bhattacharyya et al., 2019). Both the radio polarisation and the pulsed $\gamma$-rays provide constraints on the emission geometry. A 322 MHz GHRSS observation revealed an interpulse: a pulse profile component separated from roughly half a turn from the main profile component. Since the separation between the two profile components is not quite half a turn, the presence of the interpulse was taken as potential evidence of this pulsar being a relatively aligned rotator. However, using additional 610 MHz GMRT observations and the Parkes 1369 MHz observation with polarisation being recorded, we were able to infer that the pulsar is in fact an orthogonal rotator. This conclusion was reached based on the fact that the separation between the two profile components remained roughly constant as a function of frequency. This would be incompatible with an aligned rotator where the profile components arise from single magnetic pole and where the emission height is frequency dependent. Moreover, the picture of the pulsar being an aligned rotator would have been unexpected, since no strong pulsed $\gamma$-rays would be produced by an aligned rotator. By studying the polarisation properties of this pulsar, we were able to place constraints on the viewing geometry and beam configuration of the radio beam. It is deduced that the half-beam opening angle of the radio beam is $\sim 25^\circ$, which is relatively wide for a pulsar. With such a wide beam, the magnetic inclination angle does not necessarily have to be very close to orthogonality. Potentially fitting the $\gamma$-ray pulse shape together with the radio polarisation data would constrain the geometry of the pulsar magnetosphere further, which could help distinguishing between $\gamma$-ray emission models.

It is likely that, with increased signal quality, significant apparent RM variations will be identified in all radio pulsars. Here it is important to deal with polarisation imperfections of the receiver system, which we have showed to already be an important source of apparent RM variability to consider. Furthermore, with better signal quality, there will be more pulsars for which single pulse polarisation studies will be possible, allowing us to potentially constrain emission models
and understand magnetospheric propagation effects better. Moreover, improved signal quality will also allow us to determine the viewing geometry of more pulsars, which is important when linking the observations to the theoretical emission models. The number of pulsars available to study will increase drastically over the next ten years with next generation telescopes, which will have higher sensitivity, such as MeerKAT (e.g. Bailes et al. 2018), the Five hundred meter Aperture Spherical Telescope (FAST; Jiang et al. 2019) and the Square Kilometre Array (SKA; Keane 2018). Hence, the signatures described in this thesis will provide a useful tool to probe the effects of propagation of the radio emission through the magnetosphere of pulsars.
Appendix A

Phase-resolved RM Plots

In this section, we display the resulting phase-resolved RM plots for the 98 pulsars, in Fig. A.1—Fig. A.26. In each Figure, we display four plots. These plots were aligned so that the total intensity peaked at pulse longitude $180^\circ$. For the pulsars which had both a MP and an IP, we aligned them so that the MP peaked at pulse longitude $90^\circ$ the IP peaked at longitude $270^\circ$. In each plot, in the top panel, the solid line denotes Stokes $I$, the dashed line shows $L$ and the dotted line Stokes $V$. The second panel displays the PA, when $L$ exceeded $2\sigma$. The third panel shows the RM($\phi$) curve with the associated statistical uncertainties. The green shaded region represents the $1\sigma$ systematic uncertainty contour region. The horizontal dotted line plotted is $\langle$RM($\phi$)$\rangle$. The fourth panel shows the phase-resolved $\Delta(V/I)$ values with their associated statistical and systematic uncertainties. The bottom panel displays the $\chi^2_{PA(\lambda^2,\phi)}$, represented by the black circles and $\chi^2_{V/I(\nu,\phi)}$, represented by the red crosses. The horizontal line corresponds to a reduced $\chi^2$ of 1.
Figure A.1: Phase-resolved RM plots for PSR J0034–0721, PSR J0134–2937, PSR J0152–1637 and PSR J0255–5304. For more details on what is displayed in the individual panels, see Fig. 4.1.
Figure A.2: Phase-resolved RM plots for PSR J0401–7608, PSR J0452–1759, PSR J0536–7543 and PSR J0614+2229. For more details on what is displayed in the individual panels, see Fig. 4.1.
Figure A.3: Phase-resolved RM plots for PSR J0630–2834, PSR J0729–1836, PSR J0738–4042 and PSR J0742–2822. For more details on what is displayed in the individual panels, see Fig. 4.1.
Appendix A. Phase-resolved RM Plots

FIGURE A.4: Phase-resolved RM plots for PSR J0745–5353, PSR J0809–4753, PSR J0820–1350 and PSR J0835–4510. For more details on what is displayed in the individual panels, see Fig. 4.1.
Figure A.5: Phase-resolved RM plots for PSR J0837–4135, PSR J0907–5157, PSR J0908–4913 (MP) and PSR J0908–4913 (IP). For more details on what is displayed in the individual panels, see Fig. 4.1.
Figure A.6: Phase-resolved RM plots for PSR J0942–5552, PSR J1001–5507, PSR J1043–6116 and PSR J1047–6709. For more details on what is displayed in the individual panels, see Fig. 4.1.
Figure A.7: Phase-resolved RM plots for PSR J1048–5832, PSR J1056–6258, PSR J1057–5226 (MP) and PSR J1057–5226 (IP). For more details on what is displayed in the individual panels, see Fig. 4.1.
Figure A.8: Phase-resolved RM plots for PSR J1136–5525, PSR J1146–6030, PSR J1157–6224 and PSR J1243–6423. For more details on what is displayed in the individual panels, see Fig. 4.1.
Figure A.9: Phase-resolved RM plots for PSR J1306–6617, PSR J1326–5859, PSR J1326–6408 and PSR J1326–6700. For more details on what is displayed in the individual panels, see Fig. 4.1.
Figure A.10: Phase-resolved RM plots for PSR J1327−6222, PSR J1328−4357, PSR J1357−62 and PSR J1359−6038. For more details on what is displayed in the individual panels, see Fig. 4.1.
Appendix A. Phase-resolved RM Plots

Figure A.11: Phase-resolved RM plots for PSR J1401–6357, PSR J1428–5530, PSR J1430–6623 and PSR J1453–6413. For more details on what is displayed in the individual panels, see Fig. 4.1.
Figure A.12: Phase-resolved RM plots for PSR J1456–6843, PSR J1512–5759, PSR J1522–5829 and PSR J1534–5334. For more details on what is displayed in the individual panels, see Fig. 4.1.
FIGURE A.13: Phase-resolved RM plots for PSR J1539–5626, PSR J1544–5308, PSR J1555–3134 and PSR J1557–4258. For more details on what is displayed in the individual panels, see Fig. 4.1.
Appendix A. Phase-resolved RM Plots

Figure A.14: Phase-resolved RM plots for PSR J1559−4438, PSR J1602−5100, PSR J1604−4909 and PSR J1605−5257. For more details on what is displayed in the individual panels, see Fig. 4.1.
Figure A.15: Phase-resolved RM plots for PSR J1633–4453, PSR J1633–5015, PSR J1644–4559 and PSR J1646–6831. For more details on what is displayed in the individual panels, see Fig. 4.1.
Appendix A. Phase-resolved RM Plots

Figure A.16: Phase-resolved RM plots for PSR J1651−4246, PSR J1651−5222, PSR J1653−3838 and PSR J1701−3726. For more details on what is displayed in the individual panels, see Fig. 4.1.
Appendix A. Phase-resolved RM Plots

Figure A.17: Phase-resolved RM plots for PSR J1703–3241, PSR J1705–1906 (MP), PSR J1705–1906 (IP) and PSR J1705–3423. For more details on what is displayed in the individual panels, see Fig. 4.1.
Figure A.18: Phase-resolved RM plots for PSR J1709−1640, PSR J1709−4429, PSR J1717−3425 and PSR J1721−3532. For more details on what is displayed in the individual panels, see Fig. 4.1.
Figure A.19: Phase-resolved RM plots for PSR J1722−3207, PSR J1722−3712 (MP), PSR J1722−3712 (IP) and PSR J1731−4744. For more details on what is displayed in the individual panels, see Fig. 4.1.
FIGURE A.20: Phase-resolved RM plots for PSR J1739–2903 (MP), PSR J1739–2903 (IP), PSR J1740–3015 and PSR J1741–3927. For more details on what is displayed in the individual panels, see Fig. 4.1.
Appendix A. Phase-resolved RM Plots

Figure A.21: Phase-resolved RM plots for PSR J1745–3040, PSR J1751–4657, PSR J1752–2806, and PSR J1807–0847. For more details on what is displayed in the individual panels, see Fig. 4.1.
Appendix A. Phase-resolved RM Plots

Figure A.22: Phase-resolved RM plots for PSR J1817–3618, PSR J1820–0427, PSR J1822–2256 and PSR J1823–3106. For more details on what is displayed in the individual panels, see Fig. 4.1.
Figure A.23: Phase-resolved RM plots for PSR J1824−1945, PSR J1825−0935 (MP), PSR J1825−0935 (IP) and PSR J1829−1751. For more details on what is displayed in the individual panels, see Fig. 4.1.
Appendix A. Phase-resolved RM Plots

Figure A.24: Phase-resolved RM plots for PSR J1830–1059, PSR J1832–0827, PSR J1845–0743 and PSR J1847–0402. For more details on what is displayed in the individual panels, see Fig. 4.1.
Figure A.25: Phase-resolved RM plots for PSR J1848−0123, PSR J1852−0635, PSR J1900−2600 and PSR J1913−0440. For more details on what is displayed in the individual panels, see Fig. 4.1.
Figure A.26: Phase-resolved RM plots for PSR J1941−2602, PSR J2048−1616, PSR J2330−2005 and PSR J2346−0609. For more details on what is displayed in the individual panels, see Fig. 4.1.
Bibliography

Baade W., Zwicky F., 1934, Physical Review, 46, 76
Backer D. C., 1970b, Nature, 228, 42
Backus I., Mitra D., Rankin J. M., 2010, Monthly Notices of the RAS, 404, 30
Bailes M., et al., 2018, arXiv e-prints,
Basu R., Mitra D., 2018, Monthly Notices of the RAS, 475, 5098

Basu R., Mitra D., Melikidze G. I., Skrzypczak A., 2019, Monthly Notices of the RAS, 482, 3757


Beskin V. S., Malyshkin L. M., 1998, Monthly Notices of the RAS, 298, 847


Biggs J. D., 1990, Monthly Notices of the RAS, 246, 341

Biggs J. D., McCulloch P. M., Hamilton P. A., Manchester R. N., 1987, Monthly Notices of the RAS, 228, 119


Burke-Spolaor S., et al., 2012, Monthly Notices of the RAS, 423, 1351

Burn B. J., 1966, Monthly Notices of the RAS, 133, 67


Chen T., 2015, Master's thesis, The University of Manchester


Dai S., et al., 2015, Monthly Notices of the RAS, 449, 3223
Deutsch A. J., 1955, Annales d’Astrophysique, 18, 1
Dyks J., 2017, Monthly Notices of the RAS, 472, 4598
Dyks J., Rudak B., Demorest P., 2010, Monthly Notices of the RAS, 401, 1781


Force M. M., Demorest P., Rankin J. M., 2015, Monthly Notices of the RAS, 453, 4485


Gajjar V., Joshi B. C., Kramer M., 2012, Monthly Notices of the RAS, 424, 1197

Gajjar V., Joshi B. C., Wright G., 2014, Monthly Notices of the RAS, 439, 221


Gangadhara R. T., 1997, Astronomy and Astrophysics, 327, 155


Gil J., Gronkowski P., Rudnicki W., 1984, Astronomy and Astrophysics, 132, 312


Gourgouliatos K. N., Lynden-Bell D., 2019, Monthly Notices of the RAS, 482, 1942


Hamilton P. A., Lyne A. G., 1987, Monthly Notices of the RAS, 224, 1073

Han J. L., Manchester R. N., 2001, Monthly Notices of the RAS, 320, L35

Han J. L., Manchester R. N., Xu R. X., Qiao G. J., 1998, Monthly Notices of the RAS, 300, 373


Hankins T. H., Rickett B. J., 1975, Methods in Computational Physics, 14, 55


Hessels J. W. T., Ransom S. M., Stairs I. H., Freire P. C. C., Kaspi V. M., Camilo F., 2006, Science, 311, 1901


Ilie C. D., Johnston S., Weltevrede P., 2019, Monthly Notices of the RAS, 483, 2778
Johnston S., Karastergiou A., 2017, Monthly Notices of the RAS, 467, 3493
Johnston S., Karastergiou A., 2019, Monthly Notices of the RAS,
Johnston S., Kerr M., 2018, Monthly Notices of the RAS, 474, 4629
Johnston S., Weisberg J. M., 2006, Monthly Notices of the RAS, 368, 1856
Jones P. B., 2014, Monthly Notices of the RAS, 445, 770
Kalapotharakos C., Contopoulos I., 2009, Astronomy and Astrophysics, 496, 495
Karastergiou A., 2009, Monthly Notices of the RAS, 392, L60
Karastergiou A., Johnston S., 2006, Monthly Notices of the RAS, 365, 353
Keith M. J., et al., 2013, Monthly Notices of the RAS, 429, 2161
Kramer M., Johnston S., 2008, Monthly Notices of the RAS, 390, 87


Large M. L., Vaughan A. E., 1971, Monthly Notices of the RAS, 151, 277


Lewandowski W., Dembska M., Kijak J., Kowalińska M., 2013, Monthly Notices of the RAS, 434, 69

Lewandowski W., Kowalińska M., Kijak J., 2015a, Monthly Notices of the RAS, 449, 1570

Lewandowski W., Rożko K., Kijak J., Bhattacharyya B., Roy J., 2015b, Monthly Notices of the RAS, 454, 2517

Li X. H., Han J. L., 2003, Astronomy and Astrophysics, 410, 253


Lyne A. G., Manchester R. N., 1988, Monthly Notices of the RAS, 234, 477


Lyubarskii Y. E., 1996, Astronomy and Astrophysics, 308, 809


Melrose D. B., 1979, Australian Journal of Physics, 32, 61

Melrose D. B., Rafat M. Z., Mastrano A., 2018, arXiv e-prints,
Mitra D., 2017, Journal of Astrophysics and Astronomy, 38, 52


Oster L., Sieber W., 1977, Astronomy and Astrophysics, 58, 303


Petrova S. A., 2006, Monthly Notices of the RAS, 366, 1539


Radhakrishnan V., Cooke D. J., 1969, Astrophysics Letters, 3, 225
Rand R. J., Lyne A. G., 1994, Monthly Notices of the RAS, 268, 497
Ridley J. P., Lorimer D. R., 2010, Monthly Notices of the RAS, 404, 1081
Ritchings R. T., 1976, Monthly Notices of the RAS, 176, 249
Rookyard S. C., Weltevrede P., Johnston S., 2015, Monthly Notices of the RAS, 446, 3367
Schnitzeler D. H. F. M., Banfield J. K., Lee K. J., 2015, Monthly Notices of the RAS, 450, 3579
Sobey C., et al., 2019, Monthly Notices of the RAS, 484, 3646
Sotomayor-Beltran C., et al., 2013, Astronomy and Astrophysics, 552, A58
Stovall K., et al., 2015, Astrophysical Journal, 808, 156


Weltevrede P., 2016, Astronomy and Astrophysics, 590, A109

Weltevrede P., Johnston S., 2008, Monthly Notices of the RAS, 391, 1210

Weltevrede P., Wright G., 2009, Monthly Notices of the RAS, 395, 2117


Weltevrede P., Wright G., Johnston S., 2012a, Monthly Notices of the RAS, 424, 843

Weltevrede P., Wright G., Johnston S., 2012b, Monthly Notices of the RAS, 424, 843

Williamson I. P., 1972, Monthly Notices of the RAS, 157, 55

Wright G. A. E., 2003, Monthly Notices of the RAS, 344, 1041


Yan W. M., et al., 2011, Monthly Notices of the RAS, 414, 2087


van Straten W., Bailes M., 2011, Publications of the Astron. Soc. of Australia, 28, 1

van Straten W., Demorest P., Osłowski S., 2012, Astronomical Research and Technology, 9, 237