DOCTORAL THESIS

A Radio-Frequency Study of Eclipsing Pulsar Binaries

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Contents

Contents 2
List of Figures 8
List of Tables 9
Abbreviations 10
Abstract 12
Declaration of Authorship 13
Copyright Statement 14
Acknowledgements 16
Dedication 18
The Author 19

1 Introduction 20
  1.1 Pulsars ........................................... 20
    1.1.1 Population .................................. 24
    1.1.2 Emission ..................................... 27
      Radio emission .................................. 27
      High energy emission ............................ 29
      Pulsar wind .................................... 31
    1.1.3 Observations ................................. 33
      Dispersion measure ................................ 33
      Rotation measure ................................ 35
      Scattering ...................................... 36
      Timing of isolated pulsars ....................... 38
      Timing of binary pulsars ......................... 39
  1.2 Binary pulsars .................................. 41
    1.2.1 Population .................................. 41
    1.2.2 Formation ................................... 43
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evolution of high-mass X-ray binaries</td>
<td>44</td>
</tr>
<tr>
<td>Evolution of intermediate-mass X-ray binaries</td>
<td>46</td>
</tr>
<tr>
<td>Evolution of low-mass X-ray binaries</td>
<td>46</td>
</tr>
<tr>
<td>Alternative formation of millisecond pulsar binaries</td>
<td>48</td>
</tr>
<tr>
<td>Globular cluster binaries</td>
<td>49</td>
</tr>
<tr>
<td>1.3 Black widows, redbacks and transitional millisecond pulsars</td>
<td>49</td>
</tr>
<tr>
<td>1.3.1 Ablation and mass loss</td>
<td>51</td>
</tr>
<tr>
<td>1.3.2 Intrabinary shock</td>
<td>54</td>
</tr>
<tr>
<td>1.3.3 Magnetic fields</td>
<td>55</td>
</tr>
<tr>
<td>1.3.4 Eclipses</td>
<td>57</td>
</tr>
<tr>
<td>Refraction</td>
<td>57</td>
</tr>
<tr>
<td>Scattering by plasma turbulence</td>
<td>59</td>
</tr>
<tr>
<td>Induced Compton scattering</td>
<td>59</td>
</tr>
<tr>
<td>Stimulated Raman scattering parametric instability</td>
<td>60</td>
</tr>
<tr>
<td>Free-free absorption</td>
<td>60</td>
</tr>
<tr>
<td>Cyclo-synchrotron absorption</td>
<td>61</td>
</tr>
<tr>
<td>Searching for the evidence</td>
<td>61</td>
</tr>
<tr>
<td>1.4 Thesis outline</td>
<td>62</td>
</tr>
<tr>
<td>2 Radio Telescopes and Data Processing</td>
<td>64</td>
</tr>
<tr>
<td>2.1 Introduction</td>
<td>64</td>
</tr>
<tr>
<td>2.2 Radio telescopes</td>
<td>64</td>
</tr>
<tr>
<td>2.2.1 The Low-Frequency Array</td>
<td>66</td>
</tr>
<tr>
<td>2.2.2 Westerbork Synthesis Radio Telescope</td>
<td>68</td>
</tr>
<tr>
<td>2.2.3 Upgraded Giant Metrewave Radio Telescope</td>
<td>68</td>
</tr>
<tr>
<td>2.2.4 Parkes Radio Telescope</td>
<td>69</td>
</tr>
<tr>
<td>2.2.5 Lovell Radio Telescope</td>
<td>69</td>
</tr>
<tr>
<td>2.3 Data processing and analysis</td>
<td>70</td>
</tr>
<tr>
<td>2.3.1 Calibration</td>
<td>71</td>
</tr>
<tr>
<td>Beamformed data</td>
<td>71</td>
</tr>
<tr>
<td>Interferometric data</td>
<td>73</td>
</tr>
<tr>
<td>2.3.2 DM and scattering model fitting</td>
<td>74</td>
</tr>
<tr>
<td>3 The Low-Frequency Radio Eclipses of the Black Widow Pulsar J1810+1744</td>
<td>79</td>
</tr>
<tr>
<td>3.1 Introduction</td>
<td>80</td>
</tr>
<tr>
<td>3.2 Observations</td>
<td>81</td>
</tr>
<tr>
<td>3.2.1 LOFAR beamformed observations</td>
<td>81</td>
</tr>
<tr>
<td>3.2.2 WSRT beamformed observation</td>
<td>81</td>
</tr>
<tr>
<td>3.2.3 Timing ephemerides</td>
<td>84</td>
</tr>
<tr>
<td>3.2.4 LOFAR interferometric observations</td>
<td>84</td>
</tr>
<tr>
<td>3.3 Analysis</td>
<td>84</td>
</tr>
<tr>
<td>3.3.1 Analysis of beamformed data</td>
<td>84</td>
</tr>
<tr>
<td>Modification of the model</td>
<td>86</td>
</tr>
</tbody>
</table>
3.3.2 Analysis of interferometric data .......................... 87
3.3.3 Scintillation ............................................. 89
3.4 Eclipse characteristics ..................................... 89
3.4.1 Individual eclipses ...................................... 89
Scattering ...................................................... 89
Dispersion measure .......................................... 90
Flux density ................................................... 91
3.4.2 Global properties ....................................... 92
Material in the system ......................................... 95
Frequency dependence ........................................ 98
3.5 Discussion of eclipse mechanisms ......................... 102
3.6 Conclusions ................................................ 104

4 Long Term Variability of a Black Widow’s Eclipses – A Decade of PSR J2051–0827106
4.1 Introduction ................................................. 107
4.2 Observations ................................................ 108
4.2.1 Post-processing ........................................ 108
4.3 Flux density and dispersion measure ....................... 110
4.3.1 L-band .................................................... 110
4.3.2 345 MHz .................................................. 112
4.3.3 149 MHz .................................................. 114
4.4 Polarisation .................................................. 115
4.4.1 Tests at low-frequency ................................. 116
4.4.2 Tests at high-frequency ............................... 120
Depolarisation ................................................. 120
Persistent circular polarisation ............................... 126
Faraday delay .................................................... 127
4.5 Eclipse mechanisms ....................................... 132
4.5.1 Dispersion smearing ................................... 132
4.5.2 Scattering ............................................... 133
4.5.3 Cyclotron absorption .................................. 135
4.6 Discussion ................................................... 136
4.6.1 Mini-eclipses ............................................ 138
Effects of Earth’s ionosphere ................................. 138
4.7 Conclusions ................................................ 141

5 Class Segregation – Comparing Eclipses for Widely Separated Companion Masses
5.1 Introduction ................................................. 144
5.2 Observations ................................................ 145
5.3 Analysis ....................................................... 146
5.3.1 Beamformed data ....................................... 146
5.3.2 Interferometric data .................................... 147
5.4 PSR J1816+4510 ........................................... 148


**List of Figures**

1.1 Standard pulsar magnetosphere model ............................................. 22
1.2 One of the original pulsar time series ............................................. 23
1.3 Pulse period vs period derivative diagram for pulsars ....................... 25
1.4 Outer gap emission model .............................................................. 28
1.5 Schematic of a striped pulsar wind ................................................ 32
1.6 Schematic of a pulsar wind nebula .................................................. 32
1.7 Schematic of a pulse time series ..................................................... 34
1.8 Demonstration of pulse de-dispersion ............................................. 35
1.9 Demonstration of pulse scattering ................................................... 37
1.10 Schematic of a Keplerian orbit ..................................................... 40
1.11 Proportions of pulsar binary companion types .................................. 42
1.12 Schematic of a Roche lobe equipotential surface ................................ 44
1.13 Accretion in HMXBs and LMXBs .................................................... 45
1.14 Bifurcation in orbital period evolution .......................................... 47
1.15 Spider pulsar orbital periods and masses ...................................... 52
1.16 Schematic of an intrabinary shock in a pulsar binary .................... 55
1.17 Schematic of a magnetosphere in a binary companion star ............. 56
1.18 Example eclipses of PSR J1023−0038 ............................................. 58

2.1 LOFAR antennas .............................................................................. 67
2.2 DM and scattering templates ............................................................ 76
2.3 DM and scattering fit results ........................................................... 77

3.1 Folded pulse intensity time series for PSR J1810+1744 ..................... 83
3.2 Sequence of images showing eclipse ingress of PSR J1810+1744 .......... 85
3.3 Flux density, dispersion measure and scattering of pulses from PSR J1810+1744 near eclipse ............................................................... 88
3.4 Flux density of PSR J1810+1744 for all observed eclipses ............... 93
3.5 Dispersion measure of PSR J1810+1744 for all observed eclipses .... 94
3.6 Schematic of the expected geometry of the orbit of PSR J1810+1744 ... 96
3.7 Eclipses of PSR J1810+1744 in individual frequency sub-bands ....... 99
3.8 Frequency dependence of the eclipse duration of PSR J1810+1744 .... 100
3.9 Frequency dependence of eclipse ingress and egress for PSR J1810+1744 . 101
B.1 Schematic of the projection of the PSR J1810+1744 system on the sky . . . 188
B.2 Schematic of the projection of the PSR B1957+20 system on the sky . . . 188
B.3 Schematic of the projection of the PSR J2051−0827 system on the sky . . . 189
B.4 Schematic of the projection of the PSR J2215+5135 system on the sky . . . 189
## List of Tables

1.1 Typical attributes of pulsars in different populations .................................. 26  
3.1 Observations used in study ................................................................. 82  
3.2 Measured eclipse parameters for PSR J1810+1744 .................................. 92  
4.1 $\Delta$DM and $\Delta\tau$ step sizes used for template fits ............................ 110  
5.1 Orbital parameters of PSRs J1816+4510 and B1957+20 .......................... 144  
5.2 Observations used in study ................................................................. 146  
5.3 $\Delta$DM and $\Delta\tau$ step sizes used for template fits ............................ 147  
6.1 Observations used in study ................................................................. 163  
6.2 Eclipse duration power law fits for PSR J1816+4510 ............................ 168  
6.3 Orbital parameters and frequency dependence of eclipses ....................... 177  
A.1 Baseline ephemeris for PSR J1810+1744 .............................................. 185  
C.1 List of LOFAR observations with the corresponding RMs ....................... 190  
D.1 Baseline ephemeris for PSR B1957+20 .................................................. 192  
E.1 Eclipse duration measurements for PSR J1810+1744 ............................ 195  
E.2 Eclipse duration measurements for PSR J1816+4510 ............................ 195  
E.3 Eclipse duration measurements for PSR B1957+20 ................................ 196  
E.4 Eclipse duration measurements for PSR J2051−0827 ............................ 196  
E.5 Eclipse duration measurements for PSR J2215+5135 ............................ 196  
E.6 Eclipse duration power law fit parameters .......................................... 197
List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIC</td>
<td>Accretion-Induced Collapse</td>
</tr>
<tr>
<td>APERTIF</td>
<td>APERture Tile In Focus</td>
</tr>
<tr>
<td>ATNF</td>
<td>Australian Telescope National Facility</td>
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<tr>
<td>BW</td>
<td>Black Widow</td>
</tr>
<tr>
<td>DFB4</td>
<td>Digital Filterbank Mark-IV</td>
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<tr>
<td>DISS</td>
<td>Diffractive InterStellar Scintillation</td>
</tr>
<tr>
<td>DM</td>
<td>Dispersion Measure</td>
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<tr>
<td>EoS</td>
<td>Equation of State</td>
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<tr>
<td>FWHM</td>
<td>Full-Width at Half-Maximum</td>
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<tr>
<td>GBT</td>
<td>Green Bank Telescope</td>
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<td>GC</td>
<td>Globular Cluster</td>
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<td>GMRT</td>
<td>Giant Metrewave Radio Telescope</td>
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<td>HBA</td>
<td>High-Band Antenna</td>
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<tr>
<td>HMXB</td>
<td>High-Mass X-ray Binary</td>
</tr>
<tr>
<td>ICS</td>
<td>Induced Compton Scattering</td>
</tr>
<tr>
<td>IMXB</td>
<td>Intermediate-Mass X-ray Binary</td>
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<tr>
<td>ISM</td>
<td>InterStellar Medium</td>
</tr>
<tr>
<td>LAT</td>
<td>Large Area Telescope</td>
</tr>
<tr>
<td>LBA</td>
<td>Low-Band Antenna</td>
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<tr>
<td>LMXB</td>
<td>Low-Mass X-ray Binary</td>
</tr>
<tr>
<td>LOFAR</td>
<td>LOw-Frequency ARray</td>
</tr>
<tr>
<td>LoS</td>
<td>Line of Sight</td>
</tr>
<tr>
<td>MFFE</td>
<td>Multi-Frequency Front End</td>
</tr>
<tr>
<td>MS</td>
<td>Main Sequence</td>
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<tr>
<td>MSP</td>
<td>Millisecond Pulsar</td>
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<tr>
<td>NS</td>
<td>Neutron Star</td>
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<td>PulP</td>
<td>Pulsar Pipeline</td>
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<td>PWN</td>
<td>Pulsar Wind Nebula</td>
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<tr>
<td>RB</td>
<td>RedBack</td>
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<tr>
<td>RFI</td>
<td>Radio-Frequency Interference</td>
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<tr>
<td>RFM</td>
<td>Radius-to-Frequency Mapping</td>
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<tr>
<td>RL</td>
<td>Roche Lobe</td>
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<tr>
<td>RLOF</td>
<td>Roche Lobe Overflow</td>
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<tr>
<td>Acronym</td>
<td>Full Form</td>
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<tr>
<td>RM</td>
<td>Rotation Measure</td>
</tr>
<tr>
<td>RRAT</td>
<td>Rotating RAdio Transient</td>
</tr>
<tr>
<td>SKA</td>
<td>Square Kilometre Array</td>
</tr>
<tr>
<td>SNR</td>
<td>Supernova Remnant</td>
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<td>SRS</td>
<td>Stimulated Raman Scattering</td>
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<tr>
<td>TAB</td>
<td>Tied-Array Beam</td>
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<tr>
<td>TEC</td>
<td>Total Electron Content</td>
</tr>
<tr>
<td>TOA</td>
<td>Time of Arrival</td>
</tr>
<tr>
<td>TT</td>
<td>Terrestrial Time</td>
</tr>
<tr>
<td>UWL</td>
<td>Ultra-Wide Low-Frequency Receiver</td>
</tr>
<tr>
<td>WD</td>
<td>White Dwarf</td>
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<tr>
<td>WSRT</td>
<td>Westerbork Synthesis Radio Telescope</td>
</tr>
</tbody>
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In this thesis we present a detailed study into the poorly understood eclipse phenomena of Galactic field eclipsing pulsar binaries; known as the black widows and redbacks. The work is primarily based on a large set of radio-frequency observations, made up of both dedicated campaigns and archival data from a number of telescope facilities, in order to markedly increase the quality and volume of evidence to constrain future theoretical models, and as such, further our understanding. Here, we present the work in four interlinked parts:

Firstly, we observed and investigated the eclipses of PSR J1810+1744, a near-unexplored black widow, at low-radio-frequencies. In this frequency domain the pulsar is bright, and the propagation effects that are vital to understanding the eclipse medium become more pronounced. Using these observations we constrain the mechanisms responsible for the eclipse and the mass loss rate from the companion star.

Secondly, we performed an analysis of a well studied black widow, PSR J2051−0827, collating a large volume of data on its eclipses covering over a decade in time and frequencies from 100 MHz to 4 GHz. This time and frequency coverage is the most extensive used in a single dedicated eclipse study of a pulsar, and reveals variability in the eclipse phenomena on a range of timescales. Using observations sensitive to the polarisation of the pulsar radiation, we constrain the magnetic field strengths in the eclipse region.

Stemming from our work on PSR J1810+1744, we conducted a dedicated low-frequency study of two more pulsars: redback PSR J1816+4510 and black widow PSR B1957+20. These two systems have similar orbital properties, however their companion stars differ in mass by nearly an order of magnitude. We compare the eclipse phenomena in both, finding remarkable similarities, seemingly independent of the companion masses.

Finally, bringing together the four pulsars studied throughout this thesis, and adding a further redback – PSR J2215+5135 – we perform an analysis of the eclipse durations as a function of the pulsar radiation frequency. The results show that for all of the pulsars the eclipse widths scale inversely with frequency, however the rate at which they do so varies between systems. We discuss further complexities such as temporal variability of the eclipses and differing relationships acting at low- and high-frequencies.
Declaration of Authorship

I, Elliott J. POLZIN, declare that this thesis titled, “A Radio-Frequency Study of Eclipsing Pulsar Binaries” and the work presented in it are my own. I confirm that:

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• 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.

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"The last three months have been a rollercoaster, full of ups and downs. However, as I keep reminding myself, rollercoasters only move forward!"

Dean Hoyle, Huddersfield Town Chairman
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My first and foremost thanks must, of course, go to my Ph.D. supervisor René Breton. René initially took me under his supervision despite me knowing little-to-nothing about pulsars, and having only heard about Python in the context of snakes, however throughout the last three and a half years he truly provided the knowledge, advice and confidence to allow me to become a (semi-)competent independent researcher. I believe that we developed a great relationship, and I am grateful that he has always been prepared to put aside time to help, even throughout his own meteoric rise in the academic world. René went out of his way to introduce me, and/or my work, to a whole host of very impressive people, both in and outside of my field of research, that have been invaluable to my progress. Finally, I will always appreciate his inspiring – often ‘out-there’(!) – ideas that, despite sometimes stemming from my incorrect analyses, led to most of the projects making up my thesis.

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Over the last three and a half years I have had the pleasure of meeting and working with many incredible scientists. My involvement with the LOFAR Pulsar Working Group (PWG) has played a major role in this, and each member has positively influenced my work and experience. In particular, Jason Hessels provided numerous ideas, datasets and useful critiques; Vlad Kondratiev provided brilliant scripts and helped me with their usage; Cees Bassa put a lot of time into processing our joint data, and provided feedback on much of my work; Charlotte Sobey was my go-to source of knowledge and help for anything RM related and, alongside Stefan Oslowski, Simon Johnson and James Green, was influential in the success of the Parkes project; Patrick Weltevrede provided lots of useful comments and feedback on my work; Joris Verbiest, alongside Caterina Tiburzi and Julian Donner, provided me with huge amounts of data and help with all-things pulsar timing; and Sander ter Veen and Matthijs van der Wiel worked wonders with my LOFAR observations.

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performing of GMRT observations, and we have exchanged countless emails to ensure that the data is processed as well as possible. Many of my telescope proposals and works have benefited from the wise thoughts of Mallory Roberts, and Gemma Janssen provided the masses of WSRT data that made the PSR J2051–0827 project possible. The vast majority of modern pulsar astronomy relies on advanced computing and (niche) software, and without the behind the scenes relentless work of Anthony Holloway, Robert Dickson and Mike Keith very little of my research would have been possible. Finally, in my three years as a teaching assistant, Myfanwy Lloyd’s leadership was flawless and made it a joy.

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Dedicated to my Grandad, Fritz Polzin
The Author

Born in Huddersfield, West Yorkshire, UK, Elliott attended Salendine Nook High School where he attained his GCSE qualifications. Following this, Elliott went on to achieve A-Level qualifications in Physics, Maths and Chemistry at Greenhead College. Finally leaving the safety of Huddersfield, he attended the University of Manchester to study Physics with Astrophysics, achieving a 1st class M.Phys. degree. Looking for a change, he travelled further afield to undertake a professional engineering role in radio-frequency communications, where he remained for two years before returning to academia to study for a Ph.D. in Astronomy and Astrophysics, at the Jodrell Bank Centre for Astrophysics.
Chapter 1

Introduction

“There are painters who transform the sun into a yellow spot, but there are others who with the help of their art and their intelligence, transform a yellow spot into the sun.”

Pablo Picasso

1.1 Pulsars

Supernovae, some of the most extreme astronomical events thus far observed, are intense stellar explosions that can generally arise from two differing scenarios: either the core-collapse of a massive evolved star, or a white dwarf surpassing the Chandrasekhar mass (Chandrasekhar, 1967). Remarkably predicted by Baade & Zwicky (1934) soon after the discovery of the neutron, these violent supernova events often mark the birth of a neutron star (NS).

Post-supernovae, the remaining NSs are incredibly dense, compact objects, supported against gravity by the degeneracy pressure of their constituent neutrons; this pressure is the last line of defence against gravitational collapse into a black hole. The vast majority of NSs are almost undetectable from Earth as they rapidly cool in the absence of the nuclear burning that powered their massive progenitors. As a result, many of their properties have to be predicted through theoretical models. The canonical masses and radii of NSs are taken to be $1.4M_\odot$ and $\sim 10$ km, respectively, giving average densities within a NS of $\sim 10^{17} - 10^{18}$ kg m$^{-3}$, making them the most dense objects known. Theoretical upper and lower limits have been placed on the possible radii of NSs by Kalogera & Baym (1996) and Glendenning (1992), respectively, with the upper limit based on NSs resisting break up against centrifugal forces and the lower limit originates from the requirement for the speed of sound to be lower than the speed of light in a NS. Much more stringent theoretical predictions rely on estimates of the equation of state (EoS) of NS matter, which aim to define the exact relationship between the pressure and density throughout a NS (see reviews in Lattimer, 2012; Özel & Freire, 2016). Due to the difficulty in being able to directly ‘see’ these objects, many EoS models remain in contention, however recent non-direct observational measurements have identified NSs with masses $\sim 2.0M_\odot$, or higher.
1.1. Pulsars

(e.g. Linares et al., 2018; Antoniadis et al., 2013; van Kerkwijk et al., 2011; Demorest et al., 2010), providing tighter constraints and allowing a number of EoS models to be ruled out. Further to being exceedingly dense, NSs host magnetic fields with typical surface strengths of the order $10^{12}$ G. It is not precisely known how such high surface magnetic fields arise, although, for example, Ferrario & Wickramasinghe (2005) argue that they are simply a consequence of the conservation of magnetic flux throughout the gravitational collapse of a progenitor star with a radius many orders of magnitude larger than that of the remnant NS. Alternatively, Thompson & Duncan (1993) argue that the extreme magnetic fields are generated by a dynamo mechanism during the collapse. A second consequence of the gravitational core collapse formation is that NSs have rapid rotation rates, with spin periods of $\sim 1$ s. Less controversially, this is known to be due to the conservation of angular momentum of the core of the progenitor star which results in spin-up as it collapses to the smaller radius of the forming NS.

The hosted magnetic field lines are forced to co-rotate with the NS at these high rates, however as the field lines are constrained to travel at subluminal velocities, the co-rotation can only occur out to a maximum radial distance defined by the rotation rate of the NS and the speed of light. This bounding region, within which co-rotating field lines have a velocity less than or equal to the speed of light, is known as the light cylinder, as shown in Fig. 1.1. The field lines within this cylinder are closed between the magnetic poles of the NS, whereas the field lines extending out of the cylinder are forced open. The magnetic field is generally assumed to be dipolar – at least on large scales (e.g. Goldreich & Julian, 1969) – in which case the co-rotation results in a toroidal volume of closed magnetic field lines, with its axis aligned with the magnetic axis of the NS, that induces a large electric field as it rapidly rotates. The induced electric field is of high enough magnitude to pull charged particles from the NS surface, filling the toroidal magnetic field volume with a co-rotating plasma, forming the NS magnetosphere (Goldreich & Julian, 1969).

The above combination of theoretical ingredients led Pacini (1967) to predict that NSs could, even in the absence of thermal radiation, strongly emit electromagnetic radiation, and could consequently be a source of power for the Crab nebula. Only months after Pacini’s pioneering work was published, Jocelyn Bell, at the time a PhD student of Anthony Hewish at the University of Cambridge, observed remarkably regular pulsations in the readings from their newly-operational radio telescope (Hewish et al., 1968, and Fig. 1.2). The fixed celestial coordinates of the pulsating source meant that it could be confidently identified as being of astrophysical origin, but the unusual regularity and nature of the signal drew speculation that they may in fact be detecting an extraterrestrial civilization, referring to the signal as LGM-1 – a play on the term ‘Little Green Man’. This speculation was short-lived however, as the detection of a number of similar signals from different celestial coordinates strongly suggested a more common explanation. In the original publication (Hewish et al., 1968) it was postulated that the signals arose from pulsating white dwarfs or NS-like compact objects. As we now know, this was not far off the mark, and it didn’t take long for the signals to be correctly identified as being a result of rotating, as opposed to pulsating, NSs (Gold, 1968).
Figure 1.1: Generally assumed model of a pulsar magnetosphere. The magnetic and spin axes are offset from one another, and the co-rotating closed magnetic field lines are contained within the light cylinder as a result of necessary subluminal velocities. The inner and outer acceleration gaps are labelled, and correspond to possible emission regions (see Section 1.1.2). Radio beams are shown in yellow emanating from the magnetic poles. Image credit: National Radio Astronomy Observatory (NRAO).
1.1. Pulsars

During these initial works the name pulsar was coined, marking the birth of what we now know as pulsar astronomy. Specifically, pulsars are a subset of NSs that emit beams of electromagnetic radiation from above their magnetic poles (see Fig. 1.1 and Section 1.1.2), and key to their visibility is that their spin and magnetic axes are typically not aligned (an oblique rotator), thus as the pulsar rotates the two beams sweep across space. For those pulsars where at least one of the beams swings towards the Earth, one can observe regular pulsations that are coincident with the rotation rate of the pulsar. The regular period of the pulsations from an individual pulsar, and the change in the period over time, can be used to infer many of the pulsar properties, as will be explained in Section 1.1.3.

It is observed that vast majority of pulsars have spin periods, $P$, between $\sim 50 \text{ ms} - 5 \text{ s}$, although they have been remarkably measured as low as 1.4 ms (Hessels et al., 2006) and as high as 23.5 s (Tan et al., 2018). The periods are generally observed to increase with time due to loss of rotational kinetic energy, dissipated primarily as magnetic dipole radiation at the frequency of the pulsar rotation (due to the offset between the magnetic and spin axes), but also in the pulsar wind and a small fraction as radio frequency and higher energy electromagnetic radiation (Section 1.1.2). Assuming that pulsars are powered entirely by their rotational energy, the rate of loss of kinetic energy of a pulsar determines its total power output, and can be calculated by its spin period and spin period derivative, $\dot{P}$, as (Lorimer & Kramer, 2004, and references therein)

$$\dot{E}_{\text{rot}} \equiv -\frac{dE_{\text{rot}}}{dt} = 4\pi^2 I \dot{P} P^{-3}, \quad (1.1)$$

where the rotational energy, $E_{\text{rot}} = I\Omega^2/2$, and $\Omega$ is the rotational angular frequency. $\dot{E}_{\text{rot}}$, known as the spin-down luminosity, is a useful parameter as it puts an upper limit on the energy available to power various mechanisms, including emission of radio and high-energy radiation, and the pulsar wind.

A useful approximation to make is that all of the rotational energy lost is due to low frequency electromagnetic radiation from the rotation of a magnetic dipole in a vacuum.
Chapter 1. Introduction

(Gold, 1968; Pacini, 1968), in which case the spin and slow-down of the pulsar are intrinsically linked to the strength of its surface magnetic field as (Lorimer & Kramer, 2004),

\[ B = \left( \frac{3c^3I}{8\pi^2R^6 \sin^2\alpha} \right)^{1/2} \dot{P} P, \]  

(1.2)

where \( \dot{P} \) is the rate of change of the spin period, \( R \) is the pulsar radius, \( \alpha \) is the angle between the magnetic and spin axes, and \( I \) is the moment of inertia of the pulsar – typically taken to be \( I \sim 10^{45} \text{g cm}^2 \). This allows an estimate of a pulsar’s surface magnetic field strength, referred to as the characteristic magnetic field, from the observational properties \( P \) and \( \dot{P} \).

With the same assumptions of pure magnetic dipole braking, one can obtain an expression for the age of a pulsar,

\[ T = \frac{P}{2P} \left[ 1 - \left( \frac{P_0}{P} \right)^2 \right], \]  

(1.3)

which relies on knowledge of the birth spin period, \( P_0 \). As this parameter is rarely known, one can utilise the assumption that the birth spin period is significantly more rapid than the currently observed spin period, i.e. \( P_0 \ll P \). This approximation leads to an expression for the characteristic age of a pulsar (Lorimer & Kramer, 2004),

\[ \tau_c \equiv \frac{P}{2\dot{P}}. \]  

(1.4)

These characteristic parameters, calculated using the measurable properties of pulsar rotation, are used extensively throughout pulsar astronomy. One prevalent use case is the clustering of the whole pulsar population into subsets in which we expect the constituent pulsars to have similar attributes.

1.1.1 Population

Since the detection of the first pulsar, the discovery rate has generally continued to increase with time as telescope technology advances and survey techniques are improved. At the time of writing, there are more than 2600 observed pulsars listed in the Australian Telescope National Facility (ATNF) Pulsar Catalogue\(^1\) (Manchester et al., 2005), and these can be split into separate populations based on their observed properties. Pulsar populations naturally show groupings in their \( P \) and \( \dot{P} \) parameters and as such they occupy fairly distinct regions on a \( P - \dot{P} \) diagram. Fig. 1.3 shows a \( P - \dot{P} \) diagram using all currently known pulsars that have measured spin parameters, and various different sub-populations are highlighted. Note that this gives a selection bias towards pulsars for which spin parameters can be more easily measured, i.e. commonly those that display regular pulsations at radio wavelengths (see Sections 1.1.2, 1.1.3).

Depending on the goals of an analysis, the pulsar population can be clustered into differing sub-populations, however as an overview here they will be split into four high-level

\(^1\)http://www.atnf.csiro.au/people/pulsar/psrcat/
1.1. Pulsars

Figure 1.3: $P - \dot{P}$ diagram of observed pulsars. The 3 sets of diagonals represent lines of constant magnetic field strength, characteristic age and spin-down luminosity, assuming that pulsars can be well represented as rotating magnetic dipoles. To the right of the ‘death line’, the traditional emission model of Ruderman & Sutherland (1975) predicts that no radio emission should be produced. The ‘normal’ pulsars, not specifically labelled, make up the bulk of the pulsars on the diagram and are placed between $50 \text{ ms} < P < 5 \text{ s}$ and $10^{11} \text{ G} < B < 10^{13} \text{ G}$. Image credit: Sally Cooper (priv. comm.).
Chapter 1. Introduction

Normal pulsars, as the name suggests, represent the vast majority of known pulsars. Sitting centrally in the $P - \dot{P}$ diagram, normal pulsars tend to have modest values of the spin-period-derived parameters, although some do stray beyond the traditional ‘death line’ predicted by Ruderman & Sutherland (1975). Pulsars in this area can challenge emission models that predict when pulsars should no longer have the required properties to radiate at the observed frequencies. It is notable that the so-called rotating radio transients (RRATs; McLaughlin et al., 2009) appear to largely lie among the normal pulsars, only tending slightly to the upper right region of the $P - \dot{P}$ plane. RRATs have many similar properties to normal pulsars, however they are defined by having only sporadic detectable radio emission, as opposed to the regular pulsations that we expect. This property means that they are notoriously difficult to detect, and time (see Section 1.1.3), and thus are likely under-represented among the known pulsars.

Young pulsars reside in the upper left of the $P - \dot{P}$ plane with low characteristic ages. These pulsars have large spin-down power, and as such can transfer a lot of energy to their nearby environment. This attribute, along with low characteristic ages, naturally explains why they are often detected within supernova remnants (SNRs) from which they presumably recently formed, powering the visible emission from the SNRs with their spin-down energy (e.g. Pacini, 1968).

Magnetars are technically a subset of the young pulsars, with long spin periods and high spin-down rates, however they have unusually strong surface magnetic field strengths (see Olausen & Kaspi, 2014, for a review of general magnetar properties). The contribution of a high spin-down rate is to increase the amount of energy lost through rotational slow-down, however magnetars also possess particularly large spin periods resulting in relatively low theoretical energy release, $\dot{E}_{\text{rot}} \propto \dot{P}P^{-3}$. Observations of magnetars appear to oppose this theoretical prediction however, as the measured energy outputs are much higher than expected. This discrepancy implies that spin-down of magnetars is not the dominant source of energy, but instead the emission is thought to be primarily powered by dissipation of magnetic energy resulting from their high magnetic field strengths (Duncan & Thompson, 1996).

The definition of MSPs having spin periods $< 30$ ms is common, although this number varies slightly throughout literature. What is agreed upon, however, is that MSPs cluster in a distinct region in the $P - \dot{P}$ plane with low magnetic field strengths and notably slow spin-down rates. The reason for these MSP characteristics is thought to be a result

<table>
<thead>
<tr>
<th>Population</th>
<th>$P$ (s)</th>
<th>$\dot{P}$ (s s$^{-1}$)</th>
<th>$B$ (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal pulsars</td>
<td>$\sim 50$ ms – $10$ s</td>
<td>$\sim 10^{-15} - 10^{-12}$</td>
<td>$\sim 10^{11} - 10^{13}$</td>
</tr>
<tr>
<td>Young</td>
<td>$\sim 50$ ms – $10$ s</td>
<td>$\gtrsim 10^{-14}$</td>
<td>$\sim 10^{12} - 10^{16}$</td>
</tr>
<tr>
<td>Magnetars</td>
<td>$\sim 2$ s – $10$ s</td>
<td>$\gtrsim 10^{-13}$</td>
<td>$\sim 10^{13} - 10^{16}$</td>
</tr>
<tr>
<td>MSP</td>
<td>$\lesssim 30$ ms</td>
<td>$\lesssim 10^{-17}$</td>
<td>$\sim 10^8 - 10^9$</td>
</tr>
</tbody>
</table>

Table 1.1: Typical spin periods, spin-down rates, and magnetic field strengths of pulsars in the different populations.
1.1. Pulsars

of their formation from normal pulsars via accreting X-ray binaries (Bhattacharya & van den Heuvel, 1991; Alpar et al., 1982, and Section 1.2.2). Contrary to normal pulsars and magnetars, where only a small percentage are in binary systems, the majority of MSPs are found with binary companions – once again thought to be a consequence of their prior evolution. The MSP group contains the so-called black widow and redback pulsars studied in this thesis; these pulsar types are both known for their strong irradiation of a binary companion star by the pulsar wind, and are separated primarily by an observed dichotomy in companion star masses (see Fig. 1.15 and Section 1.3).

1.1.2 Emission

Emission from pulsars spans the whole frequency spectrum from radio to $\gamma$-rays, however, as is the case with much of the physics behind pulsars, the mechanisms are still debated. Observations at radio frequencies led to the first discovery of pulsars, and have been the primary method for observing them ever since. As such, many of the theories that have been put in place to describe pulsars are based on the characteristics of their radio emission. However, advances in high frequency observing are leading to much more detailed studies of pulsars across the full electromagnetic spectrum, allowing the formation of more complete emission models. Here we briefly introduce the concepts and observed properties of pulsar emission.

Radio emission

Pulsed radio emission has been observed from the vast majority of known pulsars. Generally the emission is broadband in nature with the spectrum being well approximated by a power-law; the spectral index of which varies over the population, but on average lies around $-1.8$ (Maron et al., 2000) or $-1.4$ (Bates et al., 2013) – i.e. brighter at lower frequencies.

The emission is thought to originate (at least primarily) from the polar cap region of the magnetosphere, above the magnetic poles, as shown in Fig. 1.4. This is observed to be non-thermal in nature and must be coherent in order to explain its high brightness temperature. In the polar cap, Sturrock (1971); Ruderman & Sutherland (1975) proposed that charged particles, which are torn from the pulsar surface by the generated electric field, are accelerated along the curved magnetic field lines, and as such emit $\gamma$-rays via a curvature radiation mechanism. If these $\gamma$-ray photons possess enough energy then they can produce electron-positron pairs, which are consequently accelerated by the electric field. This process can act recursively, resulting in an accelerated secondary plasma emanating from the poles of the pulsar. It is commonly believed that it is from the accelerated secondary pair plasma that the radio emission originates, however the regime under which it is produced is not fully understood, and it is possible that multiple mechanisms are at play throughout the process.

Emission from the polar cap is assumed to form a roughly conical beam with edges defined by tangents to the last open field lines, and it is these beams that we observe
Figure 1.4: Close in view of the pulsar magnetosphere showing the polar cap region and the outer magnetospheric gap. These are the two primary regions associated with pulsar emission. The bold ‘critical line’ is the last open field line of the magnetosphere, i.e. the outermost field line that crosses the light cylinder. Image credit: adapted from Takata & Chang (2009).

as pulses as they cross our line of sight every rotation. At radio frequencies the observed pulses generally show a frequency dependence, with lower frequencies resulting in wider pulses, which can be attributed to the height above the pulsar surface at which the emission occurs. This effect, first proposed by Komesaroff (1970), is known as radius to frequency mapping (RFM) (Cordes, 1978) and is a consequence of the magnetic field lines curving away from the magnetic axis with radial distance from the pulsar. Since the edges of the radio beam are defined by the tangents to the outermost field lines at the height of emission, the width of the beam will increase as the emission height increases due to the field lines being curved further from the magnetic axis. Thus, through this mechanism it is thought that lower frequency radio emission originates at a larger radial distance above the poles, forming a larger beamwidth and consequently a wider observed pulse. The frequency dependence of pulse widths is much weaker at higher radio frequencies, suggesting that the emission height above the surface is similar at these shorter wavelengths.

A large range of polarisation properties are seen in observations of the pulses from pulsars; from those with no detectable polarisation to some with high fractions of linear and/or circular polarisation. For an individual pulsar, the average polarisation properties remain roughly constant over time. Soon after the discovery of pulsars, Lyne & Smith (1968) presented the first detection of polarisation in the pulsed emission, and it has remained a very active field of study ever since. It has been noticed that, particularly for
young pulsars, the radio emission is often highly linearly polarised (Johnston & Weisberg, 2006; Weltevrede & Johnston, 2008), which is thought to be a result of naturally occurring propagation modes in the highly magnetised plasma of a pulsar magnetosphere (Arons & Barnard, 1986). The generation of circular polarisation in pulsar emission, however, is rather more mysterious; generally accepted models are yet to emerge that can naturally explain the properties of both the circular polarisation and the observed complexities of the linear polarisation (e.g. Dyks, 2017; Gangadhara, 2010; Melrose, 2003).

The general picture of pulsar emission described above can describe much of the observed characteristics of ‘well behaved’, often young, pulsars. However there are many detailed aspects, such as the location of particle acceleration and the shape and size of the emission regions, that are debated to this day. Of particular note is how this picture can transfer to the different subsets of pulsars; for example, preliminary studies of MSPs appear to show that the pulse widths vary much less with frequency than expected by the traditional models, suggesting that the emission regions in MSPs could originate from a smaller range of heights above the polar cap than in normal pulsars (Kramer et al., 1999), and there is also some evidence that MSPs typically have steeper spectral indices than the rest of the population (Kramer et al., 1999; Kuzmin & Losovsky, 2001; Kondratiev et al., 2016). Additionally, a growing number of pulsars are being found with sporadic radio emission (RRATs; McLaughlin et al., 2009), or even no detectable radio emission at all – such as many of the known magnetars (Olausen & Kaspi, 2014) – and it is not clear if a unique model of pulsar emission can be used to explain the full population. An interesting review on how future observations using the Square Kilometer Array (SKA) could shed light on the radio emission mechanisms in pulsars is provided by Karastergiou et al. (2015).

High energy emission

High energy emission from pulsars – optical to $\gamma$-rays – has been detected, at least in part, from a significant fraction of observed pulsars. It is not known whether those pulsars from which all, or parts, of the high energy spectrum are not detected are objects which simply do not emit at such energies, or instead are either too faint or have unfavourable geometries relative to Earth. However, advances in telescopes sensitive to these energy bands (e.g. the Large Area Telescope on the Fermi Gamma-ray Space Telescope, and the instruments on board the XMM-Newton X-ray observatory) are leading to rapid increases in the number of pulsars with detected high energy emission, suggesting that many sources were previously just too faint.

Emission is often observed to contain both thermal and non-thermal components. The thermal radiation is attributed to X-rays originating from the pulsar surface and usually makes up only a small fraction of the high energy emission. Whereas the majority is made up of non-thermal optical, X-ray and $\gamma$-ray radiation. Many models have been proposed to account for the non-thermal emission, often involving synchrotron and/or curvature radiation from particles accelerating along magnetic field lines. However, the location at which the photons originate is still hotly debated.
The leading models generally focus on four particular regions: the polar cap, the outer gap, the slot gap and the pulsar wind. Polar cap models proposed by Daugherty & Harding (1986); Harding et al. (2005) suggest that the high energy radiation can result from either inverse-Compton scattering of photons by the accelerated charged particles above the magnetic poles of the pulsar, or synchrotron emission in the same region, respectively. The outer gap models (e.g. Cheng et al., 1986; Romani, 1996; Cheng et al., 2000) have high energy emission originating from charge-starved regions in the outer magnetosphere where strong parallel electric and magnetic fields can be present and significant pair-creation and particle acceleration occurs. These regions are thought to be bounded by the last closed and first open field lines and the ‘null surface’ – the plane in which the local magnetic field direction is perpendicular to the spin axis (see Fig. 1.4). In slot gap models (e.g. Muslimov & Harding, 2004) the high energy emission originates in narrow regions on the boundary of last open field lines. Here it is proposed that a steady state electric field approaches a small, constant value at high altitudes above the polar cap, and this can keep electrons moving with high Lorentz factors along the field lines out to the light cylinder, emitting curvature γ-ray photons in the process. Alternatively, the pulsar wind also offers a mechanism for emission of high energy radiation from pulsars. Kirk et al. (2002) and Pétri (2012) present models which differ from those above in that the high energy emission is predicted to originate outside of the light cylinder, in the pulsar wind. Here the high energy emission is caused by synchrotron radiation from the dissipation of magnetic energy to particle energy in the pulsar wind, and the calculations performed are in good agreement with the observed emission from the Crab pulsar, suggesting that this could be a viable mechanism.

Although promising, many of these models struggle to account for the observed high-energy emission from all pulsars. Recently however, Torres (2018) proposed a conceptually simple unifying model for the high energy emission across seven orders of magnitude, above 1 keV. Remarkably, fitting the model with only four free parameters can well represent all high energy detections made thus far. In the proposed model, particles are accelerated in a gap near the light cylinder where electric and magnetic field lines align, producing X-rays via a synchrotron dominated mechanism in the initial stages of injection into the gap, followed by γ-ray emission via a synchro-curvature mechanism. The model was used to predict which γ-ray detected pulsars, from the 2nd Fermi-LAT Pulsar Catalogue (Abdo et al., 2013), could be expected to be detectable in X-rays. Three of the most promising candidates were investigated in archival X-ray data, and all were significantly detected (Li et al., 2018), giving strong backing for the proposed model.

Particularly relevant for the work in this thesis, high energy emission is also observed in binary pulsar systems to be not directly from the pulsar itself, but instead originating from either the heated surface of a binary companion due to irradiation from the pulsar (e.g. Fruchter et al., 1988b, and Section 1.3), or from an intrabinary shock region between the pulsar and its companion (e.g Arons & Tavani, 1993, and Section 1.3.2). Additionally, if a binary pulsar system is in an accreting phase, a strong flux of high energy emission is observed from an accretion disc surrounding the pulsar (e.g. in ’t Zand et al., 1998, and
1.1. Pulsars

Section 1.2.2).

Pulsar wind

The bulk of this section is based on a review of pulsar wind studies given in Kirk et al. (2009).

At the radial distance of a pulsar’s light cylinder the plasma confined within the magnetosphere would have to travel at the speed of light in order to co-rotate with the pulsar, thus co-rotation of the charged particles can not occur beyond radial distances approaching the light cylinder. At the point where co-rotation becomes impossible, the charged particles escape the confinement of the magnetosphere with ultrarelativistic energies, carrying away magnetic flux in the process, thus forming a high energy, magnetised pulsar wind. The idea of a wind emanating from pulsars was first proposed by Pacini (1967). There are various models that attempt to explain the pulsar wind (Kirk et al., 2009) which differ in the distributions of the particles within the wind depending on whether they emanated from polar or equatorial regions of the magnetosphere, and then how it acts within the shocked regions formed as the wind pressure is equalised with the pressure of surrounding material. However, an often prevailing picture is provided by the striped wind model (Coroniti, 1990; Michel, 1971).

The striped wind can be explained as follows: as pulsars are oblique rotators – i.e. their spin and magnetic axes are not aligned – then as a pulsar rotates, its magnetic equator traces out a sinusoidal pattern. In the non-rotating frame the magnetic field direction at the spin equator flips as it connects to a different magnetic pole every half-rotation. Thus, for a steady radially flowing wind, with magnetic field lines frozen in, a rippled surface expands away from the pulsar – the striped wind – as depicted in Fig. 1.5. Michel (1971) predicted that the surface of the ripples consists of cold, magnetically dominated, plasma that is separated by thin, hot current sheets.

Shock regions formed downstream in the wind, known as termination shocks, are thought to be the regions in which particles are accelerated to high energies in order to feed pulsar wind nebulae (PWN) that we often observe (Hester et al., 2002, and references therein). PWN are regions surrounding pulsars filled with highly accelerated particles, powered by the pulsar wind, that expand out to an outer boundary where they are incident upon either the interstellar medium or the supernova remnant from which the pulsar formed. The most studied PWN is the Crab Nebula, against which almost all theories of this phenomenon are tested. Emission from the nebulae spans the full spectrum from radio to TeV energies, and is thought to originate via a synchrotron mechanism (Kennel & Coroniti, 1984). Additionally, Cerutti et al. (2014) proposed a model to explain γ-ray flares observed from the Crab Nebula, for which particle acceleration in the termination shock fails to account. In this model, particles are accelerated to high relativistic energies by magnetic reconnection in the PWN before emitting the observed high energy, beamed synchrotron radiation. A schematic of a PWN is shown in Fig. 1.6, assuming this picture. As many PWN are observed to be weakly magnetised, it is thought that the Poynting flux in the pulsar wind is converted to kinetic energy of the particles in the wind, but the
FIGURE 1.5: Schematic of the ‘striped wind’ model of the pulsar wind. Shown is the corrugated surface formed as the wind emanates radially away from the central pulsar, with the offset magnetic equator tracing out a periodic pattern as the pulsar rotates. In the picture of Michel (1971), this surface represents a thin current sheet, which is thought to separate pockets of magnetically dominated plasma. Image credit: Kirk et al. (2009).

FIGURE 1.6: Schematic of a pulsar wind nebula. The pulsar wind expands up until the termination shock region where electron-positron pairs are accelerated by energy from the wind. The relativistic particles emit synchrotron radiation and are confined in a region surrounded by the supernova remnant (or the ISM). It is proposed that magnetic reconnection can also be a mechanism for the particle acceleration in the nebula. Image credit: Cerutti et al. (2014).
radius at which this becomes significant, and the mechanisms through which it occurs are not precisely known (see Section 4 of Kirk et al., 2009, for a review). Recently, Cerutti & Philippov (2017) performed two-dimensional particle-in-cell simulations of the pulsar wind, and the results suggested that the striped nature of the wind should dissipate within hundreds of light cylinder radii. This would mean that although the overall magnetic field strength in the wind persists, the alternating polarity of the field in consecutive stripes will be reduced, or even removed. Noteworthy for the work in this thesis is that significant dissipation may then occur before the wind reaches a binary companion star, even in the case of the tight binaries studied here where the binary separation is of the order $10^3$ light cylinder radii. Whether such dissipation occurs or not, the pulsar wind is expected to cause the ablation of the stellar companions in redback and black widow systems causing the observed radio eclipses (see Section 1.3).

1.1.3 Observations

As the main technique used for the work in this thesis, here we introduce some of the key concepts of observations of pulsars at radio frequencies. Radio observations have traditionally been the most prolific source of pulsar knowledge, having been used to investigate the profiles of the pulsed emission, pulsar timing and searching for new pulsars, to name but a few. As discussed above, the radio emission from pulsars, presumably from the polar cap region, is observed as regular pulses as the radiation beam periodically crosses our line of sight as the pulsar rotates. This characteristic periodicity can be seen in Fig. 1.7 which shows a simulated time series of radio frequency flux from a (bright) pulsar. Each individual pulse from a pulsar varies in intensity and shape, showing that the emission is more complex than a simple cone with a filled cross-section of constant intensity radiation. These pulse-to-pulse variations are overcome in pulse profile analysis as the pulses are folded in order to achieve an integrated pulse profile for a pulsar which represents the average emission as a function of its rotational phase. The folding technique uses a model of the pulsar rotation and the propagation of the radiation towards Earth (see Section 1.1.3) to accurately align consecutive pulses such that they can be coherently ‘stacked’, thus increasing the observed signal-to-noise. Folding of the data is often necessary as pulsars are typically very weak radio sources.

The journey taken by the pulsar radiation as it propagates towards Earth leaves a number of imprints that provide information on the interstellar medium (ISM) through which it has travelled. The downside of this is that accurate corrections need to be made to the observed radiation in order to reliably represent the emission from the pulsar itself. These phenomena are summarised in the following subsections.

Dispersion measure

The ISM, through which detected pulsar emission has travelled, consists of a cold ionised gas which affects the signals we receive. The observed emission travels from the pulsar
at a group velocity, \( v_g = cn \), where the refractive index of the medium, \( n < 1 \). As a result, the travel time of the radiation is increased from that assumed for a vacuum so that,

\[
t = \int_0^d \frac{dl}{v_g} = \frac{d}{c} + 4.15 \times 10^3 \nu_{\text{MHz}}^{-2} \int_0^d n_e dl \text{ seconds},
\]

where \( d \) is the distance to the pulsar, \( n_e \) is the electron density of the ionised gas and \( \nu \) [MHz] is the frequency of the electromagnetic wave (Lorimer & Kramer, 2004). The dependence of this delay on frequency is such that higher frequency waves experience a higher refractive index, thus having a higher group velocity and smaller delay. The integral \( \int_0^d n_e dl \) is known as the dispersion measure, DM, and is a measure of the total electron column density along the line of sight to the pulsar, generally given in units of pc cm\(^{-3}\). DM is a useful parameter to obtain when observing as it can be used to find approximate distances to pulsars if the electron density distribution of the ISM is known. Especially useful for these studies is the possibility of measuring orbital phase dependent DM variations as this can allow a measure of material within a pulsar binary system, as discussed in Section 1.3.1.

When observing over a small, finite bandwidth, the effect of the frequency dependence of the signal delay is to distort the received signal so that the pulse is smeared in time by,

\[
\Delta t \approx 8.3 \times 10^3 \text{DM} \nu_{\text{MHz}}^{-3} B \text{ seconds,}
\]

where \( B \) is the bandwidth and \( \nu \) is the central frequency of observation. A smeared, or dispersed, pulse resulting from the above effect would cause a broadened profile with low signal-to-noise, as shown in Fig. 1.8. In order to counter this, the received signal must be either coherently or incoherently de-dispersed. Incoherent de-dispersion makes use of frequency channels to divide the overall observing bandwidth into smaller bands. A separate delay can then be applied to each of these channels, based on a given value of DM, so that the pulse components observed in each channel superpose. The disadvantage of this method is that residual dispersion smearing remains within the finite bandwidth of
1.1. Pulsars

Figure 1.8: The frequency dependent effect of dispersion on pulsar observations. **Left:** A folded pulsar observation over a finite bandwidth. The lower frequency pulses are delayed relative to those at higher frequency, so much so that the pulses wrap around multiple pulse phases when the observation is folded with the rotation period of the pulsar. When averaged over the bandwidth, the pulse is almost completely smeared out (top). **Right:** The same observation after de-dispersion has been applied. The pulses now align over the full bandwidth, thus forming a clear, high signal-to-noise average pulse profile.

Each frequency channel. Alternatively, coherent de-dispersion, pioneered by Hankins & Rickett (1975), provides a method to completely remove the dispersion effects of the ISM. Here, processing of the signal occurs in the stage before detection. The full bandwidth is sampled at high speed then Fourier transformed before phase delays are applied. Finally, a reverse-Fourier transform is performed to recover the original signal without any residual dispersion effects. Although ideal, coherent de-dispersion can be computationally expensive, and the DM at which to perform the de-dispersion has to be known in advance of the observation.

**Rotation measure**

A further effect of the ISM is to rotate the linear polarisation vector of a pulsar’s radio emission. Linear polarisation of electromagnetic waves consists of both left-hand and right-hand circularly polarised components that superpose to form the observed linear vector. As a polarised electromagnetic wave travels through the ISM, the free electrons are forced into rotation by the two circularly polarised components causing an induced magnetic field. The induced magnetic field is directed in either the forward or backward direction of travel of the wave depending on the handedness of polarisation, and thus will be either parallel or anti-parallel to the component of interstellar magnetic field along the direction of travel. This phenomenon causes the two circular polarisations to
experience different refractive indices as they travel, resulting in slowing of one handedness relative to the other. The consequential phase shift, $\Delta \phi$, rotates the observed linear polarisation plane by an angle dependent on the magnetic field strength and electron content along the line of sight,

$$\Delta \phi = R M \lambda^2 \text{ radians,}$$  \hspace{1cm} (1.7)

where RM is known as the rotation measure, and is given by

$$R M = 0.81 \int n_e B \cos \theta dl \text{ rad m}^{-2},$$  \hspace{1cm} (1.8)

for $n_e$ in cm$^{-3}$, $B$ in $\mu G$ and $l$ in parsecs. RM becomes particularly useful when combined with a known value of DM for an individual pulsar as it allows determination of the average magnetic field strength along the line of sight to a pulsar, i.e. $B \cos \theta$, given by,

$$\langle B || \rangle \equiv \frac{\int_0^d n_e B || dl}{\int_0^d n_e dl} = 1.23 \mu G \left( \frac{R M \text{ rad m}^{-2}}{\text{ cm}^{-3} \text{ pc}} \right)^{-1}. \hspace{1cm} (1.9)$$

For binary pulsars, a measure of the magnetic field along the line of sight, combined with knowledge of the component of the magnetic field of the ISM in this direction, can provide an estimate of the magnetic field strengths present in the binary system itself.

**Scattering**

Scattering of pulsar radiation occurs as a result of inhomogeneities in the medium through which it travels; primarily, the ISM. The inhomogeneities cause multipath propagation of the radiation, where different rays travel along slightly different routes, and also distances, causing the detected pulse to be broadened in time relative to that emitted (see Rickett, 1990, for a review). The broadening is such that the trailing edge of a pulse becomes extended in time (see Fig. 1.9); this asymmetry arises as the earliest that an electromagnetic wave can arrive is along the direct path between the pulsar and Earth, and any deviation from this will lead to a longer travel time dependent upon the specific path taken.

The ability to accurately model this phenomenon is desirable as it can lead to a greater understanding of the medium through which the radiation has travelled. The simplest models assume a single thin screen between the pulsar and Earth, which gives corresponding broadening equivalent to the convolution of the intrinsic pulse with an exponential decay function (e.g. Williamson, 1972). The varying amounts of scattering can then be modelled through the decay parameter of the exponential, representing the characteristic scattering timescale, $\tau$.

The scattering timescale is observed to strongly depend on frequency (e.g. Lewandowski et al., 2015a), with increasing pulse broadening towards lower frequencies. Simple models of this effect have been proposed which assume either that the inhomogeneities in
1.1. Pulsars

Figure 1.9: The effect of scattering on pulsar observations. Left: An observation of the Crab pulsar with a small amount of scattering causing the trailing edges (i.e. the right-hand sides) of the pulses to be smeared to later phases. Right: An observation of the same pulsar with significantly more scattering of the pulses. The trailing edges are smeared to such an extent that flux from the separate pulses leak into one another. Careful inspection of the upper plot shows the scattering tail increasing towards lower frequencies. Image credit: adapted from Driessen et al. (2019).
the thin screen can be described as Kolmogorov turbulence (Lee & Jokipii, 1976; Rickett, 1977), or that scattering angles are distributed as a circularly symmetric Gaussian (Cronyn, 1970; Lang, 1971). These two models predict a power-law relation between $\tau$ and frequency: $\tau \propto \nu^{-\alpha}$, with $\alpha = 4.4$ or $\alpha = 4$, respectively. Although there are many observations in agreement with these models (e.g. Lewandowski et al., 2015b, for low DM pulsars), there are a significant number of studies that are inconsistent (e.g. Geyer et al., 2017; Krishnakumar et al., 2017). These inconsistencies have led to the general assumption that scattering is often complex, with anisotropic scattering (e.g. Geyer et al., 2017) or multiple scattering screens (e.g. Kuzmin et al., 2008; Smirnova et al., 2014; Driessen et al., 2019) sometimes providing better fits to observations.

**Timing of isolated pulsars**

A very useful measurement to obtain from pulsar observations is the time of arrival (TOA) of individual pulses. Much of the physics that one can learn about pulsars is inferred through precise knowledge of the rotation rate, slow-down of rotation rate over time, and any higher-order deviations or anomalies in the rotation. For example, measurements of TOAs have allowed the development of population studies and the $P - \dot{P}$ diagram (Section 1.1.1), and also the discovery and study of pulsar ‘glitches’ (Radhakrishnan & Manchester, 1969) where there is a step change in rotation rate attributed to angular momentum transfer between interior components of a neutron star. In addition, TOAs can be used to investigate external phenomena such as the dynamics of the Solar System (Caballero et al., 2018) and low-frequency gravitational waves (e.g. Tiburzi, 2018).

Pulsar timing is the act of accurately modelling the expected TOAs, both historical and future, by fitting the measured TOAs to a model incorporating parameters related to the physical properties of pulsar itself and the propagation of the electromagnetic waves between the pulsar and Earth. The first step in this process is to measure precise TOAs of observed pulses. Generally, this can be done by first folding the observed data with an initial basic model in order to build up the signal-to-noise of observed pulses (which will likely be slightly smeared due to the inaccurate model), then cross-correlating these with a model pulse profile to obtain a measurement of the TOA of a repeatable reference point in the pulse. These are known as *topocentric* TOAs and represent the TOAs of the pulses at the telescope used for the observation.

In order to be able to infer physical properties of the pulsar these TOAs must be corrected for time dependent external effects such as the motion of the Earth in its orbit. This correction aims to use the Solar System barycentre as a reference point for the arrival of pulses, and, assuming the pulsar is isolated, can be calculated as (Lorimer & Kramer, 2004)

$$\text{TOA}_{\text{bary}} = \text{TOA}_{\text{topo}} + t_{\text{corr}} - \frac{\Delta D}{\nu^2} + \Delta R_{\odot} + \Delta S_{\odot} + \Delta E_{\odot}. \quad (1.10)$$

The first correction term to the topocentric TOAs, namely $t_{\text{corr}}$, relates the telescope clock measurement to the international time standard Terrestrial Time (TT). The second term, $\Delta D/\nu^2$, corrects for the dispersion delay introduced by propagation through plasma,
and converts the TOA to one that would have been measured for an infinite observing frequency (or equivalently for propagation through a vacuum). This term is directly proportional to the DM for the pulsar. The third term, $\Delta R_\odot$, is the Römer delay and accounts for the precise location of the telescope in space relative to the Solar System barycentre. The final two terms take into account effects described by Einstein’s theory of general relativity. The so-called Shapiro delay, $\Delta S_\odot$, accounts for the curvature of space-time in the vicinity of the Solar System bodies. For electromagnetic waves passing through the Solar System this has the effect of increasing the propagation distance, and thus time, of travel between the pulsar and Earth. Finally, the Einstein delay, $\Delta E_\odot$, accounts for time dilation and redshift in the gravitational potential of the Solar System bodies.

By fitting the corrected TOAs to a model, one can not only infer physical properties of the pulsar such as its spin period, $P$, rotational deceleration, $\dot{P}$, but also the pulsar position and proper motion. The latter parameters must be part of the model because, when subtracting the Earth’s (and the observatory’s) motion, the changing position of the pulsar in the sky must be taken into account. Should all of the parameters be accurately modelled, then the residuals between the predicted and measured TOAs should resemble white noise. If this is not the case, then either the modelled parameters are incorrect or there are un-modelled parameters that require inclusion in the model. Identification of these flaws can be helped by considering the often unique signatures that each parameter has on the modelled TOAs, such as a linear trend introduced by an inaccurate rotation rate, or a sinusoidal trend introduced by an incorrect pulsar position.

**Timing of binary pulsars**

For pulsars in binary systems the pulse TOAs are not only modulated by all of the effects detailed above, but also include perturbations due to the orbital motion of the pulsar around the centre of mass of its binary system. This makes the modelling process more complex, requiring TOAs that sufficiently sample the (often short) orbital period of the pulsar, however in doing so one can learn valuable information about the attributes of the binary dynamics.

In modelling of binary pulsar TOAs, one needs to take into account two extra delay terms: $\Delta t_{\text{binary, classical}}$ and $\Delta t_{\text{binary, relativistic}}$. The first term essentially corrects for the pulsar system equivalent of the telescope-to-Solar System barycentre correction in the isolated pulsar case, and is dominated by the geometric delay caused by the line of sight component of the orbital motion of the pulsar. For binaries with orbital velocities far lower than the speed of light, the motion can be sufficiently described by Newtonian dynamics. In combination with Kepler’s laws of motion, the following parameters – the so-called Keplerian parameters – can be used to model the pulsar orbit: $P_b$ – the pulsar’s orbital period, $e$ – the eccentricity of the orbit, $a_p \sin(i)$ – the projected semi-major axis of the pulsar’s orbit onto the plane parallel to the line of sight, $\omega$ – the longitude of periastron (i.e. the closest approach of the pulsar to the binary centre of mass), and $T_0$ – the epoch of periastron. A schematic representation of these parameters is given in Fig. 1.10. Note also that some models make use of the epoch of ascending node, $T_{\text{asc}}$, in place of $T_0$.  

Chapter 1. Introduction

Figure 1.10: Schematic showing the parameters used to describe a classical Keplerian orbit for a pulsar in a binary system. The Earth lies in the direction of the z-axis, perpendicular to the reference plane. Here, $i$ is the orbital inclination, $\omega$ is the longitude of periastron, $\Omega$ is the longitude of the ascending node, $e$ is the orbital eccentricity and $a_p$ is the semi-major axis.

The latter of the additional delay terms, $\Delta t_{\text{binary, relativistic}}$, incorporates corrections to the above assumption of Keplerian motion. This consists of a series of post-Keplerian parameters, that only become significant when the orbital motion reaches relativistic velocities. Details of these parameters can be found in Damour & Taylor (1992), but are not covered here as the pulsars considered in this work reside in the non-relativistic regime.

Particularly relevant for this thesis is the observation of time dependent orbital parameters seen in some tight pulsar binary systems (e.g. Arzoumanian et al., 1994; Lazaridis et al., 2011; Shaifullah et al., 2016). These variations appear to occur preferentially in pulsars of the ‘black widow’ and ‘redback’ classes (see Section 1.3), and Shaifullah et al. (2016) show that they can be approximately modelled with smooth temporal variations of $a_p \sin(i)$, $T_0$ and $P_b$, although the resulting models are purely phenomenological and have no predictive ability for future TOAs. This effect has thus far been difficult to constrain, as not only are TOAs required that sufficiently sample the orbital phases, but they must also sufficiently sample the temporal wandering of the orbital parameters, which generally occurs on timescales of months-to-years. A number of theories have been put forward
for the physical causation of the orbital variations, such as magnetic cycles in the companion star (Applegate & Shaham, 1994, and Section 1.3.3) and/or spin-orbit coupling (Lazaridis et al., 2011), but the lack of appropriate data means that many differing theories are consistent with the observations.

1.2 Binary pulsars

Pulsars residing in binary systems occur naturally as a result of their formation from stellar binaries, which are abundant in the Milky Way. As explained in Section 1.1.3, the presence of a binary companion can hinder both searches for, and timing of, the host pulsar due to the distortion of the otherwise regular pulsations detectable from isolated pulsars. On the contrary, they open up a whole field of opportunity to study the nature of pulsars in alternative and dynamic environments. The presence of a binary companion is known to highly influence the attributes of a pulsar (see below), creating populations of pulsars that would likely not be observed should they be naturally isolated. In addition, binary pulsars can be invaluable to study theories of stellar evolution, neutron star equations of state (e.g. Özel & Freire, 2016) and even general relativity (e.g. Berti et al., 2015; Wex, 2014). This section briefly introduces the observed population of binary pulsars, and notably how this is determined by their prior evolution, thus giving a wider context to the sub-population of binary pulsars studied in this thesis – namely, the black widows and redbacks (see Section 1.3).

1.2.1 Population

At the time of writing, the ATNF Pulsar Catalogue (Manchester et al., 2005) lists approximately ten percent of known pulsars as being contained within binary systems. As shown in Fig. 1.3 the pulsars with binary companions dominate a distinct region in $P - \dot{P}$ phase space – the bottom-left quadrant signifying short spin periods, small spin period derivatives, low magnetic field strengths and high characteristic ages. It is also remarkable that not only are most binary pulsars MSPs, but most MSPs are in binaries. As we will see in Section 1.2.2, these observed properties are no coincidence, and are a direct consequence of their formation.

It can be useful to split the binary pulsar population into subsets based on the nature of their companion stars, as demonstrated in Fig. 1.11. It can be seen that the vast majority of the known pulsar binaries have degenerate companions, with only $\sim 6\%$ having main sequence (MS) companions reliably identified. This observation is likely a consequence of selection effects, as the lifetime of such a system is generally bound by the difference in lifetimes of the pulsar progenitor star and the MS companion star, which is orders of magnitude less than the lifetime of a pulsar – degenerate companion system, particularly if the pulsar is recycled. In addition, strong winds and the possibility of accretion from a MS star can have significant effects on pulsar emission processes, making these particularly difficult to observe (e.g. Lai et al., 1995, Stappers et al., 2019 in prep.).

Another key feature of pulsar binaries, shown in Fig. 1.11, is the observation that the dis-
Chapter 1. Introduction

Figure 1.11: Representation of the proportion of pulsars in binary systems along with their corresponding companion types. All values are calculated from the ATNF Pulsar Catalogue (Manchester et al., 2005), at the time of writing. Approximately 10% of known pulsars are in binaries, and the proportions of companion types are shown for both MSPs and slow-spin pulsars ($P > 30$ ms) separately, highlighting the effects of evolution. The companion categories shown are: helium white dwarfs (He WD), heavy white dwarfs and neutron stars (CO/ONeMg WDs & NS), main sequence (MS), ultra-light ($< 0.08M_\odot$, UL), triple (or more) systems (T), and those yet to be identified (Unidentified).
1.2. Binary pulsars

Distribution of companion types is distinctly different for slowly spinning pulsars than for MSPs. The slow pulsars appear to be preferentially partnered with higher mass degenerate companions – heavy white dwarfs and neutron stars – while the MSPs tend to be partnered by the lower mass helium white dwarfs and the so-called ‘ultra-light’ objects (< 0.08$M_\odot$). We will see in the following section that again this is no coincidence, and can largely be explained by a small number evolutionary scenarios beginning with different progenitor star combinations.

1.2.2 Formation

There are a number of different formation routes for binary pulsars, and these play a vital role in defining the characteristic parameters of the binary pulsar population. The ‘standard’ formation scenario for isolated pulsars as described in Section 1.1 becomes much more complex in binary systems as the evolution of each companion is highly dependent on the other. The most important factor in determining the subsequent evolution of binary stars is the exchange within the system, or loss from the system, of orbital and spin angular momentum. The change of total orbital angular momentum in binary systems is dependent upon gravitational wave radiation (Landau & Lifshitz, 1975), magnetic braking (Verbunt & Zwaan, 1981; Stepian, 1995; Eggleton, 2001), spin-orbit coupling (Witte & Savonije, 1999; Tauris, 2001; Tauris & Savonije, 2001) and finally mass loss from the system (van den Heuvel, 1994; Soberman et al., 1997). In depth reviews of formation scenarios are provided in Bhattacharya & van den Heuvel (1991); Tauris & van den Heuvel (2006) and Tauris (2015), and the formation of MSP binaries will be summarised here along with some alternative theories.

Generally, the progenitor systems to pulsar binaries are pairs of MS stars where at least one of the two is massive enough to form a NS, post-supernova. Alternatively, if the primary star is only massive enough to form a heavy WD at the end of its life, then a pulsar binary can still form as a result of accretion-induced collapse (AIC) of the primary, where mass transfer from the secondary can push the heavy WD to overcome the electron degeneracy pressure and collapse to form a NS (Hurley et al., 2010). In either case, the more massive star evolves along the MS quicker than the secondary, and the pair must remain gravitationally bound throughout the violent transformation phase (supernova or AIC) if they are to survive as a pulsar binary system. As the secondary star then evolves, further interaction between the pair can occur, thus further shaping the evolution of both bodies. The most common evolution paths thought to form MSP binaries involve a subsequent recycling phase (Alpar et al., 1982; Radhakrishnan & Srinivasan, 1982; Bhattacharya & van den Heuvel, 1991) where the pulsar is spun-up to sub-second periods via orbital angular momentum exchange in mass transfer from the binary companion. This mass transfer generally occurs due to Roche lobe overflow, where the companion star evolution leads it to expand beyond its Roche lobe radius – defined as the first gravitational equipotential surface around the star (Fig. 1.12) – leaving the outer material only loosely bound to the donor, thus allowing it to transfer to the primary star through the Lagrange point, L1. The exchanged material has a high specific angular momentum, thus, rather than
simply falling onto the NS surface, it forms a high velocity rotating disk around the NS. The interaction between the inner region of the disk and the pulsar’s magnetosphere determines the angular momentum gain of the pulsar (e.g. Ghosh & Lamb, 1992). The recycling phenomenon is observed as an X-ray binary – named so due to the relatively high X-ray luminosity. During this phase, the NS is not seen as a radio pulsar because the radio emission is quenched as a result of accretion.

The effect of companion stars at, or near, Roche lobe overflow is to circularise the binary orbit due to tidal distortion (Verbunt & Phinney, 1995), and to reduce the magnetic field of the primary star due to accretion (see Bhattacharya, 2002, for a review), which can explain the relatively low magnetic fields and orbital eccentricities that we tend to observe in binary pulsar systems. The X-ray binaries can be split into three categories based on the mass of the NS’s companion, and each leads to the formation of a different family of pulsar binary.

**Evolution of high-mass X-ray binaries**

As detailed in Tauris & van den Heuvel (2006), NSs in high-mass X-ray binaries (HMXBs) typically have companions with masses > 10\(M_\odot\). Mass transfer from the massive donor occurs primarily through a high-velocity wind (see Fig. 1.13) up until a point where the...
1.2. Binary pulsars

Figure 1.13: Typical mass transfer episodes from a donor star to a neutron star primary in high-mass X-ray binaries (HMXBs) – through a high-velocity wind – and low-mass X-ray binaries (LMXBs) – through an accretion disk fed by Roche lobe overflow of the donor. Image credit: Tauris & van den Heuvel (2006).
Chapter 1. Introduction

NS is engulfed by the extended envelope of the evolving donor. The following common-envelope evolution is not well understood, but it is assumed that it results in large orbital angular momentum losses and thus a significant decrease in orbital separation. If the binary survives this phase, then the common envelope is expelled but further mass transfer onto the NS may occur via Roche lobe overflow of the donor, spinning-up the NS for a relatively short timescale. The donor star eventually undergoes a supernova explosion forming a NS pair with a recycled (or partially-recycled, depending on the duration of the mass transfer stage) pulsar and a young, slowly spinning pulsar. The lack of accretion in the system after the second NS forms means that these binaries can have significant eccentricities induced by asymmetrical forces during the supernova. The remarkable ‘double pulsar’ system (Lyne et al., 2004) is assumed to have formed from a HMXB, however via a route slightly deviating from the final stages explained above, instead involving an electron-capture supernova of the second star (Ferdman et al., 2013); a recent review of double NS formation paths from HMXBs is given in Tauris et al. (2017).

Evolution of intermediate-mass X-ray binaries

Intermediate-mass X-ray binaries (IMXBs) – those with companions $1 M_\odot \lesssim M_C \lesssim 10 M_\odot$ – are much more difficult to observe than the other X-ray binary types, both as a result of their expected mass-transfer phases being relatively short lived, but also because the stellar wind accretion is much lower than in HMXBs, meaning that the associated bright X-ray emission of HMXBs is not formed (van den Heuvel, 1975). The evolution of such systems is as such difficult to determine, however they are assumed to be the progenitors of NS binaries with heavy CO or ONeMg white dwarfs (Tauris et al., 2012). The short-lived accretion phases in both IMXBs and HMXBs means that the recycling of the pulsar is often far from sufficient to result in millisecond spin periods, and as such we see a relatively large percentage of non- or partially-recycled pulsar binaries with the heavy companions expected from these systems. This is evident in Fig. 1.11.

Evolution of low-mass X-ray binaries

Most notable for the work in this thesis are the low-mass X-ray binaries (LMXBs) – with companions $\lesssim 1 M_\odot$. LMXBs are assumed to be the primary means of forming MSPs with low-mass companions, the most commonly observed pulsar binary type, through the standard recycling scenario (Alpar et al., 1982; Radhakrishnan & Srinivasan, 1982; Tauris & van den Heuvel, 2006). Mass transfer in LMXBs tends to occur in the form of an accretion disk surrounding the NS due to Roche lobe overflow of the evolving companion, as shown in Fig. 1.13. In comparison to HMXBs and IMXBs, this accretion is expected to be much more stable and longer lasting, resulting in pulsars being spun-up to very fast millisecond periods and potentially with high masses (Tauris & Savonije, 1999). Evolution of LMXBs tends to proceed along one of two distinct routes resulting in notably different final system parameters – those that converge to form ultra-compact
1.2. Binary pulsars

Figure 1.14: Modelled evolution paths for an LMXB with initial companion mass of $1 M_\odot$. The circles on the evolutionary paths denote the beginning of Roche lobe overflow (RLOF) and subsequent accretion onto the primary, while the triangle signify the end of RLOF. Image credit: Ma & Li (2009).

Binaries with low-mass WDs or planetary mass companions, and those that steadily diverge to form wide orbit, non-contact binaries with helium WDs (Pylyser & Savonije, 1988, 1989). The evolutionary route that an LMXB will follow depends on the duration of its orbital period relative to a bifurcation period – those with periods longer than the bifurcation period will diverge, and those with shorter periods will converge. The initial orbital period of bifurcation tends to be $\sim 1–3$ days, however this could strongly depend on the strength of magnetic braking within the system (Ma & Li, 2009), an example model of such a splitting is shown in Fig. 1.14.

Smedley et al. (2017) note that an issue with the standard recycling scenario presented above is that the observed distribution of orbital periods in MSP – helium WD binaries is only produced from an extremely narrow range of orbital periods in the progenitor systems. This ‘fine-tuning’ is deemed to be unlikely to occur in nature, and thus the formulation of an alternative evolution path is desirable. To this end, the authors propose a companion enhanced wind – a higher-than-expected mass loss from the companion, driven by tidal friction in the tight binary – that can strip the donor envelope at a faster rate, dependent upon the strength of the induced wind. Modelling of this scenario can much more reliably produce the observed distribution of MSP – helium WD binaries, and also offers a potential route to form the small proportion of slow pulsar – helium WD binaries that are observed, but difficult to form from the standard recycling scenarios.

The relative stability of LMXB evolution, and preferential formation of MSP – helium WD pairs, is key in explaining the large proportion of observed binaries of this type, shown in Fig. 1.11.
Alternative formation of millisecond pulsar binaries

Although the X-ray binary formation route, with recycled pulsars, is the most generally accepted method, there are alternative theories put forward to explain millisecond pulsar formation. One motivation for such alternatives is due to the ‘birth-rate problem’, where there is a significant discrepancy between the inferred birth rates of LMXBs to that of binary pulsars (Kulkarni & Narayan, 1988). This is noticeable in particular for short orbital period pulsar binaries where the implied birthrates are 100 times larger than that for the progenitor LMXBs, suggesting that a large proportion of binary pulsars must form by other methods. Freire & Tauris (2014) and Ablimit & Li (2015) present evolution models in which AIC of WDs can produce pulsars born with millisecond periods if the progenitor WD had already been sufficiently spun-up through accretion. Both studies show that this scenario can account for many of the MSP binaries that are difficult to produce through the standard recycling scenario, such as those with eccentric orbits (e.g. Barr et al., 2017; Stovall et al., 2019). Additionally, Jiang et al. (2015) propose a scenario that can occur after the formation of a pulsar binary in which subsequent spin-down of the massive MSP reduces centrifugal support, increasing the core pressure enough for deconfinement of quark matter. This results in rapid conversion of mass to binding energy in the NS, with the subsequent mass loss of the NS disturbing the binary orbit. This potential evolution route also offers an explanation for high-eccentricity systems that are not expected from standard recycling.

The reliance of both the recycling model, and the AIC model, on binary evolution to form MSPs has some interesting consequences. Notably, at the time of writing, ∼ 35% of MSPs are recorded as being isolated; a proportion seemingly far too high should all of these previously had binary companions, as there is no clear way how so many could become separated from their companions in the Galactic plane. To attempt to account for this a number of theories have been developed. van den Heuvel & Bonsema (1984) proposed that merger events between NSs and their WD companions could occur through angular momentum loss as the system evolves, and recent simulations by Sun et al. (2019) suggest that such a mechanism may be able to produce isolated MSPs with spin periods close to those observed. Alternatively, Bhattacharya & van den Heuvel (1991) proposed that isolated MSPs may form from a HMXBs that become unstable after the supernova of the companion, while Freire et al. (2011) and Portegies Zwart et al. (2011) suggest orbital stability in a triple system would naturally become compromised as a result of the evolution of the inner companion orbit, and could thus leave behind an isolated MSP. Finally, and particularly relevant to the work in this thesis, it may be possible to produce isolated MSPs through ablation of the companion star by the pulsar wind in tight binaries (Alpar et al., 1982; Kluzniak et al., 1988; Rasio et al., 1989; Bhattacharya & van den Heuvel, 1991, and Section 1.3.1). Possible evidence for this hypothesis is provided by observations of MSPs with planetary mass companions (Bailes et al., 2011) suggesting significant ablation of the companion could have taken place. However, mass loss rates inferred from observations and modelling (Eichler & Levinson, 1988; Stappers et al., 1996a) of such systems have thus far suggested that ablation alone is unlikely to form isolated MSPs within
Hubble time. The uncertainty surrounding these theories, with none convincingly being able to account for the observed isolated MSP population, leaves this to be an open and very much active area of debate.

**Globular cluster binaries**

The previous sections have offered explanations for the evolution and observation of binary pulsars in the Galactic field. Such information is applicable to the Galactic field pulsars that are studied in this thesis. However, as will be briefly discussed here, the evolution of binaries in globular clusters (GC) can be distinctly different, resulting in an observed population of GC pulsars that is somewhat at odds to that seen in the Galactic field. Notably, there are of the order of one thousand times as many MSPs per unit mass in GCs than in the Galactic field (Cadelano et al., 2018), and using data from the Globular Cluster Pulsar Catalogue\(^2\) at the time of writing, over half of the known GC pulsars are in binary systems, and almost 20% of the MSPs are in binaries with eccentricities, \(e > 0.2\), in stark contrast to the highly circular orbits observed for Galactic plane MSP binaries that form as a consequence of the evolution paths explained above.

In a nutshell, the primary reasons responsible for the observed differences are: 1) GCs form significantly more dense stellar environments than the Galactic field; 2) GCs have different progenitor distributions, with a higher proportion of stellar binaries than in the Galactic field (Ivanova et al., 2005). The large stellar densities in GCs mean that interaction events between stars, and star systems, are common. These interactions can not only perturb the orbital properties of a binary, but may even completely disrupt it, thus allowing swaps of companions, formation of isolated stars from binaries or vice-versa. In this way, many otherwise dead NSs find themselves in binary systems with MS stars. The evolution of the latter stars then transforms the system into an X-ray binary and then, later, into a MSP – WD system. This is the reason for the large proportion of MSPs (and also LMXBs) in globular clusters. These exchange interactions can then, in the more dense clusters, change the companions to the pulsars, forming systems that are impossible to find in the Galaxy (for a review, see Verbunt & Freire, 2014). As a result, stellar evolution is difficult to track, particularly in the case of MSPs where the previous mass and angular momentum exchange is unknown, and may even have occurred between multiple companions. It is for these reasons that this thesis largely focusses on the less chaotic population of Galactic field binaries.

**1.3 Black widows, redbacks and transitional millisecond pulsars**

It was mentioned earlier that the evolution of LMXBs hosting a NS can form either a NS – WD binary with a relatively long orbital period, or a compact NS – low-mass companion

\(^2\)http://www.naic.edu/~pfreire/GCpsr.html
binary dependent on its orbital parameters relative to the bifurcation period. For systems with initial orbital periods below the bifurcation period, the orbit shrinks primarily as a result of angular momentum loss through magnetic braking until the companion becomes degenerate (Ma & Li, 2009). The more compact of these binaries, with orbital periods $\lesssim 1$ day, are of special interest as the stellar companion is close enough to the host pulsar to potentially undergo significant irradiation from the pulsar wind, thus influencing their evolution (e.g. Jia & Li, 2016). In at least some of these systems, the irradiation of the companion continues beyond the LMXB phase, and into the long-lasting MSP – low-mass companion binary.

The first of these irradiating systems was discovered by Fruchter et al. (1988a) who named it the black widow (BW) pulsar due to the apparent evaporation or ablation of the companion star by the pulsar wind – akin to the arachnids of the same name, which are known to devour their companions! In the discovery observations the normal pulsed radio emission from the pulsar was seen to become regularly eclipsed for $\sim 10\%$ of the orbit. The long duration of the eclipses implied that the intervening body was larger than the Roche lobe of the companion, and excess plasma was detected pre- and post-eclipse through DM measurements. This led the authors to propose that this was a result of material driven from the companion star, possibly in the form of a wind, intervening the emission as it crossed the line of sight every orbit. Amazingly, this initial discovery paper proposed many of the interpretations of spider pulsars that remain prevalent to this day.

In the subsequent years more such systems were observed (e.g. Stappers, 1996) which also showed radio eclipses and had very low companion masses $< 0.1 M_\odot$, suggesting that these were all part of the BW class. However, in parallel to this, discoveries were made of a few eclipsing pulsar systems with comparable orbital periods, but much larger companion masses ($> 0.1 M_\odot$) than the previously known BWs (Lyne et al., 1990; Camilo et al., 2000; D’Amico et al., 2001b,a), but these were only found in globular clusters, where they could potentially be formed by exchange interactions. Following on, similar systems with relatively large companion masses were discovered in the Galactic disk (Archibald et al., 2009; Crawford et al., 2010; Hessels et al., 2011; Crawford et al., 2013), and due to the apparent dichotomy in the companion masses between these systems and the previous black widows, a new sub-class of irradiating pulsar binaries was spawned – the redbacks (RBs; Roberts, 2011) – creatively named after the Australian cousins of black widow arachnids. Colloquially, we refer to the BW and RB population as the spider pulsars. The first RB system found in the Galactic disk, PSR J1023+0038, is thought to represent a transitional stage between accretion-powered X-ray binaries and MSP – WD binaries. This implies that at least some RBs (e.g. Stappers et al., 2014; Papitto et al., 2013; Bassa et al., 2014) are the previously “missing links” leading to the formation of the vast majority of MSP – WD binaries, a prolonged stage where the system swings between the two phases. Since these initial discoveries there has been a steady flow of newly found irradiated pulsar binaries, boosted by a recent surge in discoveries as a result of targeted searches of $\gamma$-ray sources from the Fermi-LAT instrument (Ray et al., 2012; Grenier & Harding, 2015).

Fermi’s success in revealing many long-hidden spiders is rooted in the finding that they
often host MSPs with large spin-down powers, meaning that they are ideal factories for producing high-energy emission, the propagation of which is not hindered by the presence of the companion star. The spiders’ radio emission, on the other hand, is not free to propagate so easily to Earth, being subject to both eclipses and DM variations which make these difficult to find in traditional blind radio searches.

The growing population of spiders has strengthened the clear dichotomy of BW and RB companions (see Fig. 1.15). BWs are characterised by their visibly irradiated (e.g. Fruchter et al., 1988b), ultra-light companions in the mass range 0.01–0.05\(M_\odot\), while RBs have irradiated companions\(^3\) in the mass range 0.1–0.5\(M_\odot\) which are generally thought to be non-degenerate (D’Amico et al., 2001a; Roberts, 2013). At the time of this writing there are of the order of 50 known spider pulsars, with the BWs falling within the ‘UL’ category in Fig. 1.11, while the RBs are spread among the ‘MS’, ‘He WD’ and ‘Unidentified’ categories as a result of the difficulty in classifying the true nature of the companion stars amidst the irradiation, ablation and relatively low apparent magnitudes. However a promising future lies ahead, with the number of known systems now beginning to allow population-wide studies as opposed to independent investigations of individual systems. One such study of the known, and unconfirmed but likely, RBs (Strader et al., 2019) made use of new optical spectroscopy data, and previously published results, to stimulate a discussion on the RB population as a whole. In particular, it was highlighted that RB MSPs are generally more massive than the canonical mass (1.4\(M_\odot\)), with a median mass of 1.78 \(\pm 0.09M_\odot\), and although the majority of the companion stars lie in the previously predicted range of 0.1–0.5\(M_\odot\), there is evidence to suggest the presence of a tail in the distribution towards higher masses, \(\lesssim 0.9M_\odot\).

The separation between the two sub-classes naturally led to ongoing debates about the formation and evolutionary scenarios of spider pulsars with Chen et al. (2013) proposing that RBs and BWs form through separate formation channels determined by the efficiency of the irradiation process, while Benvenuto et al. (2014, 2015) propose theories that suggest all BWs are the descendants of RBs, with the RB phase representing a transition stage between LMXBs and BWs (although noting that not all RBs go on to form BWs).

### 1.3.1 Ablation and mass loss

The irradiation of the companion star in spider systems may occur directly, in the form of high-energy particles in the pulsar wind, or indirectly in the form of \(\gamma\)-rays from accelerated particles in a shock region between the pulsar and the companion (see Section 1.3.2). The irradiation is expected to significantly alter the companion star’s equilibrium, and is assumed to heat and/or increase the ionisation depth of the stellar envelope causing it to bloat and to drive an enhanced evaporative wind from the star (Podsiadlowski, 1991; van den Heuvel & van Paradijs, 1988; Phinney et al., 1988; Kluzniak et al., 1988). Additionally, the momentum pressure of the incident pulsar wind may be sufficient to physically drive.

\(^3\)Irradiation in RBs is often not as clearly detectable in optical observations due to the relatively high innate temperature of the larger companion meaning that irradiation heating is less significant.
Figure 1.15: Orbital periods and companion masses for recycled MSPs in the Galactic field. Here only those systems with MSP spin periods < 8 ms, and known companion star types, are shown. The black line represents the standard evolution model for MSP recycling from Tauris & Savonije (1999), and the dichotomy between BW and RB systems is clearly visible. Image credit: Strader et al. (2019).
material from the outer layers (Eichler & Gedalin, 1995). The process of this mass loss is generally referred to as the ablation of the companion star. The effect of the ablation depends on the irradiation efficiency – the fraction of incident radiation converted to heat at the surface of the companion – which has been estimated to be $\sim 10$–$30\%$ for a handful of systems (Breton et al., 2012). Significant mass loss from the companion could be expected for strongly enhanced evaporative winds, or indeed if the star bloats to fill its Roche lobe, causing further mass loss through Roche lobe overflow. However, models fit to measurements from optical observations of spider companions suggest that this is not always the case (Breton et al., 2012), which raises questions about the rate that material can be expelled from the companion surface. Brookshaw & Tavani (1995) alternatively consider the possibility that enhanced winds from the companion star may be driven by tidal distortion, rather than irradiation.

Observations of pulse time of arrivals often show excess delays either side of companion inferior conjunction that are attributed to increases in DM (e.g. Fruchter et al., 1990; Stappers et al., 2001a). This suggests that the excess material ablated from the companion surrounds the star, with Fruchter et al. (1990) observing asymmetric delays that represent a ‘cometary-like tail’ trailing behind the companion. It appears that this material must be continuously fed by ablation of the companion as it would be expected to be rapidly expelled from the system by the pulsar wind. This interpretation of the ablation can be used as an important tool to investigate the future evolution of the system. Using the excess DM measurements, in combination with an assumption about the line of sight depth, the overall density of the ablated material can be estimated. Taking this density, one can approximate the rate that mass is lost from the companion star through the use of simplified models of the outflow velocity and geometry. Such calculations have been performed for just a handful of systems (Thompson et al., 1994; Eichler & Levinson, 1988; Stappers et al., 1996a), which, interestingly, infer mass loss rates that are far below that expected to be able to fully evaporate the companion within Hubble time. However, the susceptibility of these results to the assumptions made about the geometry and outflow mean that, despite the opposing empirical evidence, the theory that spider pulsars can ablate their companions to the point of destruction (Alpar et al., 1982; Kluzniak et al., 1988; Rasio et al., 1989; Bhattacharya & van den Heuvel, 1991), leaving behind an isolated MSP, still lives on.

Recently, aided by the use of high sensitivity radio telescopes, innovative observations of the radio emission at orbital phases near eclipse have revealed that pulses can be magnified by up to approximately a factor of 100 in this region (Main et al., 2018; Bilous et al., 2018). The magnifications have been attributed to lensing from small inhomogeneities in the plasma surrounding the companion stars. The fact that the effects of the lensing are sensitive to the geometry and density profile of the plasma means that, although these studies are in their relative infancy, they offer an exciting prospect to determine properties of the ablated medium. Such constraints could have significant influences on both mass loss estimates and eclipse characterisation (see Section 1.3.4).
1.3.2 Intrabinary shock

The ablation of material from the stellar companion in an ultra-compact binary can provide a key ingredient in the formation of a shock region within a binary system, as depicted in Fig. 1.16. If the irradiating pulsar wind drives material from the companion star then there will be a region between the bodies where the pressure of the pulsar wind is equalised with that in the ejected material and, dependent on the relative strengths of the two winds, this can form an *intrabinary shock* (e.g. Arons & Tavani, 1993; Raubenheimer et al., 1995; Roberts et al., 2014). Intrabinary shocks are particularly interesting due to their very close proximity to the pulsar, in contrast to termination shocks in pulsar wind nebulae of isolated pulsars, thus offering a much deeper probe into the pulsar wind and its magnetisation parameters (Roberts, 2013).

Similarly to termination shocks, synchrotron emission is expected from intrabinary shock regions where the magnetic fields are provided by the pulsar wind or, in the case of shocks very close to the companion surface, the magnetosphere of the companion star (Roberts et al., 2014). The relative brightness of synchrotron emission from intrabinary shocks is thought to mainly depend on the pulsar spin down luminosity and the orbital separation, however the size of the companion also contributes; shocks are often observed to be brighter in RBs rather than BWs as more of the pulsar wind is intercepted (Roberts et al., 2014). Electrons in the intrabinary shock region are expected to be accelerated up to $\sim 3$ TeV (Arons & Tavani, 1993; Raubenheimer et al., 1995), thus producing high energy synchrotron emission which commonly manifests itself as orbitally modulated X-rays (e.g. Hui et al., 2015; Al Noori et al., 2018). The orbital dependence of the X-rays is thought to result from Doppler boosting of the emission along the tails of the shock, which can form double peak spectra as the line of sight slices through the two edges. Romani & Sanchez (2016) studied the plausibility of intrabinary shocks to re-process the pulsar wind energy and irradiate the companion star, finding that their models could improve fits for both observed asymmetric irradiation of companions and modulated X-ray lightcurves.

Wadiasingh et al. (2017) use the measured orbital phases of the X-ray spectra to infer whether an intrabinary shock is wrapped around the pulsar or the companion star, which in turn provides information on the relative strengths of the opposing media. In an extension of this study, Wadiasingh et al. (2018) develop models of intrabinary shocks that investigate the influence of either a companion magnetosphere, or a gas-dominated companion outflow, on the resulting shock phenomena. The authors highlight the necessity of further observations of spider pulsars at all wavelengths to constrain such models, and to consequently allow one to infer the nature of the opposing outflows.

A final note on this topic is that the acceleration of particles in the intrabinary shock region has been proposed as a contributing factor to the ‘cosmic ray excess’ observed at Earth (Venter et al., 2015).
1.3. Magneto-\textit{h}elical fields

The magnetosphere of a pulsar is crucial to its observable properties, and, as we will discuss here, the magnetic properties of a companion star may also become important in spider binaries. As such, the detection and measurement of magnetic fields originating from a companion star are highly sought after.

In Section 1.3.2 we introduced the intrabinary shock phenomenon observed in spider systems. The radiation that we detect from these shock regions originates from synchrotron emission as high energy particles accelerate along magnetic fields that permeate the shock. The origin, structure and strength of these magnetic fields are key to our understanding of the interaction between the binary companions, and a key aspect of this lies in being able to determine if the shock magnetisation arises from the magnetised pulsar wind alone, or if a significant contribution is made from a magnetosphere originating from the companion star (Arons & Tavani, 1993; Roberts et al., 2014). Additionally, as will be detailed further in Section 1.3.4, a magnetosphere hosted by the stellar companion could also help sustain a sufficient plasma density to account for the eclipses that we so often observe in spider systems (e.g. Khechinashvili et al., 2000, and Fig. 1.17). Thus, both the intrabinary shock and eclipse phenomena highlight the dependence of emission from pulsar binaries on the nature of the companion, and more specifically its magnetic field.

Another interesting hypothesis based on the presence of a companion magnetosphere is a model proposed to explain gravitational quadrupole coupling in close binary systems.
Figure 1.17: Schematic of a hypothesised companion star magnetosphere in a spider pulsar system. Here the magnetosphere is suggested to intercept our line of sight towards the pulsar as the companion orbits, affecting the propagation of the radio emission. Image credit: Khechinashvili et al. (2000).

(Applegate, 1992; Applegate & Shaham, 1994). This model attempts to link the magnetic cycles of a binary star with orbital period variations that are often observed in close binary systems (e.g. Arzoumanian et al., 1994; Shaifullah et al., 2016). In gravitational quadrupole coupling, the gravitational attraction between two orbiting bodies is dependent on their quadrupole moments, which in turn is dependent upon the oblateness of each. Thus, if the oblateness of an orbiting body is changed then the attraction between it and the binary companion, and consequently their orbital dynamics, are also changed. In the proposed model, the oblateness of the companion star is dependent on the differential rotation between its core and external layers, and it is proposed that the strength of the internal magnetic field will determine the differential rotation velocities as the field will act against this – tending towards solid body rotation – in order to reduce shearing of the field lines. Thus, as the magnetic field strength varies through the magnetic cycles of the star, the differential rotation and consequently gravitational quadrupole moment will vary in response. This mechanism has been proposed to account for the orbital period variations observed in PSR B1957+20 (Arzoumanian et al., 1994; Applegate & Shaham, 1994) and PSR J2051−0827 (Doroshenko et al., 2001; Lazaridis et al., 2011; Shaifullah et al., 2016).

The above phenomena rely on the presence of a companion magnetic field, and would be highly influenced by its properties. Despite this, detection and measurement of such fields have thus far proved problematic. Recently however, optical studies of spider systems, which are particularly sensitive to the emission from the companion star, are building increasing evidence for the presence of significant magnetic fields. In particular, observations of correlated optical and X-ray flaring from a BW companion star have been attributed to magnetic activity (An et al., 2017), while the observation of asymmetric heating of companion stars by the pulsar wind has been suggested to result from starspots or ducting of the intrabinary shock particles onto the surface along the companions magnetic field (Sanchez & Romani, 2017; van Staden & Antoniadis, 2016; Deneva et al., 2016). Further possible signatures of magnetic activity, this time in the radio frequency domain, have been detected by You et al. (2018), in which the pulses from RB PSR J1748−2446A...
become depolarised as the line of sight cuts through the ablated material surrounding the companion. However, somewhat opposing this, attempts to measure the companion magnetic field in BW PSR B1957+20 led to tight upper limits on the strength of any field, suggesting that it is far below that expected from observations of its eclipses (Fruchter et al., 1990; Li et al., 2019). These contrasting results highlight the necessity to study a wider set of spider pulsars if one is to build up a general picture of the properties and influences of companion magnetic fields.

1.3.4 Eclipses

When observing spider pulsars in the radio regime we often see the flux density of radio pulsations to drop – possibly even completely disappear – for certain orbital phases, thus we refer to these as eclipses. Studies of the eclipses (Fruchter et al., 1990; Lyne et al., 1990; Stappers et al., 1996a) inferred from the eclipse durations that the eclipsing regions are much larger than the companion star Roche lobes, and therefore suggest that the medium responsible cannot be gravitationally bound to star, and instead likely surrounds it. As the companion orbits, the medium intercepts our line of sight to the pulsar and affects the propagation of the radio emission. As shown by the authors, the eclipses are often seen to be frequency dependent with the duration of the eclipses reducing with higher observing frequency, and in some cases at high radio frequencies there are no eclipses whatsoever.

Fig. 1.18 shows observations of PSR J1023−0038 (Archibald et al., 2009) which clearly demonstrate the eclipse phenomenon and its dependence upon frequency. Another key feature demonstrated in Fig. 1.18 is the extended time delay of the pulse TOAs immediately pre- and post-eclipse. The TOAs are delayed as a consequence of increased dispersion along the line of sight, pointing directly towards an excess of electrons surrounding the stellar companion.

Unfortunately, a lack of data that sufficiently covers the radio spectrum, and variations between different spider systems, have made it difficult to characterise the exact eclipsing mechanisms. As a result, there are numerous theories that attempt to explain the radio eclipses, and fits of these to data are not usually conclusive. Thompson et al. (1994) present a thorough review of a diverse set of possible eclipse mechanisms, and attempt to apply these to observations of the two known eclipsing pulsars at the time – PSRs B1957+20 and B1744−24A. The contents of this review, along with mechanisms proposed elsewhere in the literature, are summarised here.

Refraction

Proposed as a possible eclipse mechanism soon after the discovery of the first eclipsing MSP (Fruchter et al., 1988a; Phinney et al., 1988; Emmering & London, 1990), it was suggested that the eclipses are observed as a result of the radio emission beam being refracted out of the line of sight by the density gradients present in the eclipsing material. Thompson et al. (1994) modelled this assuming an un-magnetised, sufficiently smooth plasma –
Figure 1.18: Flux densities (A–F) with corresponding average pulse profiles, and DM variation (G) of PSR J1023−0038. In the flux density plots the pulsar is generally visible as dark, double horizontal lines resulting from the double-peaked pulse profile. Near orbital phase 0.25 – corresponding to the companion stars closest approach to the line of sight between Earth and the pulsar – the dark lines fade, or disappear, showing the loss of flux from the pulsar that is referred to as an eclipse. The occasional ‘bending’ of the horizontal lines corresponds to increases in DM, which cause the pulsation to be delayed to a later phase. Image credit: Archibald et al. (2009).
allowing validity of geometrical optics – and applied it to observations of PSRs B1957+20 and B1744-24A. The frequency dependence of the eclipse duration predicted for a refractive mechanism is decided by the electron density distribution of the eclipsing material. The authors found that a power-law electron distribution of \( n_e = n_0 (r_0 / r)^\beta \) results in an eclipsing radius of \( b_c \sim \nu^{-2/(\beta+1)} \), while an exponential electron distribution leads to a weaker, logarithmic dependence of eclipse radius on observing frequency. However, this mechanism was ruled out for PSR B1957+20 due to the predicted frequency dependence of eclipse duration and time delays of the pulses being largely different from those observed, and was ruled out for PSR B1744–24A as the observed plasma density was too low to deflect the radio beam out of the line of sight.

### Scattering by plasma turbulence

In Section 1.1.3 the effects of scattering in plasma turbulence in the ISM were introduced. In general, pulsations become broadened as multipath propagation spreads out the arrival times of the radio waves. If the broadening in time exceeds the rotation period of the pulsar then the pulsations can be smeared into the baseline noise level, thus becoming undetectable. In the case of spider pulsars, it may be that the ablated plasma can result in increased scattering as it passes our line of sight, potentially causing effective eclipses. Thompson et al. (1994) stated that plasma turbulence could be induced by Cherenkov radiation from relativistic particles, however struggled to suggest this as a viable mechanism for PSRs B1957+20 and B1744–24A eclipses as it is expected that smearing of the pulses would occur well before the flux density of low frequency radio emission is reduced, in contrast to observations. They noted however that this may have a significant influence for higher frequency radio eclipses and suggested that it may account for the 1400 MHz eclipses in PSR B1957+20.

### Induced Compton scattering

Non-linear scattering mechanisms such as induced Compton scattering (ICS) may become significant when considering the high brightness temperature, and thus high photon occupation number, of pulsar radio emission. Levich et al. (1972) and Blandford & Scharlemann (1976) have studied the effects of ICS on radio emission from compact sources such as pulsars, and this theory has been examined further in Thompson et al. (1994). Here, ICS does not directly affect the photon count but it does significantly alter the radiation spectrum which can appear to have the same effect as absorption when observed with a finite bandwidth. When applied to the parameters of PSR B1957+20, Thompson et al. (1994) considered the most favourable scenario where a segment of the radio beam reflects from a region of high density material surrounding the companion and crosses the line of sight radio beam at a significant angle in the scattering region. They found that the optical depth resulting from ICS would be far too low to cause eclipse. However, in PSR B1744–24A the radio brightness temperature is higher at the companion radius than in PSR B1957+20, and so is the plasma density surrounding the
companion, thus allowing non-linear scattering to have a more significant effect. Thompson et al. (1994) find that although ICS still cannot be directly responsible the eclipses, it may induce stimulated Raman scattering parametric instabilities that could contribute.

**Stimulated Raman scattering parametric instability**

Another non-linear mechanism considered by Thompson et al. (1994) is a stimulated Raman scattering (SRS) parametric instability. In the earlier consideration of scattering of the radio beam off pre-existing plasma turbulence, the pulses can be smeared out, but the overall radio flux from the pulsar would not be diminished. An assumption made in modelling the simple scattering mechanism is that the effective temperature of the turbulence exceeds the brightness temperature of the radio emission, however in the region much closer to the pulsar where the brightness temperature is significantly higher, the radio emission may induce its own plasma turbulence through an SRS parametric instability. Should the induced turbulence persist, then the incident radio waves can scatter off this, and out of the line of sight. In this case, when the pump flux density of the radio emission exceeds a threshold value then the incident radiation beam can be strongly scattered onto a different path without significant pulse smearing. When the authors applied this with the parameters of PSR B1957+20 they found it to be a possible eclipsing mechanism at low frequency if the plasma temperature $\gtrsim 2 \times 10^5$ K and the plasma is not highly clumped. In the case of PSR B1744−24A the authors also find promising results for this as a viable eclipse mechanism if the plasma has a temperature $\gtrsim 3 \times 10^5$ K. Luo & Melrose (1995) and Luo & Chian (1997) provide alternative theories of induced scattering that involve scattering off Bernstein waves and electron acoustic waves – as opposed to Langmuir waves – respectively, and conclude that they can also plausibly fit the observed eclipses of PSRs B1957+20 and B1744−24A.

**Free-free absorption**

An alternative mechanism, based on absorption as opposed to scattering, is that of free-free absorption. This was first proposed early after the discovery of the first eclipsing MSP (Wasserman & Cordes, 1988; Rasio et al., 1989). Here, the radio emission is expected to be absorbed when incident upon free ions in a relatively cold wind, the density of which is assumed to decrease with radial distance from the companion star. Again, Thompson et al. (1994) applied this model to PSRs B1957+20 and B1744−24A assuming the wind density, $n_e \propto r^{-\beta}$, leading to an eclipse duration scaling with frequency as $\nu^{-2/(2\beta-1)}$. However, it was found that it could not reliably account for the observed eclipses in the specific cases presented by these two pulsars, as the predicted plasma temperatures for a significant optical depth are very low – not expected in a plasma in close vicinity of the energetic pulsar wind.
1.3. Black widows, redbacks and transitional millisecond pulsars

**Cyclo-synchrotron absorption**

A final mechanism considered by Thompson et al. (1994) was cyclotron/synchrotron absorption by electrons in the eclipse medium. In contrast to those above, this requires a magnetic field in the vicinity of the companion, provided by either the magnetised pulsar wind or a companion magnetosphere. Electrons originating from either the pulsar or companion wind permeate through this region, and the radio waves are absorbed at the resonant cyclotron frequency, and harmonics thereof. The expected radial dependency of the density and temperature of the eclipse medium leads to a smooth variation in the cyclotron frequency, thus wide-band absorption could occur as the radio emission traverses the full medium. In this model the optical depth of the eclipsing region reduces for higher harmonics which can explain why eclipses occur preferentially for lower frequency radiation. Khechinashvili et al. (2000) developed a comparable model whereby cyclotron damping is the cause of eclipses. Here, the companion stars are assumed to be similar to magnetic white dwarfs, and relativistic charged particles are provided by the pulsar wind which become trapped in the companion magnetic field – forming a magnetosphere. The radio waves propagating through the magnetosphere split into the eigenmodes of the pair plasma and become strongly damped at the cyclotron resonance. The frequency of radiation for which strong damping occurs is dependent on the magnetic field strength in the region – whereby high frequencies are damped at higher field strengths, closer to the companion. This has the effect of reducing the size of the eclipsing region as the frequency of radiation increases, and as a result can explain why eclipse durations are generally observed to be longer at lower frequencies. As part of the study, the model was shown to successfully represent the observed eclipse behaviour of PSRs B1957+20 and J2051−0827. In addition, Bhattacharyya et al. (2013) acknowledge that the cyclotron absorption models appear to be the most promising explanation for the eclipses in PSR J1544+4937.

**Searching for the evidence**

For the small handful of eclipsing pulsars studied thus far, at least one of the above mechanisms appears to be able to account for the observations. Notably, in a number of systems the cyclo-synchrotron absorption models provide seemingly favourable explanations. However, in every case the models are loosely constrained and depend heavily on the assumptions made about the physical properties of the eclipse medium. Furthermore, the wide range of properties across different spider systems mean that it is plausible that the eclipse mechanisms may vary from one system to another, and possibly even multiple mechanisms are at work in an individual system.

It is clear that to progress in this endeavour one requires a significant increase in observational constraints. In the near future these will start to become available across the radiation spectrum, giving ever tighter bounds on the properties of the companion stars, the intrabinary shocks and the eclipses directly. Specifically in the radio domain, much more precise measurements of DM and RM variations, pulse scatter broadening,
and wide frequency coverage will provide data that are sufficient to decisively test the validity of many of the above considered theoretical mechanisms.

1.4 Thesis outline

This thesis presents a programme of thorough research into the observable phenomena of eclipsing binary pulsars at radio-frequencies. Specifically, we have focussed on short orbital period (\( \lesssim 1 \) day), Galactic field, millisecond pulsars – the so-called black widow and redback pulsars. The overarching goal was to significantly increase the volume of observational constraints on the excess material within the binary systems, and the eclipses that occur as a consequence, in order to build up a solid base of results that can be used in future theoretical models of eclipse mechanisms, mass loss and interactions between the pulsar wind and ablated material. This study required us to obtain a large amount of radio-frequency data sets which have consisted of both archival observations and dedicated recent observations, arising from a number of successful proposals. The thesis has been partitioned into the following chapters:

Chapter 2
This chapter gives a brief introduction to radio telescopes in general, and then more specifically those telescopes that were used to perform the observations making up this thesis. This is followed by a technical description of some of the common analysis techniques that were used extensively throughout the work presented in later chapters.

Chapter 3
In this chapter we present our first investigation from the full body of eclipsing pulsar research. For this study we utilised the Low-Frequency Array (LOFAR) to observe the eclipses in the black widow pulsar PSR J1810+1744. The choice to use this telescope stemmed from the fact that the effects of dispersion and scattering increase with decreasing frequency, and LOFAR, with unprecedented sensitivity below 200 MHz allowed precise measurements of these key effects near eclipse. This pulsar was chosen due to its short orbital period – allowing observation of significant fractions of the orbit – its previously unstudied eclipses, and its notably high flux density at low-frequencies. We present an in-depth investigation into the eclipses at low-frequency, using both imaging and high-time resolution observations to measure variations in the DM, scattering and flux density, and discuss these findings in the context of the physical properties of the eclipse material.

Chapter 4
The work in Chapter 3 highlighted the value of low-frequency observations in eclipse studies, but also made clear the use of multiple eclipse observations and those at higher-frequencies for probing deeper into the eclipse medium and its variability over time. As
one of the first discovered black widows, there exists an enormous catalogue of observations of PSR J2051–0827 over a range of frequencies, and in this chapter we present a thorough analysis of a decades’ worth of these observations. The work reveals previously unknown trends in the variability of eclipses on timescales covering hours–years, and the polarised nature of the pulsar emission allowed constraints to be placed on the magnetic properties of the eclipse medium.

Chapter 5
Again building on the work of Chapter 3, where the capability of LOFAR to simultaneously perform imaging and high-time resolutions observations was demonstrated to provide a direct discriminator between eclipse mechanisms that remove flux from the line of sight and those that merely smear out pulsations, we present here a study of two further eclipsing pulsars utilising the same techniques. The two pulsars are the ‘original’ black widow PSR B1957+20, and the atypical redback PSR J1816+4510. Both of these systems have similar orbital properties, but vastly different companion masses, thus we investigate the effects that this has on the observed eclipses.

Chapter 6
As more is learned about the geometry and density profile of the eclipse material in spider pulsars, one of the key discriminators between eclipse mechanisms will be the frequency dependence of the observed eclipses. Here we bring together all of the pulsars that have been the subjects of the previous chapters in order to specifically study the dependence of the eclipses on the wavelength of the observation. Where necessary, and possible, previously published data at different wavelengths is incorporated into the study in order to get the widest available frequency coverage.

Chapter 7
Finally, in this chapter we summarise our results and discuss their impact in the field of spider pulsars and beyond. Additionally, we briefly introduce planned, and potential, future work that directly follows on from this study.
Chapter 2

Radio Telescopes and Data Processing

“Success is no accident, it is hard work, perseverance, learning, studying, sacrifice and most of all, love of what you are doing or learning to do.”

Pelé

2.1 Introduction

The aim of this chapter is to give a technical overview of the datasets and analysis techniques that were common to multiple bodies of work presented in later chapters. Section 2.2 covers an introduction to radio telescopes in general, and then more specifically to those that were used to obtain the data for the work in this thesis. Following this, Section 2.3 details data processing methods and analysis techniques that we made extensive use of throughout this study. In each case the relevant, standard observatory calibrations were applied, see references in each sub-section, which only detail the procedures specific to our data sets.

2.2 Radio telescopes

The work in this thesis heavily relied on the use of radio telescopes to observe eclipses of the radio emission from spider pulsars. As such, here a brief overview of the techniques behind these observations is given. Typically, most pulsar observations are carried out by single-dish radio telescopes; these are the archetypal radio telescope, consisting of a large parabolic reflecting surface – the ‘dish’ – which focuses incoming radio waves towards (usually) a single receiver. The parabolic dish means that these are highly directional, and thus tend to be steerable so that the antenna can ‘look’ towards chosen small areas of the sky. Through the use of a single receiver, the antenna essentially gives a ‘one pixel’ view of the area of sky, recording the intensity of radiation as a function of time. As pulsars
2.2. Radio telescopes

are point sources in the radio sky, spatial information is generally not required, and the large reflecting surface of the dish gives high sensitivity for detecting the faint sources. Alternatively, some radio telescopes come in the form of an interferometer. Interferometers are made up of multiple separate antennas, typically separated over a range of distances – on the order of metres to hundreds of kilometres. The individual antennas are often single-dish telescopes in their own right, or alternatively a large number of simpler antennas are used, such as the pyramid arrangement of 4 wires in the Low-Frequency Array interferometer (see below). Observations of pulsars with interferometers generally fall into two categories: beamformed observations and imaging observations. For both types the individual antennas are all pointed towards a single target, and the collected signals are brought to a central receiver where different artificial phase delays are added to the signals from each antenna. The phase delays correct for the relative distances between the source and each antenna and the different signal paths from each antenna to the central receiver. By making these corrections the signals from all antennas represent the coherent plane wave from the source and can be reliably combined; the difference between the two observing types lies in the nature of the signal combinations.

In beamformed observations the coherent signals from each antenna are summed together, thus effectively mimicking the total power received by a single telescope with an aperture diameter equal to the maximum antenna separation, and sensitivity approximately equal to the sum of the sensitivities of the individual antennas. This method can be advantageous over single-dish telescopes as a very large effective collecting area can be built up by combining many antennas.

On the other hand, imaging observations do not have a single-dish telescope equivalent. Here the array of antennas forms a large number of ‘baselines’ – combinations of pairs of antennas, with a ‘baseline length’ equal to the distance separating the two antennas in each pair. The signals from each antenna pair are cross-correlated, effectively producing interference fringes on the sky – analogous to pairs of slits in the famous Young’s slits experiment. The cross-correlations between antennas in a single integration time interval correspond to visibilities in the ‘u,v-plane’, which are direct samples of the 2D Fourier transform of the sky brightness distribution of the sources in the sky plane. The $u,v$-plane is a decomposition of the projected antenna baselines, as viewed from the source, into a component parallel to the section of the equator nearest to the source, $u$, and a component along the line between the nearest point of the equator and the north pole, $v$. As the Earth rotates underneath the source each baseline tracks an ellipse in $u,v$-space, meaning that measurements can be made in a large number of $u,v$ points, thus allowing the source distribution on the sky to be better constrained when the Fourier transform is taken.

The signals from sources at different positions in the sky will have different phase delays at each antenna depending on its relative direction, thus with precise knowledge of the location of each antenna these delays can be used to map the original source positions on the sky. However, due to the incomplete sampling of the $u,v$-plane, the Fourier transform of the visibilities does not produce the exact desired source distribution on the sky, and
instead produces a ‘dirty image’. This is equivalent to the actual source distribution convolved with a ‘dirty beam’ – also known as the ‘point spread function’ and is the Fourier transform of the sampling function, which is equal to 1 at measured \( u, v \) locations, and 0 at unmeasured locations. Unfortunately, the zero-valued components mean that a simple division in Fourier space to attain the genuine source sky distribution is not possible, and numerical approximations of the deconvolution of the dirty image with the dirty beam must be made. This results in a radio interferometric image, with a resolution equal to \( \frac{\lambda}{D} \), where \( \lambda \) is the observing wavelength, and \( D \) is the length of the longest baseline. Notably, the detection of sources in images is independent of whether or not the signal from the source is time dependent, as long as the integration time of the images surpass that of the signal variability. This is because the image reflects the total flux density of a source over the integration time, which will be distinguishable from the surrounding image background as long as the total source flux density is larger than the background noise level. This is in contrast to single-dish, or beamformed, observations which are sufficient only to detect variability (e.g. pulses from a pulsar) from the target point in the sky. This property can be utilised to probe spider pulsar eclipses, as images made throughout the eclipse region in spider pulsars can be used to directly discriminate between eclipse mechanisms which predict the total flux density of the pulsar to be removed from the line of sight (e.g. absorption), and those that predict the total flux to persist, but for pulsations to be smeared out (e.g. scattering).

### 2.2.1 The Low-Frequency Array

The LOw-Frequency ARray (LOFAR) is a European radio interferometer covering the frequency range 10–240 MHz. LOFAR consists of 3 major station types, the LOFAR Core, Remote stations and International stations. The Core, as the name suggests, is the main hub of the telescope and is the most densely packed station with radio antennas, located in Exloo, Netherlands. There are 24 Core stations, each made up of 48 high-band antennas (HBA) and 96 low-band antennas (LBA). There are 14 Remote stations, with locations spread further afield in the Netherlands, with each also consisting of 48 HBA and 96 LBA, however these are arranged in a different configuration than in the Core stations. Finally, 13 International stations each consist of 96 HBA and 96 LBA, and are located across 6 partner countries: France, Germany, Ireland, Poland, Sweden and UK. Further details of the array, and specifically its ability to observe pulsars are given in van Haarlem et al. (2013) and Stappers et al. (2011).

The necessity for two distinct antenna types – HBA and LBA – arises due to the observing frequency range spanning 8 octaves of the radio spectrum. Both antenna types are shown in Fig. 2.1. LBA, optimised for 30–80 MHz, each consist of a simple combination of four wires at 90° intervals connected between a flat, conducting ground plane and a raised central low-noise amplifier. This arrangement gives each antenna an omnidirectional response, with dual linear polarisation capabilities. Conversely, HBA are optimised for 120–240 MHz and consist of flat tiles, each containing 16 dual dipole antennas. Analogue
beamforming combines the response of the 16 antennas, giving each tile a single 30° beam at FWHM (at 150 MHz).

For the work presented in this thesis, observations with LOFAR utilised the HBA from \( \sim 20-24 \) Core stations. The correlators used to combine the raw complex-voltages from each station were Blue Gene/P and COBALT (Broekema et al., 2018), for observations before and after 2014-Apr-18, respectively. The data were recorded in the coherent Stokes mode (Stappers et al., 2011), forming a single tied-array beam from the stations over a 78 MHz bandwidth, centred at 149 MHz, with a sampling time of 5.12 \( \mu s \). These complex-voltage data were run through the LOFAR Known Pulsar Pipeline (PulP; Alexov et al., 2010; Stappers et al., 2011) using the pulsar ephemerides from the ATNF pulsar catalogue\(^1\) (Manchester et al., 2005) to perform coherent dedispersion and fold into PSRFITS\(^2\) (Hotan et al., 2004) archive files with sub-integrations of 5 s duration, 400, 195.3 kHz wide, frequency channels and a binning of the profile into \( 2^n \) bins, where \( n \) is decided by nearest and lowest power of two for \( 2^n \leq P/\Delta t \) where \( P \) is the pulsar period and \( \Delta t \) is the sampling time. Additionally, the files were split into four uncalibrated polarisation parameters – \( XX, YY, R[X,Y], I[X,Y] \) – corresponding to components of the coherency matrix. The resulting folded data were cleaned of RFI using the automated paz method of PSRCHIVE\(^3\) (Hotan et al., 2004).

A number of observations were also made using the commensal beamformed and imaging mode. This allowed simultaneous recording of the complex voltage data – described above – and correlated raw visibilities. The visibilities were collected with spectral and temporal resolution of \( \sim 3 \) kHz and 1 s, respectively. The maximum baseline of the Core stations is \( \sim 2 \) km, corresponding to a resolution of \( \sim 165 \) arcsec at 150 MHz with uniform weighting. These raw visibilities were reduced in an averaging pipeline and the resulting output stored in measurement sets with time intervals of 10 s duration and frequency channels of \( \sim 49 \) kHz width. Further details of the LOFAR pipeline are available in Heald et al. (2010).

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\(^1\)http://www.atnf.csiro.au/people/pulsar/psrcat/
\(^2\)https://www.atnf.csiro.au/research/pulsar/psrfits_definition/Psrfits.html
\(^3\)https://psrchive.sourceforge.net/
Chapter 2. Radio Telescopes and Data Processing

2.2.2 Westerbork Synthesis Radio Telescope

The Westerbork Synthesis Radio Telescope (WSRT; Baars & Hooghoudt, 1974) is an interferometer consisting of 14, 25 m diameter, dish antennas aligned East–West along a 2.7 km line near Westerbork, the Netherlands. Prior to mid-2015 each antenna had a Multi Frequency Front End (MFFE) with receivers allowing observations in 8 bands spanning 310 – 8650 MHz. Although this was the set-up used for the observations in this thesis, the WSRT has since been modified as part of the Aperture Tile in Focus (APERTIF) project to increase its field of view by a factor of 25 using phased-array feeds on each individual dish, operating exclusively at L-band.

In the work presented here, each observation made with WSRT was taken in one of two bands: a low-band centred at 345 MHz with a bandwidth of 70 MHz, and a high-band centred at 1380 MHz with a bandwidth of 160 MHz. The signals from individual antennas were coherently combined, and all observations utilised the PuMa-II back-end (Karuppusamy et al., 2008) to coherently dedisperse and fold the data with the pulsar ephemeris using DSPSR\(^4\) (van Straten & Bailes, 2011), and write to PSRFITS archive files. The low-band data were folded into archives with 1 min sub-integrations, 448 frequency channels of 156 kHz width, and pulse phase bins dependent on the pulsar spin period. Conversely, here the high-band data were folded into archives with 1 min sub-integrations, 512 pulse phase bins and 512 frequency channels of 312 kHz width. The resulting data were cleaned of RFI by means of the automatic median zap tool of PSRCHIVE.

2.2.3 Upgraded Giant Metrewave Radio Telescope

The Giant Metrewave Radio Telescope (GMRT), located North of Pune, India, is radio interferometer consisting of 30 single-dish antennas, each of 45 m diameter. The antennas are arranged with a central \(\sim 1\) km core containing half of the antennas, and 3 arms stretching away from the core in a “Y” shape containing the remaining half. The entire array spans \(\sim 25\) km. Over the last few years (prior to the writing of this thesis) the GMRT has undergone significant modifications as part of the Upgraded GMRT (uGMRT) project. The upgrade aims to offer as close as possible to continuous frequency coverage over 50–1500 MHz with a series of new broadband antenna feeds. The RF signals from each antenna are directly transported to a central receiver facility by optical fibre where they are converted to baseband, with a wide maximum bandwidth of 400 MHz, and sent to a digital back-end to perform correlation of the signals and beamforming. A key attribute of this system is the option to divide the array into subsets of antennas, with each subset observing in a separate frequency band. This allows for simultaneous multi-frequency observations, albeit with reduced sensitivity in each band.

For observations made with uGMRT for this work, a calibrator source, near in the sky to the target pulsar, was observed prior to the target to calibrate the phases of the signals from each individual antenna. This phase calibration was then repeated every \(\sim 1.5\) hrs

\(^4\)http://dspsr.sourceforge.net/
2.2. Radio telescopes

throughout an observation to correct for any wandering. The raw data from the observations, recorded with sampling times of either $40.96 \mu s$ or $81.92 \mu s$, were converted to filter-bank format using the `filterbank` tool from the SIGPROC\(^5\) software package. These were then folded and incoherently dedispersed using DSPSR with the most recent ephemeris for the pulsar. The resulting data represent the total intensity of recorded signals, with no polarisation information retained.

2.2.4 Parkes Radio Telescope

More traditionally, the Parkes radio telescope is a single-dish antenna that has been successfully operating since 1961. Its large 64 m parabolic collecting area, twinned with technological advancements over the years has meant that the Parkes telescope is still one of the world’s best radio frequency observatories. In contrast to the other telescopes used in this work, the Parkes observatory is located in the Southern hemisphere, near Parkes, Australia. The parabolic reflecting dish focuses incoming radio waves towards a raised central receiver, for which several options are available. The observations used as part of this thesis were made using two separate receiver–back-end combinations: the L-band Multibeam receiver with the Digital Filter Bank Mark IV (DFB4) back-end, and the newly-operational Ultra-Wideband Low-Frequency receiver (UWL) with the Medusa back-end. The DFB4 back-end recorded data in $8.81 \mu s$ samples, centred at a frequency of $1369 \text{ MHz}$ with a bandwidth of $256 \text{ MHz}$, and were later split into 1024 channels, folded and written to `PSRFITS` files. The Medusa back-end recorded data in $8.81 \mu s$ samples over $705–4031 \text{ MHz}$, split into 3328 channels, folded and written to `PSRFITS` files. Similarly to the LOFAR data, for both options the data were provided in four uncalibrated polarisation parameters – $XX$, $YY$, $\Re\{XY\}$, $\Im\{XY\}$, which were converted to Stokes parameters using pam in post-processing. `PSRCHIVE`'s `paz` tool was used for automatic RFI excision.

2.2.5 Lovell Radio Telescope

Similarly to the Parkes telescope, the Lovell telescope is a large single-dish antenna. Based at the Jodrell Bank Observatory, UK, the Lovell telescope has been operational since 1957, and consists of a 76 m diameter parabolic reflecting surface, with a central focus box containing the front-end receiver hardware. Observations made with the Lovell telescope utilised the ROACH back-end (Bassa et al., 2016). The data were recorded over a $400 \text{ MHz}$ bandwidth, centred at $1532 \text{ MHz}$. Folding of the data used DSPSR with the catalogued pulsar ephemeris, and these were written to `PSRFITS` archive files with 10 s sub-integrations, 1600 frequency channels and 512 pulse phase bins. As for the WSRT observations, the archive files were cleaned of RFI using `median zap`.

\(^5\)http://sigproc.sourceforge.net/
2.3 Data processing and analysis

For all data used to produce the work in this thesis some common steps of post-processing and analysis methods were used. These will be detailed here to avoid repetition in later chapters.

As explained above, some telescope pipelines already included automatic RFI excision steps prior to the data being made available to the user. However, the automatic excision methods are not perfect, and so whether or not this step had taken place all folded PSRFITS files were manually inspected and excised of any remaining obvious RFI using the interactive psrzap tool of PSRCHIVE.

In Section 1.1.3 the variable nature of orbital parameters in spider pulsars was highlighted. These variations had direct implications for the observations used in this work, as the accuracy of readily available timing solutions reduced quickly with time. As such, after the folded data had been excised of RFI, pulse TOAs were estimated and fit to the most recent timing solution available for the corresponding pulsar. In order to correct for the small offsets in the orbital parameters, TEMPO2 was used to optimise the solution by allowing a small number of parameters to vary freely. The choice of free parameters was determined by the accuracy of the original timing solution and the quality of the new data to fit, and in each case a trial-and-error based approach was utilised. Specific details of the method and chosen free parameters are given in later chapters for the corresponding pulsars.

In addition to variable orbital parameters, the observed DM of a pulsar can fluctuate over time. Such fluctuations are generally independent of the pulsar system itself and are dominated by changes in the ISM along the line of sight. The small fractional offsets from the original DM used to dedisperse the observation are often negligible, however at frequencies $\ll 1$ GHz they can cause significant differential delays across the observing bandwidth, and thus need to be corrected. For observations used in this work the folded data were analysed using PSRCHIVE’s pdmp tool to find the ‘optimal’ DMs. This method defines the optimal DM to be that which maximises the signal-to-noise of the pulse profile when integrated over the observing bandwidth. With a user-specified range and interval size of DM values, for each step pdmp phase rotates the profile in each frequency channel by an amount determined by the offset from the current DM of the data and the centre frequency of each channel, and then integrates the rotated profiles over all frequency channels to calculate the signal-to-noise at the corresponding DM. After application of pdmp, the DM value that provided the highest signal-to-noise profile was installed into the folded data using pam. Similarly to the method used in the pdmp search, pam performs an incoherent DM correction by rotating the phases of the pulse profiles in each frequency channel using the standard cold plasma dispersion law,

$$t_{DM} \approx 4.15 \times 10^3 \frac{DM}{\nu^2} \text{ seconds,}$$

(2.1)
where $\nu_{\text{MHz}}$ is the centre frequency of a channel in MHz, to calculate the corresponding delays.

Note that the definition of ‘optimal’ DM is not properly defined, and a number of different metrics are generally used – e.g. maximising the gradient of the leading edge of the pulse or reducing the TOA residuals between pulses at different frequencies – which may give slightly different absolute ‘optimal’ DM values. However, when the goal is to approximately align the pulses in each frequency channel for further analyses, rather than a measurement of the absolute DM of a pulsar, then any of the methods can be justified, and one has only to be consistent in the method that is used over all observations.

### 2.3.1 Calibration

In certain aspects of this work – long-duration observations in Chapter 3, polarisation studies in Chapters 3 and 4, and image-plane observations in Chapters 3 and 5 – there has been a requirement to calibrate the observed data prior to analysis. The necessity for this was to correct for often frequency-dependent instrumental effects introduced by the pointing direction, receiver and signal path that would otherwise have a significant impact on the interpretation of the data.

Here we have applied calibration methods to both LOFAR and Parkes datasets. The receivers in these telescopes use two orthogonal dipoles to measure the incident electric field components along the two axes, $E_x$ and $E_y$. As a consequence of imperfections in the signal path, and variations in pointing direction over an observation, the measured electric field components are modified relative to those of the incident radiation. This modification can be quantified as,

$$
\begin{pmatrix}
E_{x,\text{measured}} \\
E_{y,\text{measured}}
\end{pmatrix} = \mathbf{J} \begin{pmatrix}
E_{x,\text{incident}} \\
E_{y,\text{incident}}
\end{pmatrix}
$$

where the *Jones matrix*, $\mathbf{J}$, represents the instrumental response, containing information on, for example, the gain of the dipoles (absolute and relative), relative delays between signal paths, ‘leakage’ of signals from one dipole to the other and geometric projection effects. As such, in order to recover the intrinsic electric field components of the incident radiation, one must apply the inverse of the Jones matrix to the measured values. Fully defining the Jones matrix can be a complicated endeavour, especially for interferometric arrays (e.g. Lenc et al., 2017), but with knowledge of the geometry of the dipoles, possibly in combination with dedicated calibrator observations, approximations can be made that correct for the most significant factors.

**Beamformed data**

The sensitivity of LOFAR antennas is highly dependent on the beam pointing direction relative to the zenith. This is a consequence of the flat tile arrangement of the HBAs meaning that projection effects become important as the beam pointing approaches the horizon, where the sensitivity is drastically reduced. For short duration observations,
or those covering only high elevation angles, the effect of this is approximately limited to a constant scaling factor for the target flux density over the observation. In this case flux calibration is only important if one wishes to measure the absolute flux density of a source. Alternatively, for long duration source-tracking observations, or for those where the beam pointing varies over a range of low elevations, the effect becomes differential over the observation. In Chapter 3 we analyse some long-duration LOFAR observations, where the beam elevation varies significantly throughout. To this end, flux calibration was performed using lofar_fluxcal.py from the LOFAR-BF-pulsar-scripts package\(^6\), detailed in Kondratiev et al. (2016), to correct for instrumental gain variations as a function of time and frequency. In brief, this script scales each sub-integration, frequency channel and polarisation based on a theoretical flux density estimation using the signal-to-noise of the data and assumed values for instrumental effects. Specifically, this makes use of the Hamaker-Carozzi beam model (Hamaker, 2006, with \texttt{mscorpol}\(^7\)) to estimate the antenna response (i.e. the Jones matrix), system temperature estimations using the Haslam et al. (1982) sky model scaled to LOFAR frequencies as \(\nu^{-2.55}\) (Lawson et al., 1987) and model antenna temperatures from Wijnholds & van Cappellen (2011) as a function of frequency. Also accounted for are the fraction of operational HBA tiles, fraction of channels and sub-integrations that were excised due to RFI during PulP, and a power law scaling of coherent station summation based on the number of HBA stations used. The noise level in the data is estimated using the mean and standard deviation of a predefined off-pulse region of the profile in each sub-integration, channel and polarisation. Accurate polarisation calibration is in general more difficult to achieve than absolute flux calibration as the relative delays and sensitivities of the orthogonal dipoles become important. This can be understood by looking at the definition of the Stokes parameters that contain information on the polarisation properties of an electromagnetic wave,

\[
I = \langle E_x^2 \rangle + \langle E_y^2 \rangle \tag{2.3}
\]

\[
Q = \langle E_x^2 \rangle - \langle E_y^2 \rangle \tag{2.4}
\]

\[
U = 2 \langle E_x \rangle \langle E_y \rangle \cos\Phi \tag{2.5}
\]

\[
V = 2 \langle E_x \rangle \langle E_y \rangle \sin\Phi, \tag{2.6}
\]

where \(\langle \ldots \rangle\) represents the average over the sampling time, and \(\Phi\) represents the phase difference between the orthogonal electric field components. It can be seen that the total intensity, \(I\), has no dependence on the relative phases or sensitivities of the two components, instead depending only on their sum. On the contrary, the electric field polarised along the dipole axes, \(Q\), although independent of phase delays does depend on the relative magnitudes of the measured electric field components. Finally, the electric field polarised at 45° to the dipoles, \(U\), and the circular polarisation, \(V\), both depend on the phase difference between the field components, and thus on the relative delays of the signal paths. In light of the difficulty of fully defining the Jones matrix for polarisation

\(^6\)https://github.com/vkond/LOFAR-BF-pulsar-scripts
\(^7\)https://github.com/2baOrNot2ba/mscorpol
2.3. Data processing and analysis

calibration, the approximate methods explained below have been used for this work. These approximations are deemed sufficient here as our work concentrates on variations in flux and polarisation as a function of the orbital phase of binary pulsars, i.e. a function of time, thus instrumental effects such as leakage between the two dipoles, which is approximately independent of time for a given telescope, become somewhat less important.

Polarisation calibration of LOFAR observations followed the method of Noutsos et al. (2015) to apply the inverse of the instrumental response using approximations of the Jones matrices generated from the Hamaker-Carozzi beam model for each beam pointing and frequency channel. Application of the Jones matrices to perform the calibration used \textsc{psrchive}'s \texttt{pac} command. \textsc{psrchive}'s \texttt{pam} was then used to convert the calibrated data into the four Stokes parameters, $I$, $Q$, $U$, $V$. Measurement of RMs in LOFAR data, such as that performed for Chapters 3 and 4, has recently been shown to be near-independent of the calibration method, albeit with a simple sign-change of the RM that would need to be flipped should no calibration have taken place (Sobey et al., 2019). Thus, the approximate method of calibration used here does not significantly impact the results.

Parkes polarisation calibration is relatively mature in that full receiver solutions have been developed for a number of the optional receivers (e.g. Manchester et al., 2013) that accurately account for time-independent factors such as leakage. However, due to the lack of availability of these solutions to us at the time of this work, this stage of the calibration was omitted in the knowledge that we are primarily interested in variations in polarisation that correlate with the orbits of binary pulsars. To correct for the time-dependent factors of the instrumental response, specific calibration observations were made immediately pre- and post-target observation. The calibration observations consisted of pointing the telescope in a direction slightly offset from the target pulsar – so as to achieve similar background signal while avoiding any bias from the target itself – and injecting a controlled, periodic noise diode signal at the receiver. The diode signal, polarised at 45$^\circ$ to the receiver dipoles, could be folded at the known periodicity, mimicking a pulsar. The final measured Stokes parameters could be compared to the known parameters of the injected signal to approximate the Jones matrix. The Jones matrix solution was then applied to the observation of the target pulsar using \textsc{psrchive}'s \texttt{pac} command.

Interferometric data

In Chapters 3 and 4 studies of eclipse behaviours are performed that utilise the simultaneous interferometric and beamformed mode of the LOFAR Core stations. Accurate analysis of interferometric data heavily relies on calibration of the sensitivities and phase delays of each baseline (i.e. pair of antennas) in order to produce images of the target sky, and as such, calibration tools and techniques have been well developed to perform this task. In this work, we were fortunate to only require relatively ‘simple’ observations which made use of the closely-located Core stations to image a point source target at the phase centre of the beam. This rendered many (direction-dependent) calibration complications near obsolete, such as trying to account for the curvature of the Earth and different
ionospheric conditions over long antenna baselines – important when using Remote and International stations – or beam shape effects that become increasingly significant with angular separation from the beam centre. As a result, the standard set of LOFAR tools could be used to perform first order flux and phase calibration.

The data presented in Chapter 3 were analysed prior to the full development of the LOFAR pre-facet calibration pipeline (prefactor, see below), thus a more manual ‘pipeline’ approach had to be followed. The measurement sets, containing $u$-$v$ visibilities, were processed using standard LOFAR tools, with A0Flagger (Offringa et al., 2010, 2012b,a) used for RFI flagging and Black Board Self-calibration (BBS; Pandey et al., 2009) used for both flux and phase calibration. Flux calibration of the ‘calibrator’ source, 3C295, was carried out using a pre-defined LOFAR sky model for the source (Scaife & Heald, 2012) and the resulting gain solutions were applied to the measurement sets corresponding to the subsequent observation of the target pulsar. Self-calibration was performed using a sky model of the target source region from the TGSS LOFAR Sky Model Creator. Imaging of the calibrated visibilities was carried out using CASA, thus no primary beam correction was applied. This lack of correction is justified due to the location of the pulsar at the centre of the image, thus any effect of the changing beam shape over time was negligible.

For observations presented in Chapter 5, the prefactor pipeline was utilised for calibration. The pipeline automates the calibration steps explained above, including additional ionospheric RM corrections using RMextract (Mevius, 2018) and removal of the element beam. The calibrated data were imaged using WSClean (Offringa et al., 2014), allowing LOFAR-specific beam correction.

### 2.3.2 DM and scattering model fitting

Key to our understanding of eclipsing pulsars is detecting deviations from the out-of-eclipse values of pulsar flux density, DM (proportional to the amount of electrons along the line of sight) and scattering throughout the orbit in order to constrain the physical parameters of the material in the eclipsing medium. For all pulsars in this work we attempted to measure these parameters, however due to a lack of readily available software methods to make such measurements a custom Python script was developed to determine these parameters from our data as a function of orbital phase; we plan to make this available for future use. One of the main difficulties affecting measurements of DM and scattering is that these parameters can be highly covariant in their effect on a pulse profile when integrated over frequency, as both act to shift and broaden the pulse by delaying the arrival of pulsar flux more at low-frequencies than at high. As such, the method developed uses a two-dimensional pulse template, with both pulse

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8https://github.com/lofar-astron/prefactor

9https://github.com/lofar-astron/prefactor/tree/master/skymodels

10Scaife & Heald (2012) quote ~ 3% uncertainty on flux density at 149 MHz.

11http://tgssadr.strw.leidenuniv.nl/doku.php

12https://casa.nrao.edu/

13https://github.com/lofar-astron/RMextract/

14https://sourceforge.net/projects/wsclean/

15https://www.python.org/
2.3. Data processing and analysis

phase and frequency resolution, to aid in breaking degeneracies between DM and scattering through their marginally different frequency dependent signatures. The resulting template-fitting method is described in detail here.

For each pulsar a template was made by spin-phase-aligning and summing all of the out-of-eclipse observations of the pulsar along the time axis. This ensured maximum signal-to-noise templates while avoiding any pulse smearing that may appear near eclipse edges. The high signal-to-noise templates kept a frequency and pulse phase binning equal to that of the data. The next step was to apply a third-order Savitzky-Golay filter (Savitzky & Golay, 1964) along both axes to smooth out the small scale noise variations that remained. The Savitzky-Golay filter recalculates the value for a data point by fitting a third-order polynomial to all neighbouring points within a user-defined window centred on the data point in question, and takes the value of the fitted polynomial at the position of the original data point to be its new value. The window slides along the axis to the next data point, and the process is repeated. The nature of this method means that a larger window of data points used in the polynomial fit results in a smoother, i.e. reduced variance, model of the data. For this reason, the window-lengths used here were pulsar dependent as those with sharper features in their pulse profiles required a filter with a shorter window length. To test the validity of the Savitzky-Golay filter an alternative method – namely, a cubic smoothing-spline – was used to smooth one of the original raw templates, and both were fit to the same dataset using the method explained below.

The resulting best fit values of the DM offset from the out-of-eclipse level, \( \Delta DM \), and scattering timescale offset, \( \Delta \tau \), relative to the out-of-eclipse values using both templates were consistent within 1\( \sigma \) uncertainties, as expected given the high signal-to-noise of the pre-smoothed templates, thus the Savitzky-Golay filter was taken to be sufficient for all further analyses.

With a given pulsar’s smoothed template as a base, an array of further templates were made by artificially dispersing and scattering the baseline template with user-defined steps of \( \Delta DM \) and \( \Delta \tau \), over ranges of \( \Delta DM \) and \( \Delta \tau \) pre-determined by inspection of the data. The specific ranges and step sizes used are given in later chapters corresponding to the relevant pulsar. To generate the dispersed and scattered templates we assumed validity of the cold plasma dispersion relation (Equation 2.1) and modelled scattering as a convolution of the pulse with a frequency dependent exponential, \( \frac{1}{\tau} \exp^{-t/\tau} \), where \( \tau \propto \nu^{-4} \) (Lang, 1971; Lee & Jokipii, 1976). Three examples of smoothed templates are presented in Fig. 2.2, showing the baseline template, a dispersed template and a dispersed and scattered template made from observations of PSR J1810+1744, which were used in the work detailed in Chapter 3.

Using the array of templates an estimate of the \( \Delta DM \) and \( \Delta \tau \) parameters as a function of orbital phase, for a given observation, could be made. The script initially split the observation into individual sub-integrations, and ‘cleaned’ the data of residual RFI by masking any frequency channel with a mean flux level larger than 3\( \times \) the standard deviation of channel-wise mean fluxes for the corresponding sub-integration of data. The effective uncertainty in the flux of each data point was assigned by taking the standard
deviation of the user-defined off-pulse region in the pulse profile of each channel. The sub-integration of data, along with corresponding uncertainties, was then fit to the templates one at a time. The fit performed was a simple least-squares fit, with the template baseline and scale factor as free parameters, returning a minimum $\chi^2$ value per template. Thus, for every sub-integration of data, a two-dimensional $\chi^2$ map was obtained over the ranges of $\Delta DM$ and $\Delta \tau$. Finding the maximum likelihood of $\Delta \tau$ allowed the distribution of $\chi^2$ values for $\Delta DM$ to be calculated as a function of sub-integration of data, and vice-versa for $\Delta \tau$, meaning that any degeneracy between $\Delta DM$ and $\Delta \tau$ contributed to the corresponding uncertainties. The minimum $\chi^2$ values for each sub-integration were taken to represent the best estimate of $\Delta DM$ and $\Delta \tau$.

A useful feature of this method was that the scale factor, and corresponding uncertainty, of the best fitting template for each sub-integration was directly proportional to the pulsed flux density from the pulsar. Thus, as long as the data were corrected for instrumental observing effects prior to the fits, then the constant of proportionality between the template scale factor and the pulsed flux density was uniform throughout a given dataset, and the scale factor of the best fit template for each sub-integration of data represented the relative flux density of the pulsar through time. This was key for accurately identifying the pulsar eclipses. Fig. 2.3 shows the results of the method when applied to an eclipse egress observation of PSR J1810+1744.

An extension of this method was made for observations $> 1$ GHz, where 4 free param-
2.3. Data processing and analysis

Figure 2.3: Example results from the DM and scattering template fit to an eclipse egress observation of PSR J1810+1744. The top panel shows the observed data for the pulsed flux density against orbital phase, where darker shades represent higher intensity. The second panel shows the scale factor of the best fit template, which is directly proportional to the pulsed flux density. The third panel shows a contour map of the $\chi^2$ values for $\Delta$DM, where the black, dark brown and light brown regions represent those values within 1$\sigma$, 2$\sigma$ and 3$\sigma$ of the minimum, respectively. The bottom panel shows the corresponding $\chi^2$ contour map for $\Delta$\tau.
eters were included across the bandwidth to allow for different scale factors of the sub-bands in order to model the effects of diffractive interstellar scintillation (DISS) — expected to have a decorrelation bandwidth significantly wider than the channel widths. For example, for PSR J2051−0827 (studied in Chapter 4) the DISS decorrelation bandwidth at 1.4 GHz is expected to be \( \sim 25 \text{ MHz} \), which could cause large variations in the pulsar flux density across the observing bandwidth, and thus affect the template fits should only one parameter be used to model the pulsar flux. Conversely, at 149 MHz and 345 MHz – the centre frequencies of LOFAR and WSRT observations used in this work – the DISS decorrelation bandwidths are expected to be \( \sim 1 \text{ kHz} \) and \( \sim 50 \text{ kHz} \), respectively, for PSR J2051−0827. For these cases the flux density variations caused by DISS would be averaged out during frequency channelisation of the data, and thus a single parameter for scale factor across the band was taken to be sufficient. Further modifications of the method are discussed in Chapter 3, where alternative models of scattering and dispersion are investigated.
Chapter 3

The Low-Frequency Radio Eclipses of the Black Widow Pulsar J1810+1744

“It’s not only moving that creates new starting points. Sometimes all it takes is a subtle shift in perspective, an opening of the mind, an intentional pause and reset, or a new route to start to see new options and new possibilities.”

Kristin Armstrong

In this chapter we have observed and analysed the eclipses of the black widow pulsar PSR J1810+1744 at low-radio-frequencies. Using LOFAR and WSRT observations between 2011–2015 we have measured variations in flux density, dispersion measure and scattering around eclipses. High-time-resolution, simultaneous beamformed and interferometric imaging LOFAR observations show concurrent disappearance of pulsations and total flux from the source during the eclipses. The dispersion measure variations are highly asymmetric, suggesting a tail of material swept back due to orbital motion. The egress deviations are variable on timescales shorter than the 3.6 hr orbital period and are indicative of a clumpy medium. Low levels of pulse broadening detected during egress show no evidence of scattering the pulses beyond detectability in the beamformed data. The frequency dependence of the eclipses is investigated over a range of low-frequencies, and the results are utilised in an examination of possible eclipse mechanisms, finding cyclo-synchrotron to be one of the most promising. An estimate of the mass loss rate is made, finding this to be a similar order of magnitude to the mean rate required to fully evaporate the companion in a Hubble time.

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Chapter 3. The Low-Frequency Radio Eclipses of the Black Widow Pulsar J1810+1744

Contributions of others: General guidance by R. P. Breton. All LOFAR observations were performed by the LOFAR Telescope Scientists, and apart from LC2_039 the data were publicly available from the LOFAR archive. WSRT folded observation data provided by J. W. T. Hessels. Guidance and instruction on imaging provided by A. O. Clarke and J. W. Broderick. Scripts for flux calibration provided by V. I. Kondratiev. Scripts for polarisation calibration written by M. Serylak, and guidance provided by A. Bilous and C. Sobey. General discussions and advice on this study provided by all above listed co-authors of the publication that this chapter is based on.

3.1 Introduction

Until recently, only two eclipsing black widow pulsars were known in the Galactic field, PSR B1957+20 (Fruchter et al., 1988a) and PSR J2051−0827 (Stappers et al., 1996a). Observed eclipsing phenomena in both revealed the necessity of studies at radio frequencies to act as a unique probe into the pulsar wind, eclipse mechanisms and evolution of black widow systems. However, the limited sample has thus far allowed in-depth radio frequency studies to be carried out for only three Galactic field black widows: PSRs B1957+20 (Fruchter et al., 1990; Ryba & Taylor, 1991), J2051−0827 (Stappers et al., 2001a) and J1544+4937 (Bhattacharyya et al., 2013). Thus, many details of these systems remain unclear, and attempts to constrain their global properties require a larger sample to succeed.

A number of features of black widow systems lend themselves to low-frequency observing. Many of the known millisecond pulsars are steep spectrum, i.e. significantly brighter toward lower radio frequency (see Section 1.1.2). Increased dispersion and scattering of pulsations typically observed near eclipses in black widows (e.g. Stappers et al., 2001a) is much more prominent at low observing frequencies. In addition, with telescopes such as LOFAR (Section 2.2.1) offering unprecedented sensitivity at frequencies below 200 MHz – a relatively untouched area for eclipse observations – valuable opportunities to study these systems are available.

Part of the fresh influx of black widow systems (Roberts, 2013), PSR J1810+1744 was discovered in a 350 MHz survey of unidentified Fermi sources with the Green Bank Telescope (Hessels et al., 2011). The 1.66 ms pulsar hosts a companion in a tight, 3.56 hr, orbit and at low radio frequencies it is one of the brightest known millisecond pulsars (Kondratiev et al., 2016; Kuniyoshi et al., 2015). Evidence for irradiation of the companion is found in optical observations showing the signature of a heated inner-face of the tidally locked star (Breton et al., 2013; Schroeder & Halpern, 2014). Both of these papers cite difficulty in fitting realistic parameters to the observed optical light-curves, and suggest a minimum companion mass, \( M_C \gtrsim 0.045 M_{\odot} \); large for typical black widow companions. Gentile et al. (2013) observed the system in X-rays and found no clear evidence for orbital modulation of the X-ray brightness, which is normally ascribed to an intrabinary shock.

Here we present multiple low-frequency observations of the eclipses of PSR J1810+1744,
utilising both beamformed and interferometric methods, in order to probe the mass loss and eclipse mechanisms. Details of the observations are provided in Section 3.2, with analysis techniques following in Section 3.3. The observed eclipses are characterised in Section 3.4, and the measured parameters are discussed in the context of eclipse mechanisms in Section 3.5.

3.2 Observations

Aside from a single observation made with WSRT (Section 2.2.2), all of the observations presented in this chapter were carried out using LOFAR over a range of different projects between 2012-Dec and 2015-Feb. As listed in Table 3.1, in total we present $\sim 14$ hrs of LOFAR data covering two full eclipses, three eclipse ingresses and five eclipse egresses, including one full eclipse and one egress covered in an interferometric observing mode. Both interferometric and beamforming modes were used in order to provide image plane and high time resolution observations, respectively.

3.2.1 LOFAR beamformed observations

These observations utilised the wide fractional bandwidth of the LOFAR HBA, spanning the frequency range 110–188 MHz at a centre frequency of 149 MHz (Section 2.2.1). The majority of the data were collected using the LOFAR coherent Stokes mode to form 1–2 Tied-Array Beams (TABs) from the Core stations. Observations with two TABs had one beam centred on the coordinates of the pulsar and a second beam displaced by $\sim 6$ arcmin in declination. The second, off-source beam provided a means of discriminating between loss of pulsations and loss of total flux from the pulsar, and is described further in Section 3.4.

Automatic pre-processing of the data was performed in PulP (Section 2.2.1) for coherent dedispersion and folding. Further processing of the data consisted of both flux and polarisation calibration, as explained in Section 2.3.1. In order to avoid biasing the flux calibration, it was necessary to dedisperse each sub-integration individually (at the eclipse edges in particular) so that the pulsar flux did not smear into the pre-defined off-pulse region. The importance of flux calibration was clearest in the long-duration observations, where variations in beam shape and shadowing of antenna tiles became more pronounced over the range of beam elevations. The calibrated data were re-folded into sub-integrations of duration 5–60 seconds depending on the signal-to-noise in each observation. Examples of the calibrated beamformed data are shown in Fig. 3.1, where the radio pulses can be seen to be delayed and reduced in flux density near the eclipses.

3.2.2 WSRT beamformed observation

WSRT data from 2011-Jun were used to provide a comparatively higher-radio-frequency probe into the eclipse. These data were in the form of a single 5 hr observation with a bandwidth of 70 MHz, centred on 345 MHz (Section 2.2.2). The data were coherently
## Table 3.1: List of observations.

<table>
<thead>
<tr>
<th>Date</th>
<th>Telescope</th>
<th>Project ID</th>
<th>ID</th>
<th>Duration</th>
<th>Center Frequency</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013-Jul-24</td>
<td>LOFAR</td>
<td>LC2_039</td>
<td></td>
<td>1h</td>
<td>0.24–0.52</td>
<td></td>
</tr>
<tr>
<td>2014-Feb-15</td>
<td>LOFAR</td>
<td>LC2_026</td>
<td>L243355</td>
<td>1h</td>
<td>0.21–0.49</td>
<td>2 TABs</td>
</tr>
<tr>
<td>2014-Jun-03</td>
<td>LOFAR</td>
<td>LC2_026</td>
<td>L231759</td>
<td>1h</td>
<td>0.25–0.53</td>
<td>2 TABs</td>
</tr>
<tr>
<td>2013-Oct-02</td>
<td>LOFAR</td>
<td>LC0_011</td>
<td>L181912</td>
<td>5m</td>
<td>0.18–0.20</td>
<td>2 TABs</td>
</tr>
<tr>
<td>2013-Jul-26</td>
<td>LOFAR</td>
<td>DDT_005</td>
<td>L166106</td>
<td>2h 42m</td>
<td>0.81–1.56</td>
<td></td>
</tr>
<tr>
<td>2013-Jul-25</td>
<td>LOFAR</td>
<td>DDT_005</td>
<td>L165490</td>
<td>2h 12m</td>
<td>0.20–0.83</td>
<td></td>
</tr>
<tr>
<td>2012-Dec-20</td>
<td>LOFAR</td>
<td>LC0_011</td>
<td>L81280</td>
<td>20m</td>
<td>0.12–0.22</td>
<td></td>
</tr>
<tr>
<td>2011-Jun-06</td>
<td>WSRT</td>
<td>S11A008</td>
<td></td>
<td></td>
<td>1.18–1.28</td>
<td></td>
</tr>
</tbody>
</table>

*Note: All observations are at 345 MHz, except for the observation on 2011-Dec-06, which is at 1.18–1.28 GHz.*
3.2. Observations

Figure 3.1: Calibrated, folded beamformed data from observations of PSR J1810+1744. Top, Middle: Pulse phase against orbital phase for three observations near eclipse. Observation IDs are indicated in the plots. An orbital phase of 0.25 corresponds to inferior conjunction of the companion. Delays in the pulse arrival times are apparent in the two eclipse egresses. Bottom: Pulse profiles, each integrated over 1 min of data from the observation L231759. The orbital phases of the centre of each 1 min integration are shown as dashed vertical lines in the upper-right egress plot, with numbers corresponding to the labels in the profile plots. Each profile has been normalised to the maximum flux density of profile no.1.
dedispersed and folded into 1 min sub-integrations, 128 pulse phase bins and 512 frequency channels. Here, a simpler flux calibration method was used which, although not providing an absolute flux density scale, normalised the profile in each sub-integration and frequency channel based on the off-pulse noise level in order to remove telescope gain variations to first-order. Once again the data were dedispersed separately for each sub-integration around eclipse orbital phases to avoid leakage of pulsar flux into the baseline noise estimation.

### 3.2.3 Timing ephemerides

Initial visual inspection of the data showed the pulses to drift significantly in phase within each observation, highlighting the lack of a satisfactory long-term timing solution for this pulsar. As often observed in black widows, due to as-yet undetermined mechanisms, the orbital period can vary on relatively short timescales, leading to difficulties in defining an ephemeris that can be used to correctly fold data over a range of observations (Section 2.3). To account for this, TEMPO2 was used to find a satisfactory ephemeris for each individual observation by fitting the out-of-eclipse pulse TOAs through adjustment of the spin frequency and its derivative (F0, F1), binary period (PB) and time of ascending node (T0) timing parameters. See Appendix A for the baseline orbital ephemerides used.

### 3.2.4 LOFAR interferometric observations

Simultaneous interferometric and beamformed LOFAR observations were undertaken in 2015-Feb. Using the LOFAR Core HBA beam the interferometric data were collected and pre-processed as described in Section 2.2.1. The 5 hr observing time was split into alternate beam pointings of 7 min centred on flux calibrator 3C295, followed by 30 min centred on the pulsar, leading to coverage of slightly over one orbit. The measurement sets were calibrated using standard LOFAR methods as explained in Section 2.3.1. Due to the brightness of PSR J1810+1744, we were able to make images of the field using 1 min time intervals of data, over the full ∼ 80 MHz bandwidth, with the pulsar detectable at ∼ 40× the typical RMS noise of ∼ 12 mJy in the 1 min images. A sequence of the 1 min images, zoomed into a $1^\circ \times 1^\circ$ area centred on the pulsar, is shown in Fig. 3.2, as the pulsar enters into eclipse.

### 3.3 Analysis

#### 3.3.1 Analysis of beamformed data

Characterisation of eclipses in spider pulsars requires a thorough study of the variations in pulsar flux density, DM and scattering throughout the orbit. Here we adopted the template fitting method described in Section 2.3.2 to measure these parameters in our data as a function of orbital phase. For LOFAR, templates were made for $0 \leq \Delta DM \leq 0.01$ in $5 \times 10^{-5}$ pc cm$^{-3}$ steps, and $0 \leq \Delta \tau \leq P$, where $P$ is the pulse period, in steps of 0.02$P$. 
FIGURE 3.2: A sequence of LOFAR images showing eclipse ingress. The position of PSR J1810+1744 is at the centre of the red circle in each image. The images were formed with an integration time of 1 min, and are cropped to a $1^\circ \times 1^\circ$ square centred on the pulsar coordinates. The orbital phase at the centre point of each integration time is shown in the top right hand corner of each image, with a phase of 0.25 corresponding to inferior conjunction of the companion. The synthesised beam shape is shown in the lower left hand corner of each image.
For WSRT, templates were made for $0 \leq \Delta DM \leq 0.03$ in $1 \times 10^{-4}$ pc cm$^{-3}$ steps, and similarly $0 \leq \Delta \tau \leq P$, in steps of $0.02P$.

The contour maps of $\Delta DM$ and $\Delta \tau$ that result from the fits are shown in Fig. 3.3 with contours plotted for $1\sigma$, $2\sigma$ and $3\sigma$ deviations from the minimum $\chi^2$, taking into account any degeneracy between $\Delta DM$ and $\Delta \tau$. Fig. 3.3 also shows the scale factor, and corresponding uncertainty, of the best fitting template for each sub-integration, directly relating to the detected pulsed flux density from the pulsar throughout the orbit. For display, these light-curves are normalised so that the out-of-eclipse flux densities are equal to unity. The average out-of-eclipse flux density that we measure for the calibrated beamformed data is $(297 \pm 33)$ mJy, however the nominal uncertainty here is assumed to be an underestimate of the true value, and instead we propose a 50% uncertainty of $\sim 150$ mJy based on previous studies of LOFAR flux density measurements (Bilous et al., 2016; Kondratiev et al., 2016).

Modification of the model

To investigate the validity of the scattering model used, we re-created sets of templates for different frequency power-law exponents, $\tau \propto \nu^{-\alpha}$, with $\alpha = 2.0, 2.5, 3.0,$ and $3.5$, based on recent work by Geyer et al. (2017) whereby forward fitting of simulated scattering profiles to LOFAR observations yielded values of $1.5 \leq \alpha \leq 4.0$. In addition, templates were made assuming the scattering model of Williamson (1972) for a thick screen positioned close to the pulsar, with scattering function,

$$\left(\frac{\pi \tau^4}{4t^3}\right)^{1/2} \exp\left(-\pi^2 \tau/16t^3\right).$$

(3.1)

However, due to both the low-level scattering variations present and the low signal-to-noise of the pulse profile on timescales short enough to track variations, no statistically significant deviations from the presented results were found.

Alternatively, to further investigate the dispersion we referred to the general form of the plasma dispersion law (Phillips & Wolszczan, 1992) where, as discussed in Hassall et al. (2012), the quartic term,

$$\Delta t_{EM} = \frac{EM}{4\nu^4},$$

(3.2)

may become detectable for low observing frequencies traversing a clumpy medium. Here, the Emission Measure, $EM = \int_0^D n_e^2 dl$, where $n_e$ (cm$^{-3}$) represents number density of electrons and $D$ (pc) is the distance to the source. Incorporating this additional term into our fits yielded some qualitatively interesting initial results, with occasional ‘spikes’ during egress reaching $EM \sim 10^5$ pc cm$^{-6}$. In contrast, compact HII regions typically have $EM \gtrsim 10^7$ pc cm$^{-6}$ (Table 1 of Kurtz, 2002). However, statistical comparison between this, and the original simpler DM model, using both the Akaike and Bayesian Information Criterion (Akaike, 1974; Schwarz, 1978, respectively) suggested that the likelihood of the more complex EM model is slightly lower than that of the more favourable simple DM model. This likelihood takes into account the fact that the increased number
3.3. Analysis

of degrees of freedom in the EM model is expected to lower the minimum $\chi^2$ of the fit, irrespective of the model being a better or worse representation of the "true" mechanism. In light of these inconclusive results, we plan to further investigate the general plasma dispersion law for low-frequency observations of black widow pulsars.

3.3.2 Analysis of interferometric data

Interferometric data are sensitive to both pulsed flux and any continuum, un-pulsed flux from the black widow system. Each of the 1 min images, described in Section 3.2.4, was analysed with PyBDSF\textsuperscript{1} to measure the average flux density from the pulsar within that interval. PyBDSF automatically identifies ‘islands’ of emission in the image, and for each island it fits two-dimensional Gaussians to individual sources. The flux density of each source is calculated directly from the fitted Gaussians, thus with knowledge of the expected coordinates of the pulsar, the flux density and associated uncertainty were retrieved. For the case of eclipsing pulsars this process can falter as the signal-to-noise decreases, or fully disappears, near eclipse. To counter this we used a high signal-to-noise ‘detection image’, made by combining several out-of-eclipse observations, to identify islands of emission and consequently passed these onto the 1 min images for flux density extraction. The resulting light-curve is shown plotted with the simultaneously observed beamformed flux density as blue points in Fig. 3.3(a), (b) and (c).

Out-of-eclipse, we detected PSR J1810+1744 at an average flux density of $$(483 \pm 5)\, \text{mJy}$$ in the 78 MHz wide LOFAR band centred on 149 MHz. This is significantly higher than the value quoted in Section 3.3.1, even with the estimated 50% uncertainty on that measurement. Although this discrepancy can suggest systematic errors in the flux density calibration methods, we note that the interferometric flux density quoted here is measured from observations covering just one orbit of the system, whereas the beamformed flux density from Section 3.3.1 is averaged over observations spanning $> 2$ years and thus is much more susceptible to the effects of refractive scintillation (see Section 3.3.3). Direct comparison with the 150 MHz flux density found in the GMRT TGSS survey (Intema et al., 2017) required us to re-image the field with the same $\sim 17$ MHz bandwidth used in that survey, resulting in a measured flux density for PSR J1810+1744 of $$(380 \pm 10)\, \text{mJy}$$ from our observations. Investigation of the MJDs of the observations used to calculate the flux density quoted from TGSS led to the finding that the pulsar was in typically eclipsed orbital phases for $\sim 30\%$ of the scans, thus scaling to account for this leads to a TGSS flux density from PSR J1810+1744 of $$(390 \pm 40)\, \text{mJy}$$; consistent with the value found here. Finally, a similar analysis was carried out by re-imaging the field with an 8 MHz bandwidth centred on 150 MHz in order to allow direct comparison with the equivalent flux density found in the GLEAM survey (Hurley-Walker et al., 2017). This led us to find a flux density of $$(335 \pm 15)\, \text{mJy}$$, consistent with the flux density of $$(321 \pm 88)\, \text{mJy}$$ reported from GLEAM.

\textsuperscript{1}http://www.astron.nl/citt/pybdsf/
Figure 3.3: Detected flux density (top panel of each sub-plot (a)–(m)), deviation of dispersion measure, \( \Delta DM \) (middle panels) and deviation of scattering timescale, \( \Delta \tau \) (bottom panels) relative to the out-of-eclipse values. The out-of-eclipse flux density is normalised to unity for each observation independently, with black curves showing beamformed flux density, blue curves showing interferometric flux density (a)–(c), and red crosses showing beamformed flux density normalised by an off-source beam ((h), (j), (l)). For \( \Delta DM \) and \( \Delta \tau \) panels the black, dark and light brown contours represent 1, 2 and 3\( \sigma \) uncertainties, respectively. An orbital phase of 0.25 corresponds to the companion’s inferior conjunction. Sub-plot (m) corresponds to the 345 MHz WSRT observation and is plotted on a different phase and \( \Delta DM \) scale for display purposes, while the rest show 149 MHz LOFAR data. Green boxes represent ingress and egress from a single eclipse.
3.3.3 Scintillation

Studying flux density variations in eclipsing pulsars can be complicated by interstellar scintillation effects that can mask, or mimic, genuine flux density variations in the system depending on the bandwidth and timescale of the scintles (Fruchter et al., 1990; Stappers et al., 2001a). At LOFAR frequencies however, the decorrelation bandwidth for diffractive scintillation for PSR J1810+1744 is $\sim 2$ kHz, thus any effects are averaged out over the 80 MHz band (Archibald et al., 2014). Scaling this to 345 MHz using the measured dependence of decorrelation bandwidth on observing frequency, $\Delta \nu_d \propto \nu^{4.5}$, for this pulsar (Archibald et al., 2014) gives a decorrelation bandwidth for diffractive scintillation of $\sim 90$ kHz for the WSRT observation, thus also too small to have significant effects over the full band. Conversely, refractive scintillation can affect the observed flux densities, however with a decorrelation timescale on the order of weeks it has little effect on flux density variations within orbital timescales. As such, the short timescale flux density variations presented here are assumed to be largely independent of interstellar scintillation. On the other hand, we caution that the measured out-of-eclipse, absolute flux densities presented here are expected to be influenced by the long-term refractive variability. Measurements of the flux density of the source in each of the beamformed LOFAR observations used here appear to show a smooth trend over the $\sim 2$ year range, with a factor of $\sim 2$ separating the lowest flux density from the highest.

3.4 Eclipse characteristics

3.4.1 Individual eclipses

Fig. 3.3 shows the measured deviations of flux density, DM and scattering time for all detected eclipses. Here we highlight the variability between separate eclipses and the timescales over which these occur.

Scattering

Leading into eclipse, and during eclipse recovery, where the flux density $\gtrsim 20\%$ of the out-of-eclipse level, little to no additional scattering is seen. However, very close to eclipse edges the results from the fits are unreliable. Here, inspection of the observed data showed no evidence of increased scattering tails in the pulsations and any apparent sharp increases (e.g. Fig. 3.3(k)) are assumed to be artefacts of the fit to low signal-to-noise data. The eclipse egresses in general show $\Delta \tau < 20\%$ of the pulse period, with occasional short timescale rises up to $\sim 40\%$. This low level scattering is far from that required to reduce the pulsed flux density beyond detection, unless a sharp rise were to occur at eclipse boundaries. Such a sharp rise would have to occur on a timescale shorter than 10 s, equivalent to the shortest integration times presented here, to avoid detection. In addition, in the higher-frequency WSRT observation in Fig. 3.3(m) the pulsar flux remains detectable for orbital phases closer to inferior conjunction of the companion, thus
probing further into the eclipsing medium, and shows no evidence of steep scattering variations.

**Dispersion measure**

Similarly to scattering, the DM (or electron column density) shows no clear evidence of increasing prior to loss of pulsations in eclipse ingress. Significant deviations from the out-of-eclipse electron column density can regularly be seen in eclipse egresses. The duration of these deviations varies from ~ 5–10 min (2–5% of the orbit) between observations. Features in the electron column density profiles show clear distinctions in each eclipse, with notable extremes in Fig. 3.3(l) – where multiple rises and falls are present, including a sharp boundary to the out-of-eclipse level, and Fig. 3.3(j) – where the electron column density decreases slowly and smoothly away from eclipse. Of particular interest for the timescale of variations is the fact that these two eclipses were observed on consecutive days. Placing even tighter constraints on the time variability of the DM features during egress are the consecutive eclipses in Fig. 3.3(b) and (c). The prominent DM feature in Fig. 3.3(b), extending out to orbital phase 0.36, shows no sign of detection in the egress observed one orbit earlier in Fig. 3.3(c), demonstrating that the DM features are variable within the orbital timescale of 3.6 hrs.

Assuming these electron column density deviations are a result of material within, or in close proximity to, the binary system we are likely to be sampling the outer edges of the eclipsing medium with such low observing frequencies being sensitive to small variations in DM. The extended egress variations are indicative of a ‘tail’ of material, swept-back due to orbital motion (Fruchter et al., 1990; Stappers et al., 2001a; Wadiasingh et al., 2017). In this case, our results suggest that the material in the tail is dynamic within orbital timescales, and sharp electron column density variations imply the material to be clumpy in nature. This timescale is plausible if the material travels at near or above the escape velocity of the companion star, \( v_{esc} = \sqrt{2GM/R} \approx 300 \text{ km s}^{-1} \), as the required velocity to travel ~ 1\( R_{\odot} \) – the order of the orbit size – within the 3.6 hr orbital period is around an order of magnitude lower. On the other hand, there is some evidence of a commonly appearing peak, or flattening, of the electron column density around orbital phases 0.33–0.34, which could be suggestive of a quasi-static dense region, or represent the geometry of the tail.

At 149 MHz the maximum detected \( \Delta M_{149} < 0.006 \text{ pc cm}^{-3} \), while at 345 MHz, \( \Delta M_{345} < 0.015 \text{ pc cm}^{-3} \). For dispersion smearing across the width of a channel to reach the pulse period, and thus remove the pulses, would require \( \Delta M_{149} > 1.3 \text{ pc cm}^{-3} \) and \( \Delta M_{345} > 38.3 \text{ pc cm}^{-3} \); many orders of magnitude above those detected. However, in the case of short timescale DM variations, an additional case of DM smearing can be encountered. Should the DM change significantly over the duration of a single sub-integration, the resulting pulse, averaged over the integration time, would be smeared by an amount dependent on the observed frequency. Due to the measurement of DM utilising templates with the full frequency resolution of the data, this smearing would be problematic if the change in DM within a sub-integration, \( \Delta (\Delta M) \), became large enough as to cause
3.4. Eclipse characteristics

the integrated pulse within a channel to smear over the full pulse phase. This would have the most significant effect on the channels with the lowest frequencies, and would occur at the bottom of the respective frequency bands for $\Delta (\Delta DM_{149}) > 0.005 \text{ pc cm}^{-3}$ and $\Delta (\Delta DM_{345}) > 0.04 \text{ pc cm}^{-3}$ for 149 MHz and 345 MHz, respectively. Although not an issue at 345 MHz, at 149 MHz the maximum gradient detected across a single sub-integration is $\sim 0.002 \text{ pc cm}^{-3}$, which would smear the pulse by 0.7 ms, or $\sim 40\%$ of the pulse period at the lowest side of the frequency band, causing an apparent decrease in detected flux density within the sub-integration. In general however, this gradient is much lower than that required to smear the pulses beyond detection.

**Flux density**

At 149 MHz, the pulsed flux density typically decreases much faster at eclipse ingress in comparison to the egress, in agreement with that expected for a swept-back tail of material. However, in the single 345 MHz eclipse this relationship is much more symmetric, although with a hint of the relationship being reversed where pulsed flux density recovers marginally quicker post-eclipse, being largely independent of the material in the extended tail.

In all observed eclipse ingresses, and most notably that in Fig. 3.3(g), the pulsed flux density begins to attenuate without any detected increase in the electron column density. Should the attenuation be a result of additional material along the line of sight, then a $\Delta DM_{149} < 0.0003 \text{ pc cm}^{-3}$ would be required to avoid detection amongst the typical out-of-eclipse 3$\sigma$ uncertainties. This would correspond to an electron column density of eclipsing material, $N_e \lesssim 10^{15} \text{ cm}^{-2}$.

Similarly to the DM, at 149 MHz the pulsed flux density takes $\sim 5$–$10 \text{ min}$ to recover in eclipse egress. The egress in Fig. 3.3(l) shows a clear anti-correlation between the flux density recovery and DM, with the pulsed flux density rising and falling with corresponding troughs and peaks in DM, respectively. The flux density variation associated with the sharp DM boundary to the out-of-eclipse level should be interpreted with care however, as a bias could be introduced by DM smearing with this steep gradient. In contrast to this, the pulsed flux density recovery in other eclipse egresses show no obvious correlation with the electron column density, as multiple peaks and troughs in pulsed flux density occur with no detected change in DM. In addition, the electron column density often shows a plateau, or even peak, closely after eclipse, throughout which the pulsed flux density continuously recovers, apparently independently of the electron column density. Although the pulsed flux density varies significantly in the egress region, there are no detectable mini-eclipses (such as those seen in, e.g., PSR B1744$-$24A and PSR J1023+0038; Lyne et al., 1990; Archibald et al., 2009, respectively) in any of the observations outside of the orbital phases 0.15–0.40 shown here. Also note that any apparent re-appearances of flux density during an eclipse (e.g. Fig. 3.3(d)) show no sign of being realistic upon inspection of the data, and thus are likely to be artefacts of the fitting method.

For the three eclipse egress observations that utilised a second, simultaneous off-source beam we were able to investigate the variation in the un-pulsed continuum flux density
Table 3.2: Duration, $\Delta \phi_{\text{eclipse}}$, radius, $R_E$, centre point, $\phi_c$, and asymmetry, $\Delta \phi_{\text{eg}} / \Delta \phi_{\text{in}}$, for the 149 MHz and 345 MHz eclipses. $\Delta \phi_{\text{eclipse}}$ and $\phi_c$ are in units of orbital phase. The top row shows $\Delta \phi_{\text{eclipse}}$, $\phi_c$ and $\Delta \phi_{\text{eg}} / \Delta \phi_{\text{in}}$ measured using the half-maximum flux density as eclipse boundaries, with $R_E$ calculated assuming an orbital inclination, $i = 90^\circ$. The bottom row shows the extrapolated duration and radius of the eclipse within the orbital plane assuming that the observed eclipse is for an orbital inclination, $i = 50^\circ$, the eclipse medium is spherically symmetric and centred in the orbital plane at the distance of the companion. The uncertainties on the extrapolated values are formally calculated through error propagation, however assume zero uncertainty on the orbital inclination.

<table>
<thead>
<tr>
<th>$\nu$ (MHz)</th>
<th>$\Delta \phi_{\text{eclipse}}$</th>
<th>$R_E$</th>
<th>$\phi_c$</th>
<th>$\Delta \phi_{\text{eg}} / \Delta \phi_{\text{in}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i = 90^\circ$</td>
<td>149</td>
<td>0.130 ± 0.002</td>
<td>$(0.51 \pm 0.01)R_\odot$</td>
<td>$0.265 \pm 0.002$</td>
</tr>
<tr>
<td>345</td>
<td>0.090 ± 0.002</td>
<td>$(0.37 \pm 0.01)R_\odot$</td>
<td>$0.264 \pm 0.002$</td>
<td>1.88 ± 0.02</td>
</tr>
<tr>
<td>$i = 50^\circ$</td>
<td>149</td>
<td>0.23 ± 0.001</td>
<td>$(1.2 \pm 0.01)R_\odot$</td>
<td>1.1 ± 0.01</td>
</tr>
<tr>
<td>345</td>
<td>0.21 ± 0.001</td>
<td>$(1.1 \pm 0.01)R_\odot$</td>
<td>1.1 ± 0.01</td>
<td></td>
</tr>
</tbody>
</table>

from the pulsar, independent of smearing or scattering of the pulse. By assuming both beams are affected equally by the telescope, sky and RFI, the off-source beam was used to normalise, and essentially flat-field, the pulsar centred beam. Thus, by averaging the normalised data over all pulse phases and subtracting unity, the remaining flux density in each sub-integration is proportional to that of the total flux density from the pulsar, independent of pulsations. The resulting light-curves, plotted in red on Fig. 3.3(h), (j) and (l), appear to show the total flux density disappearing in eclipse.

Stronger evidence of this is provided by the simultaneous beamformed and interferometric observations shown in Fig. 3.3(a), (b) and (c). The interferometric flux density, sensitive to the total, pulse phase averaged flux density from the pulsar, is shown to track the same disappearance and re-appearance as the pulsed flux, giving clear evidence that flux is removed from the line of sight, rather than smeared or scattered.

### 3.4.2 Global properties

Figs. 3.4 and 3.5 show the flux density and DM variations for all combined observations, respectively. The mean duration, radius, centre points and asymmetry of the eclipses are shown in Table 3.2. The duration is taken to be the full-width at half-maximum of the flux density, and was calculated by fitting the normalised ingress and egress flux densities with Fermi-Dirac functions, 

$$f = \left( e^{\frac{\phi - p_1}{p_2}} + 1 \right)^{-1},$$ 

where $f$ is the normalised flux density, $\phi$ is orbital phase and $p_1$ and $p_2$ are the fitted free parameters. Calculation of the eclipse radius, $R_E$, assumes the eclipsing medium resides at the orbit of the companion, with orbital separation $a = 1.33R_\odot$ and mass ratio $q = 0.045/1.4$ (Breton et al., 2013).

The asymmetry of the eclipses is characterised by the ratio of egress to ingress phases about $\phi = 0.25$, i.e. $(\phi_{\text{eg}} - 0.25) / (0.25 - \phi_{\text{in}})$, where $\phi_{\text{in}}$ and $\phi_{\text{eg}}$ correspond to the phase at half-maximum flux density found from the Fermi-Dirac fits for ingress and egress, respectively.

Similarly to black widow PSRs B1957+20 (Fruchter et al., 1990), J2051−0827 (Stappers et al., 1996a) and J1544+4937 (Bhattacharyya et al., 2013), the low-frequency eclipse lasts...
3.4. Eclipse characteristics

Figure 3.4: Measured flux density as a function of orbital phase for all observations. The out-of-eclipse flux density is normalised to unity. The pulsed flux density at 345 and 149 MHz is shown in red and grey, respectively. The total continuum flux density at 149 MHz is shown in blue. The dashed line at phase 0.25 corresponds to inferior conjunction of the companion star.
Figure 3.5: Deviation of dispersion measure relative to mean out-of-eclipse value for all beam-formed observations. The observations at 345 and 149 MHz are shown in red and grey, respectively. The dashed line at phase 0.25 corresponds to inferior conjunction of the companion star.
for $\sim 10\%$ of the orbit, irrespective of the distinctly different system parameters. The centre points of the eclipses, $\phi_c$, occur at a similar phase after inferior conjunction of the companion at both 149 MHz and 345 MHz, in contrast to that seen for PSR B1957+20 (Fruchter et al., 1990) where the eclipse is centred near orbital phase 0.25, and PSR J1544+4937 (Bhattacharyya et al., 2013) where the eclipse is centred slightly prior to 0.25. Due to the shorter duration of the 345 MHz eclipse the asymmetry, as defined by the ratio of egress to ingress durations, is unusually larger than at 149 MHz. Although the electron column density can be highly variable from one eclipse to the next, the disappearance and reappearance of flux can be seen to occur regularly at the same orbital phases, with very little deviation.

Note that these calculations assume the orbit to be edge-on. Fits to optical light-curves for this system in both Breton et al. (2013) and Schroeder & Halpern (2014) find best fitting orbital inclinations of $\sim 50^\circ$, suggesting that we are sampling the outer edges of the medium where the density is likely to be lower and eclipse width shorter than that in the orbital plane. The expected geometry of this system is shown in Fig. 3.6 and Fig. B.1. Should the eclipsing material be spherically symmetric and centred in the orbital plane at the distance of the companion, then an edge-on view of this system would result in eclipse radii of $1.2R_\odot$ and $1.1R_\odot$ for 149 MHz and 345 MHz, respectively; similar in magnitude to the orbital separation.

Using the polarisation calibrated LOFAR data, we measure the pulsar to have an average rotation measure, $RM = (90.48 \pm 0.02)$ rad m$^{-2}$, prior to ionospheric correction (see Sobey et al., 2019, for further information, including the ionosphere–corrected value). Using the measured RMs to correct for Faraday rotation, we find average linear and circular polarisation fractions of $\sim 0.01$ and $\sim 0.05$, respectively. The small polarisation fractions did not allow us to place any constraints on the magnetic fields in the eclipse medium.

**Material in the system**

The combined $\Delta DM$ measurements in Fig. 3.5 demonstrate the strong asymmetry of material either side of the low-frequency eclipse, much the same as that observed for black widow PSR B1957+20 (Ryba & Taylor, 1991). The Roche lobe of the companion, assuming $R_L = 0.19R_\odot$ and orbital inclination of 50$^\circ$ (Breton et al., 2013), is not intersected by our line of sight and as such the medium causing these eclipses cannot be gravitationally bound to the companion. Fig. 3.6 highlights the remarkable extent to which the eclipsing medium may have to be distributed in order to intercept the line of sight. Should the inclination estimate be doubted, in order for the line of sight to touch the Roche lobe an orbital inclination $\gtrsim 80^\circ$ would be required, and even for an edge-on view the Roche lobe would span the orbital phases $\sim 0.23-0.27$; inside the eclipse at both ingress and egress. Attempts to constrain the density of material in the eclipsing medium are at best an order of magnitude estimates. The asymmetry between ingress and egress, with barely any detectable rise in electron column density at ingress provides very little insight to the leading edge of the medium. In addition, being far from the gravitational grasp of the companion, the eclipse tail material could well extend far outside the orbit.
Figure 3.6: Expected geometry of the PSR J1810+1744 system, schematic is drawn to-scale. The Roche lobe and companion orbit are calculated assuming a pulsar mass of $1.4M_\odot$, companion mass of $0.045M_\odot$ and an orbital separation, $a = 1.33R_\odot$ (Breton et al., 2013). Note that no attempt is made to display the physical size of the companion star. Top: a 'side-on' view from the orbital plane, the line of sight (LoS) is drawn assuming an orbital inclination, $i = 50^\circ$ (Breton et al., 2013; Schroeder & Halpern, 2014). Bottom: a view from perpendicular to the orbital plane, the line of sights corresponding to eclipse edges (half-maximum flux density) and post-eclipse egress DM variations are shown by red (345 MHz) and green (149 MHz) dashed lines. The grey arrows indicate the companion’s direction of motion.
With this in mind, to allow comparison between systems we choose to follow previous considerations where it is assumed that all of the material is contained within an approximately spherical region, centred on the companion, of diameter equal to the eclipse width (Thompson et al., 1994). Thus, at 149 MHz with an eclipse width, $2R_E \sim 1.0 R_\odot$ and electron column density, $N_e \approx 1 \times 10^{16} \text{ cm}^{-2}$, the electron density at egress is

$$n_{e,149} \approx 1.4 \times 10^5 \left( \frac{2R_E}{1.0R_\odot} \right)^{-1} \text{ cm}^{-3}. \quad (3.3)$$

While at 345 MHz, with eclipse width, $2R_E \sim 0.8 R_\odot$ and egress column density, $N_e \approx 3 \times 10^{16} \text{ cm}^{-2}$, we find

$$n_{e,345} \approx 5 \times 10^5 \left( \frac{2R_E}{0.8R_\odot} \right)^{-1} \text{ cm}^{-3}. \quad (3.4)$$

At 345 MHz this is an order of magnitude larger than the equivalent density found for PSR B1957+20 in Thompson et al. (1994), but similar to that found for PSR J2051—0827 at 436 MHz (Stappers et al., 1996a).

As stated in Section 6.3 of Thompson et al. (1994), should the ablated material become entrained in the pulsar wind then the mass loss rate from the companion can be estimated as, $M_C \sim \pi R_E^2 m_p n_e V_W$, where $R_E$ is taken to be the eclipse half-width and represents the radius of the projected circle through which the mass is assumed to be lost, and $V_W$ is the outflow velocity of ablated material in the pulsar wind. Taking into account the expected geometry of the PSR J1810+1744 system, we take as $R_E$ the inferred radius of eclipse material should it be a sphere centred on the companion, i.e. $1.2 R_\odot$ and $1.1 R_\odot$ for 149 MHz and 345 MHz, respectively. If the momentum flux of the ablated material is taken to be equal to the momentum flux of the pulsar wind at the distance of the companion, then $V_W = (U_E/n_e m_p)^{1/2}$. Assuming the pulsar wind to be isotropic then we find the energy density of the wind at the companion distance,

$$U_E = \frac{\dot{E}}{4\pi c a^2} = 12.3 \left( \frac{a}{1.33 R_\odot} \right)^{-2} \text{ ergs cm}^{-3}, \quad (3.5)$$

where $\dot{E}$ is the spin-down power of the pulsar. Thus, for the 149 MHz observations using $R_E = 1.2 R_\odot$ and $n_e = 1.4 \times 10^5 \text{ cm}^{-3}$, we find an estimated mass loss rate of $M_C \sim 6 \times 10^{-13} M_\odot \text{ yr}^{-1}$. Instead using the inferred values from the 345 MHz observation of $R_E = 1.1 R_\odot$ and $n_e = 5 \times 10^5 \text{ cm}^{-3}$, we find $M_C \sim 1 \times 10^{-12} M_\odot \text{ yr}^{-1}$. In comparison, to fully evaporate the companion over a timescale of $\sim 5 \text{ Gyr}$ would require an average mass loss rate of $M_C \sim 9 \times 10^{-12} M_\odot \text{ yr}^{-1}$, only factor of $\sim 10$ larger than that estimated at 345 MHz. Considering that these estimates depend rather heavily on the assumptions made about the geometry and mechanics of the mass loss, it may not be unreasonable for the companion to be fully evaporated within Hubble time, especially if there is a large neutral component to the material avoiding detection through $\Delta DM$. However, we note that the long-term orbital dynamics of the system will also likely influence an evolution of the mass loss over time; in the presence of negligible magnetic
braking and gravitational radiation, mass loss from the system will act to widen the orbital separation between the two bodies. When combined with spin-down of the pulsar, it would be naively expected that this predicted decrease in irradiation of the companion star over time will reduce the probability of complete evaporation.

In this model, with the ablated material entrained in the pulsar wind, we note that the observed low column densities suggest that the material would be emitted approximately radially from the orbit. This assumes that the material initially flows from the companion at the escape velocity, thus the momentum flux of the thin material would be far lower than that of the pulsar wind and it would be carried away at $\sim V_W$. With such a high-velocity radial flow we would not expect to see large asymmetries in the measured column densities about inferior conjunction of the companion, in contrast to that observed. To reconcile this, it can be proposed that the companion hosts a magnetosphere filled with material of much higher density, and that is compact enough so as to not be intersected by our line of sight. This scenario allows for the denser magnetosphere to be swept back due to the orbital motion causing measurable asymmetry of the eclipses. Magnetic reconnection between the pulsar wind magnetic field and the companion’s magnetosphere allows for material to leak into the pulsar wind, detectable as additional egress column densities as the companion continues through its orbit (Thompson, priv. comm.).

**Frequency dependence**

The wide fractional bandwidth of these observations allows for a thorough investigation of the frequency dependence of the eclipse across the range of observed frequencies. The LOFAR observations were re-analysed with the bandwidth split into four sub-bands of logarithmically increasing widths, centred on 118, 134, 154 and 176 MHz. Similarly, the WSRT eclipse was re-analysed with three sub-bands centred on 321, 344 and 369 MHz.

The eclipse, as observed in each frequency sub-band, is shown in Fig. 3.7, along with the corresponding Fermi-Dirac fits plotted as black solid lines. The eclipse durations, $\Delta \phi_{\text{eclipse}}$, were calculated for two of the observed full eclipses, taken as the width of the eclipse at half of the out-of-eclipse flux density, and are shown in Fig. 3.8. A power law was fit to the data of the form $\Delta \phi_{\text{eclipse}} \propto \nu^\alpha$, where $\nu$ represents observing frequency, finding $\alpha = -0.41 \pm 0.02$, consistent with $\alpha \sim -0.4$ found for PSR B1957+20 (Fruchter et al., 1990) and redback PSR J2215+5135 (Broderick et al., 2016).

Due to the observed asymmetry of the eclipses, we carried out similar analysis treating ingress and egress independently. The corresponding durations were taken to be the deviation of half-maximum flux density for each ingress and egress from orbital phase 0.25. Power laws of the same form were fit to both ingress and egress durations, and are shown in Fig. 3.9. While the egress durations appear to be well modelled by a best fit power law with $\alpha = -0.35 \pm 0.03$, the ingress durations do not seem well explained by a single power law. All three of the plotted LOFAR ingress display little frequency dependence over the LOFAR band, suggesting a much shallower $\alpha$ at these frequencies.

This could be expected for a sharp boundary at the leading edge of the eclipse medium, however it would need to be of very specific density in order to allow the continuation
3.4. Eclipse characteristics

Figure 3.7: Normalised flux density for the full eclipses observed on 2011-Jun-06 (WSRT) and 2013-Jul-25 (LOFAR). The flux densities as measured in each of the frequency sub-bands centred on 118 (blue), 134 (green), 154 (red), 176 (cyan), 321 (pink), 344 (yellow) and 369 MHz (purple) are shown. Wider eclipses are observed for lower-frequency sub-bands. The black curves show least squares fits of Fermi-Dirac functions to the ingresses and egresses in each frequency sub-band.
Chapter 3. The Low-Frequency Radio Eclipses of the Black Widow Pulsar J1810+1744

Figure 3.8: Eclipse duration, $\Delta \phi_{\text{eclipse}}$, taken as full-width at half-maximum of out-of-eclipse flux density, for observed full eclipses. The error bars correspond to 1\(\sigma\) uncertainties from the Fermi-Dirac fits to the measured flux densities. The dashed line shows a best fit power law with $\alpha = -0.41$. Different colours represent separate eclipses.

of 345 MHz radiation further into the medium. Equally, the 345 MHz DM measurements show no sign of a step change in electron column density at the 149 MHz ingress phase, thus it is not clear what could be causing such a phenomenon.

One potential source of this observed effect is the plasma frequency within the medium reaching that of the observing frequency. For the plasma frequency to reach these thresholds would require electron densities of $n_e = 3 \times 10^8 \text{ cm}^{-3}$ and $n_e = 1.5 \times 10^9 \text{ cm}^{-3}$ for 149 MHz and 345 MHz, respectively. These are many orders of magnitude higher than those inferred earlier from the observed electron column densities and eclipse widths, and as such could only be a feasible cause of eclipses if the material was contained within a thin region along the line of sight. Such a region may occur in an intrabinary shock, where the opposing pulsar and companion winds reach a pressure balance. X-ray observations of this system show possible evidence of count-rate modulation characteristic of such a shock, however due to large measurement uncertainties no significant detection is claimed (Gentile et al., 2013).

As an added insight into the eclipse mechanism, the line of sight optical depth as a function of orbital phase can be calculated for each frequency sub-band. Assuming a power law dependency of optical depth with frequency of the form $\tau \propto \nu^\beta$, and fitting to egress data for four LOFAR observations and the single WSRT observation, we find $\beta$ to increase
3.4. Eclipse characteristics

Figure 3.9: Ingress and egress durations, taken as $|0.25 - \text{phase of half-maximum flux density}|$. Egress: four LOFAR and one WSRT observation, the dashed line shows a best fit power law with $\alpha = -0.35$. Ingress: three LOFAR and one WSRT observation, the dotted line shows a best fit power law with $\alpha = -0.41$. The error bars correspond to $1\sigma$ uncertainties from the Fermi-Dirac fits to the measured flux densities. Different coloured symbols represent separate eclipses. Durations, taken at 118, 134, 154, 176, 321, 344 and 369 MHz, are plotted with small frequency offsets for clarity.
approximately linearly over orbital phases 0.32–0.34 within the range \(-2 \lesssim \beta \lesssim -5\). Similar fits to the eclipse ingresses find \(\beta \sim -1\) over the much narrower orbital phase range.

### 3.5 Discussion of eclipse mechanisms

Once again, to allow direct comparisons we choose to follow the steps of previous black widow studies to evaluate possible eclipse mechanisms using the analysis in Thompson et al. (1994) as a basis. Immediately here we can rule out pulse smearing and small-angle scattering as eclipse mechanisms due to the disappearance of flux density seen in the interferometric observations. Refraction is commonly disfavoured due to the lack of expected frequency dependence of the resulting eclipses and smaller than required excess delays in pulse arrival times at eclipse boundaries (Thompson et al., 1994; Stappers et al., 2001a; Bhattacharyya et al., 2013). Similarly, with corresponding pulse delays < 1 ms measured here, to produce a caustic would require such a high density gradient at eclipse edges that the eclipse duration would be almost independent of frequency (Section III(b) of Emmering & London, 1990), contrary to the clear frequency dependence in duration observed here, making refraction unlikely to be the primary source of the low-frequency eclipses in PSR J1810+1744. We note, however, that the apparent clumpy nature of the eclipsing medium, and very shallow frequency dependence for the 100–200 MHz eclipse ingress could allow refraction to have some role in the process. Additionally, refraction would provide an explanation for observed features such as the brief enhancements in flux density seen in the egress in Fig. 3.3(j), where the line of sight could pass a caustic.

For free-free absorption, using Equation (11) of Thompson et al. (1994) with an electron column density from the 345 MHz egress, \(N_e \approx 3 \times 10^{16} \text{ cm}^{-2}\), and absorption length equal to the eclipse width of \(5.6 \times 10^{10} \text{ cm}\), we find a required temperature of the eclipse medium, \(T \lesssim 10^3 f_{cl}^{2/3} \text{ K}\), with clumping factor \(f_{cl} = \langle n_e^2 \rangle / \langle n_e \rangle\), for an optical depth \(\tau_{ff} > 1\). The same temperature constraint is found for the 149 MHz eclipse parameters. This is equal to the limit calculated for PSR B1957+20 in Thompson et al. (1994) and is understood to be orders of magnitude colder than that expected in such a medium with a realistic clumping factor.

Should the eclipse region material increase in density closer to the companion (as expected from the observations), off-axis radio beams could reflect or refract from the higher density regions into the line of sight radio beam, causing induced Compton scattering in the line of sight radiation. As explained in Thompson et al. (1994) this would alter the observed radiation spectrum, appearing to act as absorption of low-frequency radiation. Using Equation (26) of Thompson et al. (1994) with the measured flux density of PSR J1810+1744, \(S_0^0 = 480 \text{ mJy}\), a spectral index \(\alpha = -2.3\) (Murphy et al., 2017), electron column density \(N_e \approx 10^{16} \text{ cm}^{-2}\), a source distance of \(d = 2.0 \text{ kpc}\) and orbital separation \(a = 9.3 \times 10^{10} \text{ cm}\) from Breton et al. (2013), we find an optical depth at 149 MHz of \(\tau_{ind} \lesssim 0.5M\), where \(M \sim (R_C/2r)^2\) is the magnification factor of the reflected radio beam, \(R_C\) is the radius of curvature of the reflecting region and \(r\) is the distance from the centre of curvature to the scattering region (Section 2.4.1. of Thompson et al., 1994).
3.5. Discussion of eclipse mechanisms

For PSR J1810+1744 we estimate the radius of curvature of the higher density region to be equal to the Roche lobe radius, \( R_C \sim 0.19R_\odot \), and take the scattering region to be at the distance of the 149 MHz ingress from the centre of the companion, assuming the material surrounds the companion and that the system has an orbital inclination of 50°, thus \( r \sim 0.95R_\odot \). As such, we calculate \( M \sim 0.01 \) and a corresponding optical depth at 149 MHz, \( \tau_{\text{ind}} \lesssim 5 \times 10^{-3} \). This suggests that induced Compton scattering is unlikely to be sufficient to cause the low-frequency eclipses.

With the relatively high radio flux density of PSR J1810+1744 the non-linear mechanism of a stimulated Raman scattering parametric instability may be significant. Here, the radio flux incident on the eclipsing medium is theorised to generate turbulence in the plasma that can consequently scatter further radio waves out of the line of sight. Using distance to the pulsar, \( d = 2.0\ \text{kpc} \) and \( a = 9.3 \times 10^{10} \text{cm} \), we estimate the radio flux from the pulsar at the companion’s orbit to be 0.02 ergs cm\(^{-2}\) s\(^{-1}\) Hz\(^{-1}\) at 149 MHz. Following the analysis using Equation (32) of Thompson et al. (1994) with an electron density at the 149 MHz eclipse, \( n_e \approx 1.4 \times 10^5 \text{cm}^{-3} \), we find that the critical flux incident on the eclipsing medium required for strong scattering is exceeded here if the temperature of the medium, \( T \gtrsim 10^4 \text{K} \), which is expected to be satisfied in the eclipse medium. Using the same parameters, the growth time of instabilities is found to be \(< 1 \text{ sec}\) which will be less than the characteristic flow time for any realistic flow velocity of the medium, hence allowing instabilities in the medium to form before the medium disperses. Thus, as for PSR B1957+20 in Thompson et al. (1994), two of the requirements of Raman scattering are satisfied. However, although considered a possible mechanism, doubt is cast over the apparently satisfied conditions if the material is clumped, as higher densities in the medium increase the required critical flux incident on the medium. Additionally, should the medium be hot enough, the plasmon (plasma oscillations required to create turbulence) escape rate can become significant, causing a reduction in plasma turbulence present to scatter the incident radio flux. Equally, the lack of scattering observed at eclipse ingress and egress means that the transition into the eclipsing regime would have to be very abrupt. As a result, although we do not dismiss this as a possible mechanism, it appears unlikely given the observations.

Considered as one of the most likely eclipse mechanisms in PSRs B1957+20 (Thompson et al., 1994), J2051–0827 (Stappers et al., 2001a) and J1544+4937 (Bhattacharyya et al., 2013) is cyclotron-synchrotron absorption. This can either occur in material entrained in the magnetised pulsar wind (Thompson et al., 1994), or in a magnetosphere of the companion filled with relativistic particles from the pulsar wind (Khechinashvili et al., 2000). Following the analysis in Thompson et al. (1994), to balance the pulsar wind energy density at the orbit of the companion requires a magnetic field strength, \( B_E \sim 18 \text{ G} \) in the eclipse region. With such a magnetic field the fundamental cyclotron frequency would be \( \sim 50 \text{ MHz} \), thus absorption of 149 MHz and 345 MHz radiation would occur at cyclotron harmonics 3 and 7, respectively. Similar conditions calculated for PSR B1957+20 in Thompson et al. (1994) find a cyclotron optical depth power law index at least as steep as \( \tau \propto \nu^{-4} \) over the range 318–1400 MHz, for expected temperatures in
the eclipse medium. Alternatively, for synchrotron absorption by relativistic electrons, the authors find a shallower frequency dependence of optical depth, \( \tau \propto \nu^{-13/4} \), from their Equation (67) assuming a power law non-thermal electron distribution and magnetic field lines at an angle 45° to the line of sight. The model in Khechinashvili et al. (2000) assumes the companion to be a magnetic white dwarf, with surface magnetic field \( B_S \gtrsim 10^4 \) G. The authors predict the duration of the eclipses to scale as \( \propto \nu^{-0.33} \) for given temperature and electron distributions. The consistency of these models with our results suggests that cyclotron-synchrotron absorption is a comparatively likely primary eclipse mechanism for PSR J1810+1744. However, a better knowledge of the eclipse medium would be required to decipher the best model.

3.6 Conclusions

In this chapter, we present a detailed account of the low-frequency eclipses in the black widow pulsar system of PSR J1810+1744. We measure the dispersion, scattering, and both pulsed and continuum flux densities as a function of orbital phase as a sensitive probe into the eclipsing medium. At these low-frequencies, we expect to be sampling the outer edges of the eclipsing medium, which we show to have a highly variable structure over timescales shorter than the 3.6 hr orbital period. The disappearance of both pulsed and continuum flux density regularly occurs between orbital phases \( \sim 0.18-0.35 \), with little deviation in phase from one eclipse to the next. A clear frequency dependence is seen in eclipse duration, however asymmetry between ingress and egress reveal the danger of relying on duration to constrain the eclipse mechanism. Eclipse egress durations are shown to be well modelled by a single power law between 110–380 MHz, whereas the ingress shows evidence for a more complex dependence on observing frequency over this range.

Dispersion measure variations suggest a tail of material flows behind the companion as a result of orbital motion, similar to that seen in a number of other black widow systems. The tail material appears clumpy, and measurements show a possible hint of higher order pulse dispersion. Further high signal-to-noise observations of this bright system could attempt to track the variability of tail material and constrain a potential deviation from the typical \( \propto \nu^{-2} \) dispersion relation. In addition, the inferred mass loss rate suggests that it may just be possible to fully evaporate the companion in a Hubble time, although this relies on idealised assumptions. Higher-frequency radio observations would probe the density of material further into the eclipse, and thus add further constraints to the inferred mass loss rate.

The analyses of Thompson et al. (1994) and Khechinashvili et al. (2000) are followed with the measured system parameters to add constraints on the eclipse mechanism. The eclipse duration and line of sight optical depth are consistent with cyclotron-synchrotron absorption as a primary eclipsing mechanism, although the apparently less likely non-linear scattering mechanisms cannot be completely ruled out. In addition, the clumpy nature of the medium could allow refraction to play a minor role. These results provide
3.6. Conclusions

a much needed insight into the variabilities, and similarities, between eclipsing media in black widow pulsars, allowing further studies on the elusive black widow population as a whole (e.g. Wadiasingh et al., 2017).
Chapter 4

Long Term Variability of a Black Widow’s Eclipses – A Decade of PSR J2051−0827

“Don’t knock the weather. If it didn’t change once in a while, nine out of ten people couldn’t start a conversation.”

Kin Hubbard

In this chapter we report on ∼ 10 years worth of observations of PSR J2051−0827, covering frequencies over the range 149–4031 MHz. All observations of the eclipse region are fit for models of increased dispersion and scattering in the eclipse medium, revealing both variability on timescales as short as the orbital period, and previously unknown trends on timescales of months–years. Links between the low-frequency eclipse widths, orbital period variations and trends in the material density are investigated, but no clear pattern is found. We provide a thorough study into the case of magnetic fields in the eclipse region, and present the first available limits on the strength of such fields in this system. The results are considered in the context of eclipse mechanisms, and find scattering and/or cyclotron absorption provide the most promising explanation, while dispersion smearing is conclusively ruled out. Finally, an estimate of the mass loss rate suggests that the companion will not be fully evaporated in any reasonable timescale.

Contributions of others: General guidance and discussions by R. P. Breton and B. W. Stappers. LOFAR observations were performed by LOFAR Telescope Scientists, and apart from LC2_039 and the DDT observation, all data were publicly available from the LOFAR archive. WSRT folded observation data provided by G. Janssen. Parkes observations performed by S. Johnson, C. Sobey and S. Oslowski. uGMRT DDT observation performed by B. Bhattacharyya. Lovell observations planned/ performed by C. Bassa, C. A. Jordan, A. Lyne, M. B. Mickaliger and B. W. Stappers. Scripts for LOFAR polarisation calibration written by M. Serylak, and guidance provided by C. Sobey. Guidance and instruction of
4.1 Introduction

PSR J2051−0827, the second BW discovered (Stappers et al., 1996a), is a 4.5 ms pulsar in a tight, 2.38 h orbit with a 0.05 $M_\odot$ companion (assuming a pulsar mass of 1.8 $M_\odot$ as in Lazaridis et al., 2011). The system was intensively studied in the few years after its discovery, with radio observations giving insight into its eclipse properties (Stappers et al., 1996a, 2001a) and optical observations showing irradiation of the companion by the pulsar wind, also allowing its orbital inclination to be estimated to be $\sim 40^\circ$ (Stappers et al., 1996b, 1999, 2001b). Although thorough, with the data available these early studies left many properties loosely constrained with little still known about the eclipse mechanism, mass loss and orbital parameters of the system. However, more recent studies are beginning to shed further light on the phenomena; observations of high-energy emission by Wu et al. (2012) suggest the presence of an intra-binary shock between the pulsar wind and the material ablated from the companion star, and continuous long-term radio timing of the pulsar allowed the orbital variations to be mapped over the last two decades (Lazaridis et al., 2011; Shaifullah et al., 2016).

Inspired by the vast amount of data now available on PSR J2051−0827 we present here a comprehensive study of the eclipse phenomena over a decade of observations – the first such study for a black widow system. Details of the observations used are given in Section 4.2, while in Section 4.3 we present long-term measurements of flux density and DM modulation.

As explained in Section 1.3.3, some of the more promising eclipse mechanisms require magnetic fields in the eclipse medium (e.g. Khechinashvili et al., 2000), the presence of which is also suggested by depolarisation of pulses near eclipse in the pulsar PSR J1748−2446A (You et al., 2018) and rapid orbital variability possibly attributed to magnetic cycles in the companion (Arzoumanian et al., 1994). On the contrary, recent work by Li et al. (2019) places doubt on the presence of significant magnetic fields near the eclipse boundaries in the BW PSR B1957+20. PSR J2051−0827 represents an apparently rare case among known spider pulsars where the pulses have detectable linear and circular polarisation components, thus in Section 4.4 we investigate the possible presence of magnetic fields within the binary through measurements of RM, Faraday delay and depolarisation. Section 4.5 gives a critique of the eclipse mechanisms, building on the work of Stappers et al. (2001a), while Section 4.6 provides a general discussion of the system in light of the new data.

Pertinent to this work, in Fig. B.3 we show the expected projection of the binary system on the sky, approximately to scale assuming parameters inferred in the previous studies mentioned above. The inclined view of the system is key to bear in mind when inferring parameters of the medium causing eclipses of the pulsar’s radio emission.
4.2 Observations

The data presented in this chapter originate from just over a decades worth of observations of PSR J2051–0827 using LOFAR (Section 2.2.1), WSRT (Section 2.2.2), upgraded-GMRT (Section 2.2.3) and the Lovell and Parkes Radio Telescopes (Sections 2.2.5 and 2.2.4). The dates of the specific observations used are shown in Fig. 4.1, with observation durations ranging from 15 min to 3 h (surpassing the 2.4 hr orbital period of the binary). The frequency coverage allowed by the telescopes and corresponding back-ends spans 110–4031 MHz.

Observations with LOFAR utilised the HBA from ~ 20–24 Core stations. The data, recorded over the frequency range 110–190 MHz, were processed as per Section 2.2.1, including polarisation calibration (Section 2.3.1), prior to analysis. Each WSRT observation was taken in one of two separate bands: 310–380 MHz or 1300–1460 MHz. The data were recorded and processed as detailed in Section 2.2.2, with the ~ 4.5 ms pulsar spin period allowing the low band data to be split into 256 pulse phase bins. Observations with the Lovell Telescope were recorded over 1332–1732 MHz, and the data were processed via the methods in Section 2.2.5. To add valuable frequency coverage to complement the archival data, dedicated observations have been performed with uGMRT and the Parkes Radio Telescope. A single 2 hr observation with uGMRT was made with all available antennas recording total intensity data over a 300–500 MHz bandwidth split into 4096 channels, and the data were processed as detailed in Section 2.2.3. Two Parkes observations were obtained, the first covering 3.6 hrs over 1241–1497 MHz and the second covering 2.7 hrs over 705–4031 MHz. Both datasets were processed as explained in Section 2.2.4, including polarisation calibration (Section 2.3.1).

4.2.1 Post-processing

The folded PSRFITS files for all observations were cleaned as per the method in Section 2.3, and the orbital variations were accounted for by installing up-to-date ephemerides; for observations made prior to 2014-May the continuous BTX timing model from Shaifullah et al. (2016) was used for this, while for those data taken after 2014-May the TEMPO2 package was used to find pulse time-of-arrivals (TOAs) in 1 min integrations of the observations, then we fit new timing solutions to TOAs grouped into 6 month intervals. To perform the fits we initially used the best-fitting T2 model of Shaifullah et al. (2016) as a baseline ephemeris, and adjusted the T0 and A1 parameters – epoch of periastron and projected semi-major axis of the orbit, respectively (Section 1.1.3) – in TEMPO2 to minimise the RMS residuals of the TOAs for the first 6-month grouping after 2014-May. The timing solution from each 6-month interval was then used as a baseline for the next. Similarly to solving for the variable orbital parameters, we made use of the DM values given in Shaifullah et al. (2016) to correct for the long-term drift of the out-of-eclipse DMs. For observations made after 2014-May PSRCHIVE’s pdmp tool was used to find the DM that maximised the integrated pulsed flux for out-of-eclipse observations in 1 year intervals.
Figure 4.1: Dates of eclipse observations from each telescope used in this analysis. The y-axis location and extent of the markers represent the frequency coverage of the observations. The numerous LOFAR markers correspond to observations at all orbital phases – not necessarily covering an eclipse – as the out-of-eclipse data was used for polarisation studies.
Table 4.1: Step sizes in DM and $\tau$ used in the model fits to data observed at different centre frequencies. $\Delta \tau$ is expressed in units of the pulse period, $P = 4.51$ ms.

<table>
<thead>
<tr>
<th>Centre frequency (MHz)</th>
<th>$\Delta$DM (pc cm$^{-3}$)</th>
<th>$\Delta \tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>149</td>
<td>$2 \times 10^{-4}$</td>
<td>$0.005P$</td>
</tr>
<tr>
<td>345</td>
<td>$4 \times 10^{-4}$</td>
<td>$0.01P$</td>
</tr>
<tr>
<td>1380</td>
<td>$2 \times 10^{-3}$</td>
<td>$0.005P$</td>
</tr>
<tr>
<td>1530</td>
<td>$2 \times 10^{-3}$</td>
<td>$0.005P$</td>
</tr>
</tbody>
</table>

4.3 Flux density and dispersion measure

Stappers et al. (1996a, 2001a) report flux density variations and increases in DM near inferior conjunction of the companion for PSR J2051−0827. The flux at low radio frequencies ($< 1$ GHz) was shown to drop below detection thresholds (i.e. eclipse) regularly at these orbital phases, offering some insight into the physical properties of the material ablated from the companion. With the wealth of data now afforded to us, here we present a much more in-depth investigation of these effects, and their long-term time dependency.

To measure the flux density and deviation of DM and scattering timescale, $\tau$, from the out-of-eclipse values, as a function of time, in these observations we employed the template fitting method as explained in Section 2.3.2. The templates were generated with the step sizes of $\Delta$DM and $\Delta \tau$ given in Table 4.1. For observations $> 1$ GHz we included 4 free parameters across the bandwidth to allow for different scale factors of the sub-bands in order to model the effects of diffractive scintillation – expected to have a decorrelation bandwidth of $\sim 25$ MHz.

4.3.1 L-band

With both high frequency WSRT and Lovell observations covering relatively similar radio frequencies, we treat these as being equivalent for these studies. Three L-band observations covering inferior conjunction of the companion, separated by months–years, are shown in Fig. 4.2. Pulse TOA delays are clearly visible in all three, however each shows distinctly different TOA delay structure. In agreement with Stappers et al. (2001a) the L-band radio emission is generally detected throughout the orbit, with only sporadic, short duration dips in flux density coincident with the TOA delays in some observations.

Using the DM and scattering timescale template method, fits were performed to all L-band observations covering inferior conjunction of the companion. Depending on the signal-to-noise of individual observations the fits were performed on sub-integrations of durations between 20 s – 2 min. The resulting best-fit DMs, along with the corresponding $1\sigma$ uncertainties, are shown in Fig. 4.3. The standout feature from these observations is the long-term time evolution of the DM structure in the typical orbital phases corresponding to eclipses. Over the years 2011–2014 we detect a significant amount more material crossing the line of sight towards the pulsar than either before or after these times, suggesting that trends in the material outflow from the companion can occur on timescales of a few years. The most recent, late-2018, observations appear to show the
4.3. Flux density and dispersion measure

Figure 4.2: 1530 MHz observations over the low-frequency eclipse orbital phase range. Delays in the pulse time-of-arrivals can be seen, accompanied by occasional short duration reductions in flux density. Note the distinctly different delay patterns for each of the three dates.
DMs once again becoming more pronounced, and notably Stappers et al. (1996a) show similar pronounced DM profiles in observations made in 1995, suggesting that the period of enhanced DMs seen here is not an isolated ‘event’. In further detail, specific structure in the DM profiles persists on timescales of months, such as the sharp DM ‘spike’ over the phase range $\sim 0.21–0.25$ that regularly occurs in the observations throughout 2014, shown in the inset plot of Fig. 4.3. This structure is of specific interest as it occurs prior to inferior conjunction of the companion, leading the star in its orbit. Additionally, the relatively low density of the material means that it would presumably be carried away by the supersonic pulsar wind on timescales much shorter than the orbital period, unless magnetic fields were present to balance the pulsar wind pressure (Stappers et al., 2001a). These observations support the idea of the presence of magnetic fields throughout the material ablated from the companion, and also suggest that particular magnetic structures can persist in the system for many months. It may be that such variations in the DM profiles are linked to variations in an intra-binary shock, or activity in the companion such as those suggested by Cho et al. (2018) and Yap et al. (2019).

### 4.3.2 345 MHz

Similar template fits to the WSRT 345 MHz observations were performed for sub-integrations of 1 min duration. The resulting best fit DMs and corresponding flux densities are shown in Fig. 4.4. To make the plot clearer, the flux densities have been normalised so that the out-of-eclipse levels are equal to unity, thus removing long-term flux density variations associated with refractive interstellar scintillation. The flux density of the pulsar regularly drops below detection thresholds throughout the companion inferior conjunction, and is never detected between phases $\sim 0.23–0.27$, in agreement with the earlier observations of Stappers et al. (2001a). There is variability in the shape of the eclipse edges on timescales shorter than 2 days – the shortest time interval between observations. Additionally, the large time-span covered by these observations reveals a longer-term trend in the eclipse duration; over the $\sim 7.5$ yr duration the orbital phase of the eclipse egress can be seen to significantly shift, with the eclipses in 2015 persisting to later orbital phases than those previously. There is also some evidence of the pulsar re-emerging from eclipse slightly earlier in the 2008 observations, although this is not conclusive. Any variations present in the eclipse ingress are much less prominent than those post-eclipse, being much more stable over time. The extension of the eclipse egress in 2015 relative to the rest of the observations does not have any clear correlation with the higher frequency DM trends over the same date range, shown in Fig. 4.3. Note that these eclipse phase shifts are many orders of magnitude larger than the orbital period variations reported in Shaifullah et al. (2016).

The deviations in DM in the 345 MHz eclipse observations, shown in the lower panel of Fig. 4.4, are also variable on timescales shorter than the 2 day observation interval. In some observations there are sharp rises in DM at the eclipse boundaries, while in others the pulsar falls into, or re-emerges from, eclipse without any significant change in the DM. The deviations in DM generally persist for longer post-eclipse than they do in the
4.3. Flux density and dispersion measure

**Figure 4.3:** Deviation from mean out-of-eclipse dispersion measures for all observations above 1 GHz that cover the low-frequency eclipse region. The DMs are all plotted on the same scale, with an offset of 0.2 pc cm$^{-3}$ applied between consecutive observations. Error bars represent 1σ uncertainties from the simultaneous DM and scattering fits, as explained in the main text. The dashed grey line marks orbital phase 0.25, where the companion passes closest to our line of sight to the pulsar. The colour of the lines represents the date of observation, with large ticks on the colourbar marking each individual observation on a linear time scale.
Chapter 4. Long Term Variability of a Black Widow’s Eclipses – A Decade of PSR J2051–0827

Figure 4.4: Top: Measured flux densities for all 345 MHz observations covering the eclipse region, with each normalised so the out-of-eclipse mean flux density is unity. The horizontal dashed line corresponds to the detection limit of the telescope. Bottom: Deviation from mean out-of-eclipse dispersion measures for the same set of observations. Error bars represent 1σ uncertainties from the simultaneous DM and scattering fits, as explained in the main text.

Ingress, often taking \( \sim 6–7\% \) of the orbit to return to the out-of-eclipse level. The eclipses are generally centred near to phase 0.25, although the extended egresses in 2015 shifts the centre point to a later orbital phase. This shift in the eclipse centre, along with the more prominent flux density variations and slow DM decay in egress are indicative of the ablated material being swept-back due to the orbital motion of the star (Chapter 3; Fruchter et al., 1990; Stappers et al., 2001a).

4.3.3 149 MHz

Finally, template fits to 149 MHz LOFAR observations were performed for sub-integrations of durations between 30–60 s. The normalised flux densities and deviations of DM from the out-of-eclipse level are shown in Fig. 4.5. As for the 345 MHz data, the flux densities were normalised such that the out-of-eclipse level was equal to unity, thus removing the effects of long-term refractive interstellar scintillation. The LOFAR eclipse observations span only 3 yrs; much shorter than the observations at higher frequencies. Moreover, only a handful of observations are available that cover eclipse boundaries, with only one
4.4 Polarisation

Should the eclipse medium be magnetised, we may be able to detect its influence on the pulsar radio emission as it passes through this material. Previous attempts to detect orbit-dependent polarisation variations have been hampered by the lack of linearly polarised flux from many black widow pulsars, although very recently You et al. (2018) observed depolarisation of pulses near eclipse in the globular cluster pulsar PSR J1748−2446A (PSR
B1744–24A), which they attribute to both, or either one of, magnetic field variations and multipath propagation through a magnetised, turbulent medium. Fruchter et al. (1990) and Li et al. (2019) instead used circular polarisation measurements of normal, lensed and giant pulses in the black widow PSR B1957+20 to strongly disfavour the presence of strong magnetic fields, either parallel or perpendicular to the line of sight, in the eclipse ingress and egress. However the reliance on detection of pulses meant that no constraints could be made on fields closer to the companion, in the region masked by the eclipse. Here we investigate the polarisation properties of PSR J2051–0827, and discuss the possible correlation with orbital phase.

4.4.1 Tests at low-frequency

The low-frequency, wide-bandwidth nature of LOFAR observations lends itself to studies of the frequency-dependent Faraday rotation of the pulsar radio emission as it traverses any ionised and magnetised medium along the line of sight. This allows for precise measurements of pulsar RM for those pulsars with significant linearly polarised flux densities (Sobey et al., 2019).

The polarisation calibrated LOFAR data were analysed using PSRCHIVE’s `rmfit` tool. This performs a brute-force search over a user-specified range of RM values, calculating the linearly polarised flux density for each RM and automatically fits a Gaussian to peaks in the spectrum. The resulting spectra were manually inspected to check that the fit corresponded to a visually significant peak, and also avoided an occasionally occurring peak at zero RM due to instrumental leakage of the total intensity signal into the orthogonal polarisations. The resulting RM values were ionosphere-corrected using the `ionFR` code (Sotomayor-Beltran et al., 2013) to calculate the expected ionosphere induced Faraday rotations from total electron content (TEC) ionosphere maps, and subtracting these from the measured `rmfit` values. As the `ionFR` output RMs had a temporal resolution of 1 hr, and the observation durations ranged from 10–30 mins, the `ionFR` values were linearly interpolated to estimate the ionosphere Faraday rotation at the start time of each observation, which was then assumed to be constant for the observation duration. Note that the interpolation always resulted in changes smaller than the 1σ uncertainties on the `ionFR` values, thus these approximations do not significantly bias the results. As suggested by Sobey et al. (2019), in Appendix C we have included a list of the publicly-available LOFAR data used here, along with the measured RM values and calculated ionosphere corrections, should more precise ionosphere correction methods become available in future.

We measure PSR J2051–0827 to have a weighted mean RM = (−32.61 ± 0.03) rad m⁻². The RM-corrected linear polarisation profile is shown in Fig. 4.7, and the linear polarisation fraction is found to be ~ 10%, which appears to be approximately consistent across observations with high enough signal-to-noise to detect an RM. The calculated RMs for the individual observations are plotted in Fig. 4.6 as a function of orbital phase. The histogram shows that the bulk of the RMs are approximately normally distributed about the mean, and the colourmap shows that there is no clear long-term evolution of the RM. Although we detect no regular rise, or fall, in RM near eclipse, we note that this would not
necessarily be expected given the aforementioned highly variable nature of the eclipse material. Instead we highlight a possible increase in variance of RMs post-eclipse, in the orbital phase range \( \sim 0.3 - 0.65 \). Performing an \( F \)-test between the egress and all other RMs, with the null hypothesis of equal variances, results in a \( p \)-value of \( 5 \times 10^{-5} \), however this relies on both distributions being near-Gaussian, which is not obviously the case in the egress region. Thus, we perform both a Levene’s test (Levene, 1960) and a Fligner-Killeen test (Fligner & Killeen, 1976), which are more robust to non-normality of the distributions of data (Conover et al., 1981). These result in \( p \)-values of 0.010 and 0.057, respectively. Thus, for the most conservative estimate given by the Fligner-Killeen test, we could expect to observe such data 1 in 20 hypothetical repeats of the observations, assuming that the true variance is the same in both regions. However, the lower \( p \)-values from the \( F \) and Levene’s tests make it intriguing to investigate this further as more LOFAR data is collected.

Moreover, assuming that the two highest (least negative) RMs at orbital phases \( \sim 0.4 \) and \( 0.45 \) represent physical changes in the Faraday rotation, as opposed to statistical fluctuations, we can use these to estimate the line of sight magnetic field strength in the eclipse medium. Using,

\[
\text{RM} = \frac{\langle B_{||} \rangle}{1.23 \mu \text{G}} \text{DM},
\]

with PSR J2051−0827 parameters: \( \text{DM} = 20.729 \text{ pc cm}^{-3} \) and weighted mean \( \text{ RM} = (-32.61 \pm 0.03) \text{ rad m}^{-2} \), we find the mean line of sight magnetic field strength towards the pulsar to be \( \langle B_{||} \rangle = (-1.935 \pm 0.001) \mu \text{G} \) for the out-of-eclipse orbital phases. We attribute this component to the ISM, \( \langle B_{||,\text{ISM}} \rangle \). Then, taking the maximum measured egress \( \text{RM} = (-31.85 \pm 0.19) \text{ rad m}^{-2} \), Equation 4.1 gives the mean line of sight magnetic field strength towards the pulsar to be \( \langle B_{||,\text{egress}} \rangle = (-1.890 \pm 0.008) \mu \text{G} \), during egress. By assuming that this discrepancy was caused by the medium within the binary system we can break the average magnetic field, DM and RM into components: one corresponding to the medium within each region to be homogeneous, these reduce to:

\[
\text{DM} = \int_0^{D-a} n_{e,\text{ISM}} dl + \int_{D-a}^D n_{e,\text{sys}} dl,
\]

\[
\text{RM} = \int_0^{D-a} n_{e,\text{ISM}} B_{||,\text{ISM}} dl + \int_{D-a}^D n_{e,\text{sys}} B_{||,\text{sys}} dl,
\]

where the subscripts ISM and sys correspond to the components along the line of sight towards the binary and within the binary, respectively. By approximating the medium within each region to be homogeneous, these reduce to:

\[
\text{DM} \approx (D - a) \langle n_{e,\text{ISM}} \rangle + a \langle n_{e,\text{sys}} \rangle,
\]

\[
\text{RM} \approx (D - a) \langle n_{e,\text{ISM}} \rangle \langle B_{||,\text{ISM}} \rangle + a \langle n_{e,\text{sys}} \rangle \langle B_{||,\text{sys}} \rangle.
\]
Figure 4.6: Right: Rotation measure values found to maximise the linear polarisation flux density in 149 MHz observations (see main text), plotted at the central orbital phase of the corresponding observation. The mean observation duration used to calculate each data point was ~13 mins (0.09 P_b), and the grey region represents the typical eclipse.

Left: Histogram representing the empirical distribution of measured rotation measure values.
Thus, using Equation 4.1, the average line of sight magnetic field strength over the full distance to the pulsar is given by

\[
\langle B_\parallel \rangle = \frac{(D - a) \langle n_e,\text{ISM} \rangle \langle B_\parallel,\text{ISM} \rangle + a \langle n_e,\text{sys} \rangle \langle B_\parallel,\text{sys} \rangle}{(D - a) \langle n_e,\text{ISM} \rangle + a \langle n_e,\text{sys} \rangle},
\]

(4.6)

There are two scenarios to consider: one with additional electron density in the system at egress orbital phases, and one without. These can give estimations of lower and upper limits, respectively, on the magnetic field within the binary at these orbital phases, assuming the RM deviations are attributed entirely to the intra-binary medium.

Firstly, taking the case of no additional material in the system, we have \(\langle n_e,\text{sys} \rangle = \langle n_e,\text{ISM} \rangle\). Equation 4.6 then simplifies to

\[
\langle B_\parallel \rangle = \frac{1}{D} \left( (D - a) \langle B_\parallel,\text{ISM} \rangle + a \langle B_\parallel,\text{sys} \rangle \right),
\]

(4.7)

thus, by rearranging we find the mean line of sight magnetic field strength within the binary to be

\[
\langle B_\parallel,\text{sys} \rangle = \frac{1}{a} \left( D \langle B_\parallel \rangle - (D - a) \langle B_\parallel,\text{ISM} \rangle \right).
\]

(4.8)

Now, if we take the scenario where extra material is present within the binary, we can manipulate Equation 4.6 to explicitly show that the system material is made up of an equivalent ISM electron density, plus a term relating to the additional eclipse material, i.e. \(\langle n_e,\text{sys} \rangle = \langle n_e,\text{ISM} \rangle + \langle \Delta n_e \rangle\). Equation 4.6 then leads to,

\[
\langle B_\parallel \rangle = \frac{(D - a) \langle n_e,\text{ISM} \rangle \langle B_\parallel,\text{ISM} \rangle + a \langle \langle n_e,\text{ISM} \rangle + \langle \Delta n_e \rangle \rangle \langle B_\parallel,\text{sys} \rangle}{D \langle n_e,\text{ISM} \rangle + a \langle \Delta n_e \rangle},
\]

(4.9)

giving,

\[
\langle B_\parallel,\text{sys} \rangle = \frac{(D \langle n_e,\text{ISM} \rangle + a \langle \Delta n_e \rangle) \langle B_\parallel \rangle - (D - a) \langle n_e,\text{ISM} \rangle \langle B_\parallel,\text{ISM} \rangle}{a \langle \langle n_e,\text{ISM} \rangle + \langle \Delta n_e \rangle \rangle},
\]

(4.10)

where we have \(\langle n_e,\text{ISM} \rangle = \frac{\text{DM}_\text{out-of-eclipse}}{D}\) and \(\langle \Delta n_e \rangle = \frac{\Delta \text{DM}}{a}\), with \(\Delta \text{DM}\) given by the LOFAR measurements in Section 4.3. As the LOFAR observations show no detectable increase in DM at orbital phases 0.4–0.45, we can place an upper limit corresponding to the typical 1σ uncertainties on the LOFAR ΔDM measurements of 0.001 pc cm\(^{-3}\). Taking relevant parameter values of DM\(_{\text{out-of-eclipse}}\) = 20.729 pc cm\(^{-3}\), \(D = 1.47\text{kpc}\) (DM-derived distance using the electron density model of Yao et al., 2017), \(a = 1.1 R_\odot\) (from the orbital parameters given in Section 4.1), \(\langle B_\parallel,\text{ISM} \rangle = (-1.935 \pm 0.001) \mu\text{G}\), \(\langle B_\parallel \rangle = (-1.890 \pm 0.008) \mu\text{G}\) and accounting for only the uncertainties on \(\langle B_\parallel,\text{ISM} \rangle\) and \(\langle B_\parallel \rangle\) using standard error propagation, Equations 4.8 and 4.10 loosely constrain the mean line of sight magnetic field strength within the binary to be \(9(2) \times 10^2 \lesssim \frac{\langle B_\parallel,\text{sys} \rangle}{\mu\text{G}} \lesssim 2.7(5) \times 10^9\), where the number in brackets represents the uncertainty on the last digit, should an intra-binary field be responsible for the observed change in RM at orbital phase 0.4.
4.4.2 Tests at high-frequency

Observing at high-frequencies offers an invaluable complement to the LOFAR observations discussed above; although the measurements are much less sensitive to small variations in RM, the radio pulsations from the pulsar are detectable throughout the entire eclipse region. As such, they provide a probe into the medium directly responsible for the eclipses at low-frequencies. To this end, two observations were recently performed using the Parkes Radio Telescope, with the primary aim to measure the polarisation properties of PSR J2051–0827 throughout its orbit. The first of the observations spanned 1241–1497 MHz and covered ∼ 1.5 consecutive eclipses, while the second spanned 705–4032 MHz and covered 1 eclipse, offering an unprecedented simultaneous wide-band view of the eclipse region. The resulting polarisation calibrated data were RM corrected using a value of RM = (−33.1 ± 1.0) rad m\(^{-2}\), measured with \textsc{rmfit} on the out-of-eclipse, wide-band data.

The data, in form of the \(I, Q, U, V\) Stokes parameters, were dedispersed in each sub-integration and frequency channel using the DM values measured through the template fitting technique discussed in Section 4.3, thus removing the effects of increased dispersion during the eclipse. In the absence of any flux calibrator observations, the data were normalised to reduce any instrumental effects on the flux densities. This normalisation consisted of two steps: firstly, the mean off-pulse levels were subtracted from the corresponding profiles in each frequency channel, sub-integration and Stokes parameter, and secondly, the profiles were divided by the standard deviation of the corresponding off-pulse regions of the Stokes \(I\), total intensity, data. At this stage, the wide-band observation data were split into 3 sub-bands, and each summed along the frequency axis for analysis. Finally, the Stokes \(Q\) and \(U\) profiles in each sub-integration were combined in quadrature to give the total linear polarisation profiles as a function of time. The resulting total intensity, \(I\), linear, \(L\), and circular, \(V\), average profiles are shown in Fig. 4.7 for the 3 sub-bands.

**Depolarisation**

In order to test for depolarisation effects, such as those reported in You et al. (2018), we measure the flux densities of \(L\) and \(V\) as a function of the pulsar’s orbital phase. The average \(I, L\) and \(V\) profiles were smoothed using a Savitzky-Golay filter (similar to the method in Section 4.3) to create one-dimensional profile templates. The relative flux density in each sub-integration was determined through a least-squares fit of the template amplitude (multiplication factor). To remove the influence of variations in the total intensity flux, each of the \(L\) and \(V\) amplitudes were divided by the corresponding amplitude of the \(I\) fits. Finally, the relative amplitudes were multiplied by the ratio of the sum over the \(L\) (or \(V\)) template profile to the sum over the \(I\) profile in order to give the absolute polarisation fractions. The resulting polarisation fractions as a function of orbital phase are shown in Figs. 4.8 and 4.9 for the first and second observations, respectively, along with the corresponding ΔDM measurements found previously.
4.4. Polarisation

FiguRE 4.7: Total intensity, $I$ (black), linear polarisation, $L$ (red), and circular polarisation, $V$ (blue), average pulse profiles of PSR J2051$-$0827 in three simultaneously observed sub-bands using the Parkes radio telescope, and a low-frequency profile averaged over all out-of-eclipse LOFAR observations. The data were calibrated and RM corrected as explained in the main text.
Chapter 4. Long Term Variability of a Black Widow’s Eclipses – A Decade of PSR J2051−0827

Figure 4.8: Circularly (top) and linearly (middle) polarised fractions of the total intensity flux of PSR J2051−0827 measured in a single frequency band, as a function of the pulsar’s orbital phase. Bottom: Measured DM relative to the out-of-eclipse mean for the same observation. Observed on 2018-Sep-23 with the Parkes radio telescope.

In both observations the circular polarisation fraction is shown to persist at a constant level of $\sim 10\%$, within uncertainties, throughout the full orbit. In contrast, the linear polarisation fraction reduces to zero during the orbital phase range $0.15 \lesssim \phi \lesssim 0.35$, corresponding to the typical low-frequency eclipse region. It is interesting to note that this is the case in both observations, despite the much smaller DM increases in the $\sim 1.5$ eclipses in the first observation. The evidence is also strengthened by the finding that the depolarisation is measured independently in the three wide-spread sub-bands in the second observation. Due to the relatively low signal-to-noise of the narrow linear polarisation profile, it may be possible that scattering could smear out the profile, as the pre-processing of the data only corrected for the variable DMs. However, as shown in Fig. 4.10, the total intensity profiles at orbital phases $\phi = 0.21, 0.26, 0.32$ show only minimal scatter broadening in comparison to other phases, whereas the linear polarisation profile is not visible at all at phases $\phi = 0.21, 0.26$, and begins to reappear at phase $\phi = 0.32$.

An alternative possibility is that the RM increases, decreases or fluctuates such that the integrated linear polarisation profile, corrected with the ‘wrong’ RM is smeared out. As an unfortunate consequence of the low signal-to-noise of the linearly polarised flux density, we find that even in the brightest sections of the observations more than 10 mins of
Figure 4.9: Circularly (top) and linearly (middle) polarised fractions of the total intensity flux of PSR J2051−0827 measured in three simultaneously observed, frequency sub-bands, as a function of the pulsar’s orbital phase. Bottom: Measured DM relative to the out-of-eclipse mean for the same observation. Observed on 2018-Dec-03 with the Parkes radio telescope.
Figure 4.10: Total intensity (blue) and linear polarization (orange) pulse profiles in integrations of 8 mins for a Parkes radio telescope observation of PSR J2051−0827 on 2018-Dec-03. The profiles are integrated over the sub-band with the highest signal-to-noise, 1345–2369 MHz. The orbital phase at the centre point of each integration is indicated in the top-right corner of each subplot.
4.4. Polarisation

data must be integrated in order to reliably detect a peak in the RM spectrum produced
by \texttt{rmfit}. Such long integrations span nearly the full duration of the eclipse region, thus
our measurements are restricted to attempting to detect either an increase or decrease
in RM, which remains at a nearly constant value throughout the eclipse region, before
returning to the out-of-eclipse level. Using Equation 1.7 one can calculate the maximum
detectable RM in a dataset through the requirement that the polarisation position angle
must turn through \(< 2\pi\) within a frequency channel in order to avoid complete smearing.
In the data used here the lowest frequency channel spans 704–705 MHz, which gives
a maximum RM \(\sim \pm 12000 \text{ rad m}^{-2}\) in order for the intra-channel position angle rotation
to remain \(< 2\pi\). Using \texttt{rmfit} to search a 16 min integration over the dedispersed
eclipse region, we find no significant peak in the RM spectrum anywhere in this range.
In contrast, searches in all other 16 min integrations throughout the orbit detect signif-
ificant peaks consistent with the average out-of-eclipse RM value. Using Equation 4.10,
assuming values applicable to these observations of \(\Delta \text{DM} \approx 0.1 \text{ pc cm}^{-3}\) and an eclipse
RM \(\sim 12000 \text{ rad m}^{-2}\), the inferred intra-binary magnetic field would be \(\sim 10^7\) G. As any
RM larger than this would require even more unrealistically large magnetic fields, the
possibility of an increased (or decreased), but constant, RM within the eclipse region can
be ruled out.

These measurement imply that, as for PSR J1748–2446A (You et al., 2018), the pulsar
flux from PSR J2051–0827 becomes depolarised as it traverses the intra-binary medium
responsible for the low-frequency eclipses. You et al. (2018) postulate that the depolarisa-
tion occurs as a result of rapid RM fluctuations in a magnetised turbulent medium caus-
ing smearing out of the linear polarisation. In light of our observations, and their similar-
ity to those attained for PSR J1748–2446A, it appears plausible that the same mechanism
is responsible here. As such, it is fruitful to follow their analysis using values applicable
to these observations.

By approximating the inferred RM fluctuations, and thus polarisation position angle fluc-
tuations, to be normally distributed with standard deviations of \(\sigma_{\text{RM}}\) and \(\sigma_\psi = \lambda^2 \sigma_{\text{RM}}\),
respectively, You et al. (2018) derive the depolarisation resulting from integration over
the fluctuations to follow,

\[
L = L_0 \exp \left( -2\lambda^4 \sigma_{\text{RM}}^2 \right),
\]  

(4.11)

where \(L_0\) and \(L\) represent the linear polarisation magnitude before and after the inte-
gration over the fluctuations, respectively, and \(\lambda\) is the observing wavelength. Since all
three of the observing sub-bands become depolarised for the second observation of PSR
J2051–0827, the tightest constraint that can be placed is a lower limit on the magnitude
of the RM fluctuations that would be necessary to depolarise the highest-frequency radio
emission under these assumptions. Taking the depolarised fraction to be equal to the mean
1\(\sigma\) uncertainties on the high-frequency measurements, \(L_0/L \approx 0.01\), the polarised
fraction to be equal to the mean out-of-eclipse value, \(L/L \approx 0.045\), and the observing
wavelength to be \(\lambda \approx 9\) cm, Equation 4.11 gives \(\sigma_{\text{RM}} \gtrsim 100 \text{ rad m}^{-2}\). Further, by assum-
ing that DM fluctuations from the medium are also normally distributed, with standard
deviation $\sigma_{\text{DM}} \sim 0.01 \text{ pc cm}^{-3}$, then Equation 4.1 can be modified to give

$$\frac{B_{\parallel}}{1.23 \mu \text{G}} = \left( \frac{\sigma_{\text{RM}}}{\sigma_{\text{DM}}} \right)^{1/2}. \quad (4.12)$$

Using values relevant to PSR J2051−0827 implies that the mean magnetic field parallel to the line of sight in the eclipse medium, $B_{\parallel} \gtrsim 100 \mu \text{G}$. This is around an order of magnitude larger than the lower limit placed on PSR J1748−2446A through the same method (You et al., 2018). Assuming that such a field would be provided by a dipolar magnetic field originating at the companion, and taking the orbit to be inclined at 40° (Stappers et al., 2001b), with further orbital parameters as in Shaifullah et al. (2016) and Lazaridis et al. (2011), the closest approach of the line of sight to the companion centre is $\approx 0.83 R_\odot$. With a Roche lobe radius of $R_L \approx 0.15 R_\odot$, the implied surface magnetic field strength of the companion is $B_S = B_{\parallel} \left( \frac{0.83}{0.15} \right)^3 \gtrsim 2 \times 10^4 \mu \text{G}$. Note also that this rules out the possibility of a completely balanced pair plasma, which could be produced if the eclipse material was predominantly fed by pulsar wind particles (Li et al., 2019). In the case of a pair plasma, the induced rotations of the linear polarisation vector would be equal and opposite for the positive and negative charged particles, and as such, no net rotation would occur and the linear polarisation would not be depolarised.

**Persistent circular polarisation**

Recent work by Li et al. (2019), in which the authors placed strong upper limits on the presence of magnetic fields near the eclipse region in the black widow pulsar PSR B1957+20, highlighted the usefulness of circular polarisation measurements for investigating the effects of intra-binary magnetic fields. Their study suggested that generalised Faraday rotation (Kennett & Melrose, 1998) may become important in the context of spider pulsars. Specifically, in the case of a strong magnetic field directed near-perpendicular to the line of sight the natural propagation modes through the plasma become strongly elliptical, or entirely linear for a completely perpendicular field. This contrasts with the two circular polarisation natural modes corresponding to a weak, or near-parallel, magnetic field which are relevant to the above investigation of ‘normal’ Faraday rotation. For circular natural modes Faraday rotation refers to the rotation of the linear polarisation vector around the natural axis of the plasma, which has a dependence on the frequency of the radiation and thus if not corrected for will effectively smear out the linear polarisation when integrated over a finite bandwidth, while leaving the circular polarisation unaffected. Alternatively, for elliptical natural modes the differential rotation of the polarisation vector occurs in the linear and circular planes, and can act to depolarise both when integrated over a finite bandwidth. Finally, for the case of entirely linear natural modes, a strong perpendicular field, the rotation occurs in the circular polarisation domain, causing this to depolarise while leaving the linear polarisation unaffected. Considering the case of a strong near-perpendicular field, the differential rotation of the
linear ‘x’ and ‘o’ natural modes can be approximated (Thompson et al., 1994; Li et al., 2019) to lead to a phase difference between the two modes:

\[ \Delta \Phi_{x,o} \approx \Delta \Phi_{\text{DM}} \frac{\langle f_{B}^2 \rangle}{f^2}, \quad (4.13) \]

where \( \langle f_{B}^2 \rangle \) represents the electron-density weighted average of the (squared) cyclotron frequency, \( f_{B} = \frac{qB}{2\pi m_e} \approx 2.8 \left( \frac{B}{G} \right) \) MHz, \( f \) is the observation frequency, and \( \Delta \Phi_{\text{DM}} = 2\pi k_{\text{DM}} \Delta f_{\text{DM}} / f \) is the additional dispersion-induced phase delay, with \( k_{\text{DM}} = \frac{e^2}{2\pi m_e c} \approx 4149 \text{s MHz}^2 \text{cm}^3 \text{pc}^{-1} \). In the presence of a sufficiently strong field, the phase difference between the two modes will vary over the observing band, causing the circular polarisation vector to rotate and effectively depolarise when integrated over frequency. Thus, the fact that we observe no significant depolarisation of Stokes \( V \) with orbital phase in Figs. 4.8 and 4.9 suggests that the differential phase difference between the top and bottom of the band is less than one full rotation, i.e. \( \lesssim 2\pi \). As such, we can derive:

\[ \Delta \Phi_{x,o,\text{low}} - \Delta \Phi_{x,o,\text{high}} \lesssim 2\pi \quad (4.14) \]
\[ \langle f_{B}^2 \rangle 2\pi k_{\text{DM}} \Delta f_{\text{DM}} \left( \frac{1}{f_{\text{low}}^3} - \frac{1}{f_{\text{high}}^3} \right) \lesssim 2\pi \quad (4.15) \]
\[ \frac{B_{\perp}}{G} \lesssim \frac{1}{2.8} \left[ k_{\text{DM}} \Delta f_{\text{DM}} \left( \frac{1}{f_{\text{low}}^3} - \frac{1}{f_{\text{high}}^3} \right) \right]^{-1/2}. \quad (4.16) \]

Taking values corresponding to the wide-band Parkes observation, \( \Delta f_{\text{DM}} \sim 0.1 \text{ pc cm}^{-3} \), \( f_{\text{low}} = 705 \text{ MHz} \) and \( f_{\text{high}} = 4031 \text{ MHz} \), we find \( B_{\perp} \sim 0.3 \text{ G} \) in the eclipse region. Note, however, that this calculation is only valid for a (near-)perpendicular field and the limit could be larger should the magnetic field be directed away from the perpendicular to the line of sight, i.e. if there is a parallel component of similar or larger magnitude, which appears possible given the detected depolarisation of \( L \).

**Faraday delay**

A final investigation of the polarisation properties of the eclipse concerns Faraday delay. As considered in Fruchter et al. (1990) and Li et al. (2019) for PSR B1957+20, Faraday delay refers to the differential group delay between the left- and right-handed circular polarisation components which could become detectable in the presence of sufficiently large parallel magnetic fields. Such a study is useful here in the region where \( L \) becomes depolarised, and no RM is measurable, while \( V \) remains detectable. The Faraday delay is expected to arise for propagation through a magnetised plasma and is given by,

\[ \Delta t_{\text{FD}} = \frac{4f_{B}}{f} \Delta f \quad (4.17) \]
where $\Delta t_f$ is the excess delay induced by dispersion at frequency $f$ and $f_{B||} = \frac{q B||}{2 \pi m_e} \approx 2.8 \left( \frac{B||}{100} \right) \text{MHz}$ is the cyclotron frequency in terms of the average parallel component of the field (Li et al., 2019). Rearranging this we find,

$$\frac{B||}{[G]} \approx \frac{1}{2.84} \frac{f \Delta t_{FD}}{\Delta t_f}.$$ (4.18)

Using the full bandwidth of the first Parkes observation, and the low-frequency band (705–1345 MHz) of the second Parkes observation – where the delays would be expected to be the largest – we cross-correlated the left- and right-hand circular polarisation profiles in integrations of 16 mins with the template profile used previously in the flux fitting. Here we take positive $V$ to represent left-hand circularly polarised radiation, and negative $V$ to represent right-hand circularly polarised radiation, as defined as the PSR convention (van Straten et al., 2010). The resulting cross-correlation functions are shown in Figs. 4.11 and 4.12. For each integration, the difference between the maximum points of the left- and right-hand cross-correlation functions is taken as the Faraday delay. As in Li et al. (2019), with the lack of an analytical method we estimated the uncertainties by bootstrapping. Here, this consisted of ‘resampling’ each circular polarisation profile by replacing the flux in each profile bin with a value sampled from a normal distribution, $\mathcal{N}(\mu, \sigma^2)$, with $\mu$ equal to the original bin flux, and $\sigma$ equal to the sample standard deviation of the off-pulse bin fluxes in the original profile. The resampled profile was cross-correlated, and the difference between the maxima measured. This was repeated 1000 times for each profile, and the standard deviation of the 1000 delays was taken to be the uncertainty. The dispersive delay was estimated using Equation 2.1 with the mean $\Delta DM$ within the integration and centre frequencies of 1369 and 1024 MHz for the first and second observations, respectively.

The resulting Faraday delays are shown in Figs. 4.13 and 4.14 along with the corresponding estimates of $B||$ for those points with $\Delta t_f > 0$. The plots show that all of the $B||$ values are consistent with zero, however the uncertainties are very large – a consequence of both small dispersion delays at these relatively high observing frequencies, and low signal-to-noise of the circular polarisation profiles. The tightest constraint, where the dispersion delays are large approaching the eclipse egress in observation 2, suggests an average parallel field of $B|| = (20 \pm 120) \text{G}$. For a parallel magnetic field of the order of 100 G, or less, in the eclipse region, assuming the orbital parameters stated previously, implies a magnetic field strength at the companion surface of $B_S = B|| \left( \frac{0.83}{0.75} \right)^3 \lesssim 2 \times 10^4 \text{G}$. This is of the order of the surface field strengths considered previously for the companion in PSR J2051−0827 (Khechinashvili et al., 2000).

Similarly to the Faraday rotation study above, this analysis suffers from the low signal-to-noise of the polarised radiation, requiring integrations of $\sim 16$ mins in order to achieve reliable cross-correlation spectra. These integrations are of the order of the eclipse duration, and as such average over the likely variable polarisation effects. Therefore, the Faraday delay measurements here are not sensitive to the case of a highly variable magnetic field, with a mean over the eclipse region of near to zero. Thus, the constraint here
4.4. Polarisation

![Figure 4.11: Cross-correlation functions for left- and right-handed circular polarisations corresponding to a Parkes observation of PSR J2051−0827 on 2018-Sep-23. Each panel shows the cross-correlations between template left- and right-hand circular polarisation profiles and observed profiles integrated over 16 mins and 1241–1497 MHz. The blue curves represent the positive Stokes $V$ profile peak – as shown in Fig. 4.7 – while the orange curves represent the negative peak. The orbital phase at the centre point of each integration is indicated in the upper-right of each panel.](image-url)
Figure 4.12: Cross-correlation functions for left- and right-handed circular polarisations corresponding to a Parkes observation of PSR J2051−0827 on 2018-Dec-03. Each panel shows the cross-correlations between template left- and right-hand circular polarisation profiles and observed profiles integrated over 16 mins and 705–1345 MHz. The blue curves represent the positive Stokes V profile peak – as shown in Fig. 4.7 – while the orange curves represent the negative peak. The orbital phase at the centre point of each integration is indicated in the upper-right of each panel.
4.4. Polarisation

**Figure 4.13:** Top: Measured Faraday delays between left- and right-hand circular polarisation profiles integrated over 16 mins and 1241–1497 MHz. Bottom: The implied average magnetic field parallel to the line of sight, shown only for those points where $\Delta DM > 0$.

**Figure 4.14:** Top: Measured Faraday delays between left- and right-hand circular polarisation profiles integrated over 16 mins and 705–1345 MHz. Bottom: The implied average magnetic field parallel to the line of sight, shown only for those points where $\Delta DM > 0$. 
Chapter 4. Long Term Variability of a Black Widow’s Eclipses – A Decade of PSR J2051−0827

represents the average parallel field over the 16 min integration, but does not directly rule out large variability. On the other hand, should fluctuations in the field between the different lines-of-sight be extreme then they would significantly broaden the integrated circular polarisation profiles as a result of averaging over differential delays. Fluctuations of the magnetic field of a similar order of magnitude to our uncertainties on $B_\parallel$ would go undetected in this analysis.

4.5 Eclipse mechanisms

Stappers et al. (2001a) presented an investigation of possible eclipse mechanisms for the pulsed radio emission from PSR J2051−0827 in the frequency range 234–1660 MHz. The study dismissed the possibility of pulse smearing (430 MHz and above), refraction, reflection, free-free absorption and induced Compton scattering as possible eclipse mechanisms. However, the data available were not sufficient to be able to rule out either scattering of the pulses, pulse smearing at the lowest frequencies or cyclotron damping as the cause of the observed eclipses.

The observations that we present in this chapter are consistent with the conclusions to dismiss the above-listed mechanisms, and here we further investigate those mechanisms deemed possible by the previous study, in light of the new data.

4.5.1 Dispersion smearing

Stappers et al. (2001a) concluded that smearing of the pulses, due to variations in DM within the typical integration times, was not sufficient to broaden the pulses beyond the intrinsic pulse width at frequencies of 430 MHz and above. Their arguments could not, however, rule this out at lower-frequencies as the dispersion broadening increases as the inverse-square of observing frequency.

Fig. 4.15 shows the modelled effect of dispersion smearing on the 345 MHz pulse, where each smeared pulse represents an integration over a range of pulses delayed such as to model a linear change in DM over the integration time. Taking smearing of 30% – where the dispersion delay at the end of an integration is $0.3P$ larger than that at the beginning of the integration – as sufficient to cause significant difficulty in detecting the pulse, the required change in DM to surpass this limit at 345 MHz is $\sim 0.04$ pc cm$^{-3}$. Examination of the DM variations found from the high frequency observations in Fig. 4.3 can be used to investigate this, as they probe the DM variations throughout the eclipse region. In the most active eclipses (2011–2014) the DM changes over typical integration times are large enough to reach the required smearing limit, however often the DMs are not consistently this variable throughout the full eclipse region. This, in combination with the DM trends in the more quiescent periods (pre-2011, post-2014) where the variability is rarely sufficient to reach the required limit, shows that DM smearing cannot offer a reliable eclipse mechanism at 345 MHz.

Similar calculations for the 149 MHz radio emission yield a required change in DM, within a sub-integration duration, of only $\sim 0.007$ pc cm$^{-3}$. This is the same order of
4.5. Eclipse mechanisms

Figure 4.15: Modelled effect of dispersion smearing on the 345 MHz pulse profile. The model applies a linearly increasing dispersion measure delay to an array of pulses, then sums these to find the resulting integrated pulse profile. The smearing % corresponds to the ratio: \(100 \times \frac{\text{dispersion delay between first and last pulse}}{\text{pulse period}}\).

magnitude as the 1σ uncertainties in the high-frequency derived DMs, thus even for those observations where little deviation is seen we cannot rule out the possibility of the limit being surpassed throughout the bulk of the eclipse region. However, tighter constraints on the DM variations are provided by the 345 MHz observations at the eclipse edges. Fig. 4.16 shows the 149 MHz flux density over-plotted with 345 MHz DMs at four separate epochs, in order to suppress the effect of long-term eclipse variations. In all of the epochs the 149 MHz flux drops into eclipse without the DM rising above the DM smearing limit calculated above. The only exception to this is the eclipse ingress in the third panel from the top, however even here the flux density begins to attenuate without any detected rise in DM. This provides significant evidence against DM smearing as a feasible eclipse mechanism, even at frequencies as low as 149 MHz.

4.5.2 Scattering

In a similar fashion to DM smearing, scattering of the radio emission in the eclipse medium could act to broaden the pulses, and should the broadening become larger than the fundamental pulse width then the pulsations would become extremely difficult to detect. As with the above analysis, taking pulse broadening of 30% of the pulse period as an approximate detection limit, for the 345 MHz emission to become eclipsed would require a scattering timescale at 1400 MHz of \(\sim 5 \mu s \ (0.001 P)\), assuming that the timescale, \(\tau \propto \nu^{-4.4}\). This is smaller than the 1σ uncertainties on the scattering values measured.
Figure 4.16: 149 MHz flux density (grey, solid) at eclipse edges, with the four panels showing different epochs to reduce the effect of temporal variability of the eclipses. Over-plotted are the deviations in dispersion measure from the out-of-eclipse level, measured from 345 MHz observations (blue and orange). The dashed grey line simultaneously marks the out-of-eclipse dispersion level, and the minimum flux density detection limit of the telescope. The black dash-dotted line marks the dispersion smearing threshold required to broaden the 149 MHz pulse by 30% of the pulse period (see main text).
from the data, and often the scattering is seen to significantly exceed this during parts of the eclipse region. Similar calculations give a threshold scattering timescale at 345 MHz of $\sim 30 \mu s$ (0.007$P$) in order for the 149 MHz pulses to become eclipsed. This is only marginally greater than the typical 1σ uncertainties on the measured scattering values from the 345 MHz data, and is occasionally measured to be exceeded at orbital phases corresponding to the LOFAR eclipse boundaries. This analysis favours broadening of the pulses through scattering as a possible eclipse mechanism, however higher signal-to-noise observations would be required in order to determine whether the scattering thresholds are always exceeded at the eclipse boundaries. It is worth noting that the scattering timescale is always measured to be $0 \lesssim \tau \lesssim 0.1P$ at the eclipse boundaries in both the 345 MHz and 149 MHz data, thus although there is often increased scattering present, it would need a fairly steep gradient in order to reach the $\sim 0.3P$ threshold within a typical interval duration (20 s – 2 min) at the eclipse boundaries.

4.5.3 Cyclotron absorption

Should magnetic fields be present in the eclipse region, then these can play a significant role in the mechanism behind the eclipses. The above analysis suggests that the average parallel component of the magnetic field in the typical eclipse region can not be much larger than $10^2$ G. In addition, should the field be directed near-perpendicular to the line of sight, then the field is of the order of 1 G or less. Khechinashvili et al. (2000) specifically investigated the case of PSR J2051−0827; in their work they considered the companion to be a magnetic dwarf star, and suggested that eclipses occur as a result of cyclotron damping in a magnetosphere with a field strength at the companion surface of $10^4$–$10^7$ G. With this model they derive a direct dependence between the frequency of damped radiation and the magnetic field strength in the eclipse region (Equation 13 in their paper):

$$\nu_d \approx \frac{2.8 \times 10^{-3} B_C}{\gamma_p (1 - \cos \theta)} \left( \frac{R_C}{r} \right)^3,$$  \hspace{1cm} (4.19)

where $\nu_d$ is the frequency of radiation that is damped, $\gamma_p$ is the Lorentz factor of particles filling the companion magnetosphere, $\theta$ is the angle between the wave propagation and the magnetic field, and $B_C$, $R_C$ are the surface field strength in Gauss and radius of the companion star – i.e. $B_C \left( \frac{R_C}{r} \right)^3$ represents the field strength in the eclipse region for a dipolar field. Taking our upper limit estimate of the eclipse field strength of $\sim 10^2$ G, and $\gamma_p (1 - \cos \theta) \sim 1$, we find that frequencies of $\sim 300$ MHz would be strongly damped, whereas those higher, i.e. $> 1$ GHz, would be largely unaffected. This is in remarkable agreement with our observations. On the other hand, should the field strength be lower than this apparent upper limit, and Lorentz factors of 10–100 are considered as in Khechinashvili et al. (2000), then the model would predict that no eclipses would occur $> 100$ MHz. In addition, their model relies on a magnetosphere filled with a pair plasma from the pulsar wind, which as discussed above appears unlikely given our detected depolarisation, although propagation through an unbalanced pair plasma could potentially
satisfy both scenarios. In light of the significant assumptions that are required for both of our results, we deem this model to be still plausible, however further scrutiny of the model parameters and assumptions are now possible.

Prior to the development of this model, Thompson et al. (1994) investigated the potential effects of cyclotron absorption in spider eclipses in terms of the optical depth at both the fundamental and higher harmonics as a function of the plasma properties. In contrast to Khechinashvili et al. (2000), this modelling does not assume a pair plasma, and in fact somewhat relies on Faraday rotation to ensure absorption of both assumed propagation modes. The authors find that for black widow PSR B1957+20 an eclipse magnetic field of $\sim 10$ G, provided by either a companion magnetosphere or the magnetised pulsar wind, and a plasma temperature of $\sim 10^8$ K can account for eclipses at frequencies $\lesssim 1$ GHz, but higher temperatures would likely be required to absorb higher frequencies. Our observations are consistent with a magnetic field of similar strength in PSR J2051−0827, and as the authors note, such temperatures correspond to only a tiny fraction of the incident pulsar wind energy density, thus it appears plausible that this mechanism could indeed also account for the eclipses in PSR J2051−0827.

4.6 Discussion

Wu et al. (2012) infer the presence of an intra-binary shock between the pulsar and companion winds in the PSR J2051−0827 system from the observed X-ray spectra. Shock structure in the eclipse material could vastly increase the density compared to that implied by assuming the material is evenly distributed over a depth equivalent to the eclipse radius. Archibald et al. (2009) discussed the possibility of the density in the shock being high enough for the eclipses to be caused simply by the plasma frequency being larger than the observing frequency. From our observations the lowest frequency for which the radiation is not eclipsed is $\sim 700$ MHz, and the tightest upper limit on the column density of material in the eclipse region is provided by the ‘quiescent’ DM periods, in which the $1\sigma$ uncertainties suggest $N_e \lesssim 3 \times 10^{15}$ cm$^{-2}$. In this case, for the plasma frequency to reach 700 MHz would require a shock only $\sim 5 \times 10^5$ cm, or $\sim 10^{-5}$ orbital radii thick, containing all of the intervening plasma column.

In modelling of intra-binary shocks in spider pulsars, Wadiasingh et al. (2017) estimate that the contribution to magnetic fields in the shock region by the pulsar wind is of the order $10^{-1} \lesssim \frac{B}{k_B} \lesssim 200$. This could feasibly account for the required magnetic fields for a number of theorised eclipse mechanisms – e.g. cyclotron-synchrotron absorption (Thompson et al., 1994), induced scattering (Luo & Melrose, 1995) – and possibly the RM variations measured in this study, without the need to infer a companion magnetosphere. Alternatively, the vast extent of the low density ablated material that shocks the pulsar wind and the persistent structures that we observe it to form (Fig. 4.3), can be attractively explained by a magnetic field provided by the companion star giving support to the material, as is also noted in Stappers et al. (1996a, 2001a). Further modelling of intra-binary shocks, presented in Wadiasingh et al. (2018), suggests that pressure balance in the shock
can be achieved in a number of redback pulsars if the companion has a surface magnetic field strength on the order of kilogauss. It is interesting to note that such a field is consistent with the loose constraints found here, and is also of a similar magnitude to that required for cyclotron damping to cause the eclipses (Khechinashvili et al., 2000).

Such a magnetic field can be inferred to account for the orbital fluctuations that are detected in PSR J2051−0827 (Lazaridis et al., 2011; Shaifullah et al., 2016) due to the companion star’s magnetic cycles causing variations in its oblateness (Applegate & Shaham, 1994). These variations could presumably be expected to influence the ablation of the companion and consequently the eclipsing medium which forms. Comparison of the long-term changes in the high-frequency DM patterns, measured here, with the timing variations presented in Shaifullah et al. (2016) reveals no clear correlation between the two, however this is not surprising based on the short overlap in our datasets relative to the timescale of the orbital variations. We note that the rise and fall-off of eclipse DMs that we detect over our observation range could be interpreted as following a similar trend, albeit with a lag of ~ 500 days, as the lattermost peak in the measured time of ascending node parameter (Fig. 6 of Shaifullah et al., 2016), although more observations would be required to see if such a pattern persists. A more stringent test of this would be provided by comparison of the two measurements during a less ‘quiescent’ time of the orbital parameter variations, or in a different eclipsing system with more pronounced orbital fluctuations. On the other hand, with the apparent lack of correlation between the measured high-frequency DMs and the low-frequency eclipse variations, it may be that the DMs that we detect are not very representative of the parameters of the eclipse medium as a whole, especially when the line of sight is so far inclined from the orbital plane.

Inferring a mass loss rate for the companion of PSR J2051−0827 has an added complication due to the small ~ 40° inclination angle of the orbit, suggesting that our line of sight samples only the outer edges of the eclipse medium. Somewhat naively we can make an estimate by assuming that the material is spherically symmetric about the companion, in which case the material is ejected from the system through a circular region, centred on the companion, perpendicular to the orbital plane. With this assumption we can follow the analysis in Section 6.3 of Thompson et al. (1994), whereby the ablated material, approximated to balance the momentum flux of the pulsar wind at the orbital separation, becomes entrained in the pulsar wind. Given the orbital parameters listed in Section 4.1, and taking the eclipse duration to be 10% of the orbit, the corresponding eclipse width is ~ 0.7 R⊙. As this corresponds to a chord across the projected circle of material around the companion due to our inclined view of the system, we estimate the actual diameter of the circle to be ~ 1.8 R⊙. Taking the column density of material to be ~ 0.1 pc cm−3 (note that this could be much higher in the orbital plane, closer to the companion), and the depth to be of the order of the eclipse radius, the density of material in this region is n_e ~ 10^7 cm−3. The velocity of the material entrained in the pulsar wind is then V_W = (U_E/n_e m_p)^1/2 ~ 5 × 10^8 cm s−1, where U_E ~ 2.4 ergs cm−3 is the energy density of the pulsar wind at the companion. This leads to an estimated mass loss rate
Chapter 4. Long Term Variability of a Black Widow’s Eclipses – A Decade of PSR J2051−0827

of $M_\text{C} \sim \pi R_\text{E}^2 n_\text{p} n_\text{e} V_\text{W} \sim 10^{-12} M_\odot \ yr^{-1}$; similar to that calculated for black widow PSR J1810+1744 (Chapter 3). This value, although subject to much uncertainty, is likely to act more as an upper limit on the long-term evolution of the system as the orbital separation is expected to increase as mass is lost from the system, reducing the irradiative influence of the pulsar wind. In addition, the presence of a companion magnetosphere could effectively contain, or shield the ablated material, reducing the estimated rate of mass loss from the system. With these caveats, the observations presented here appear to disfavour the possibility of the companion being fully evaporated within a Hubble time.

4.6.1 Mini-eclipses

Figs. 4.17 and 4.18 show short duration flux density reductions – ‘mini-eclipses’ – at orbital phases far from the main eclipse; more commonly associated with redback systems that have much larger main eclipse fractions (Lyne et al., 1990; Archibald et al., 2009; Deneva et al., 2016). It is interesting to note that all of the mini-eclipses were detected in a 2 week period in 2015-Feb, and no other convincing mini-eclipses were seen at any other time. The small diffractive interstellar scintillation (DISS) bandwidths of $\sim 1 \ kHz$ and $\sim 50 \ kHz$, for 149 MHz and 345 MHz centre frequencies respectively, for PSR J2051−0827 mean that any effects of DISS will be well averaged out over the observing bandwidths, and thus cannot be responsible for such variations. These are of particular interest for eclipse mechanisms that require the presence of a companion magnetosphere, as this would have no influence at orbital phases so far from companion inferior conjunction. Considering the lack of magnetic fields to shield this material from the pulsar wind, it presumably must have been ejected far from the orbit in the time taken to cross our line of sight. No significant pulse delay or broadening is seen around the mini-eclipses, suggesting that the material causing the reduction in flux density either has a very low density, or relatively sharp boundaries such that the increase and decrease in density evades detection within the observation time integrations. The presence of material at multiple orbital phases, all observed within a short 2 week period may be linked to variations in the intra-binary shock or flaring of the companion star, such as those suggested by Cho et al. (2018) and Yap et al. (2019), which could lead to more erratic mass ejection from the system.

Effects of Earth’s ionosphere

A recent study by Scholte et al. (in prep.) into the effects of the ionosphere on LOFAR observations of pulsars found correlations between the measured pulsar flux density in beamformed data with the variable apparent position of sources in the image-plane. The variations were seen to occur on timescales of minutes and were attributed to turbulence in the ionosphere displacing the target source from the centre of the low-frequency tied-array beam, thus reducing its sensitivity. Although it is not clear how the effects of the turbulence scale with the line of sight TEC of the ionosphere, we note that the TEC values at times corresponding to the mini-eclipse observations, found from the ionFR code
FIGURE 4.17: Short duration flux density modulations detected in 149 MHz observations over a 2 week period in 2015. The modulations occur at orbital phases far from the typical eclipse.
Figure 4.18: Short duration flux density modulations detected in 345 MHz WSRT observations on 2 consecutive days in 2015. Each observation has been split over 2 panels, showing the top and bottom halves of the 70 MHz bandwidth to highlight the wide band nature of the flux density variations, distinguishing these from diffractive scintillation (see main text).
4.7. Conclusions

We present a large number of observations of the black widow pulsar PSR J2051−0827 at observing frequencies spanning 149–4031 MHz, over ∼ 10 years. Fitting for dispersion and scattering delays simultaneously, we detect variations in the material ablated from the companion on timescales ranging from shorter than the 2.4 hr orbital period, to multiple years. These pronounced fluctuations in the DMs throughout the eclipse region do not show any clear correlation with the variable eclipse widths seen at lower observing frequencies, nor do they convincingly relate to the timing variations presented in Shaisfullah et al. (2016). On this topic, we plan to continue to monitor the source with regular 1 hr observations using the Lovell telescope, allowing a thorough test of whether or not a pattern develops between the eclipse and timing behaviours. The current lack of correlation may be due to the variable DMs not being representative of the behaviour of the eclipse material as a whole, which would be understandable bearing in mind the ∼ 40° inclination of the orbit.
We detect DM structures that persist for many months, present a possible increase in variance in Faraday rotation values in eclipse egress, and find depolarisation of the linear polarisation components of the pulse throughout the low-frequency eclipse region, all of which could be explained by magnetic fields in the ablated material. Consideration of the depolarisation of the linear components, and Faraday delay measurements between the two hands of circular polarisation, allow us to place limits on the average magnetic field parallel to the line of sight of $10^{-4} \lesssim \frac{B_||}{|B|} \lesssim 10^2$ in the eclipse region. In addition, if the field were to be directed near-perpendicular to the line of sight, then a lack of depolarisation of the circular polarisation components allows us to constrain $B_\perp \lesssim 0.3$ G. We argue that such fields are consistent with those required for cyclotron damping (Khechinashvili et al., 2000; Thompson et al., 1994) as an eclipse mechanism, although scattering of the low-frequency emission is also fully consistent with the observations, in agreement with the calculations of Stappers et al. (2001a).

An updated estimate of the mass loss rate from the companion, $\dot{M}_C \sim 10^{-12} M_\odot$ yr$^{-1}$, is orders of magnitude higher than previously calculated in Stappers et al. (1996a), although still appears to be too low to realistically fully ablate the companion in a Hubble time. Finally, we show a series of mini-eclipses detected over a 2 week period at orbital phases far from inferior conjunction of the companion. Such a phenomena is more commonly associated with redback systems, and any models of these systems would need to infer where such material is located along the line of sight.
Chapter 5

Class Segregation – Comparing Eclipses for Widely Separated Companion Masses

“It's not the size of the dog in the fight, it's the size of the fight in the dog”

Mark Twain

In this chapter we present a comparative study into the low-frequency eclipses of PSR B1957+20 and PSR J1816+4510. These two systems have similar orbital properties, but the companions to the pulsars have masses that differ by an order of magnitude. A dedicated set of observations to simultaneously observe the pulsed, and continuum, unpulsed flux densities throughout the eclipses are analysed, revealing many similarities between the excess material within the two binaries, irrespective of the companion star properties. The observations show that the pulsar flux is removed from the line of sight throughout the main body of the eclipses, with cyclotron-synchrotron absorption, or nonlinear scattering providing consistent eclipse mechanisms. However, in the egress of PSR J1816+4510 we often observe smearing out of the pulsations after the continuum flux has recovered, and claim that this occurs as a result of scattering in the tail of material flowing behind the companion. Inferred mass loss rates for both systems are found to be seemingly too low to evaporate the companion stars on a reasonable timescale.

Contributions of others: General guidance and discussions by R. P. Breton. LOFAR observations by M. van der Wiel. uGMRT observation performed by B. Bhattacharyya. Setting up and guidance on the usage of \texttt{prefactor} provided by D. Scholte and J. W. Broderick. PSR B1957+20 original timing solution provided by J. Donner, and discussions and guidance on the timing irregularities provided by B. W. Stappers, J. W. T. Hessels, C. Bassa, J. Donner and J. P. W. Verbiest.
Chapter 5. Class Segregation – Comparing Eclipses for Widely Separated Companion Masses

5.1 Introduction

In Chapter 3 we introduced some advantages behind observing eclipsing pulsars at low-frequencies. To recap, it is observed that the radio emission from pulsars is in general significantly brighter toward lower-frequencies (Section 1.1.2), secondly, the LOFAR telescope (Section 2.2.1) offers unprecedented sensitivity at frequencies < 200 MHz, allowing high signal-to-noise detections, and finally, the observable effects of scattering and dispersion scale strongly with the inverse of frequency, and when twinned with the wide fractional bandwidth of LOFAR, allow precise measurements of these phenomena at eclipse edges. An additional advantage provided by LOFAR, unrelated to observing frequency, is the capability to simultaneously record high-time resolution beamformed data and also visibilities that can be used to produce images of the sky. This capability allows direct discrimination between eclipse mechanisms that remove pulsar flux from the line of sight, from those that only smear out the pulsations. The success of such observations for determining many of the useful eclipse metrics was also demonstrated in Chapter 3, inspiring us to perform a programme of similar observations for other spider pulsars.

Two spider systems were chosen for this study, namely, PSR B1957+20 and PSR J1816+4510 (hereafter B1957 and J1816, respectively), both of which were known to be particularly bright at low-frequency and easily detectable with LOFAR (Kondratiev et al., 2016). Furthermore, both systems have similar orbital properties, with comparable pulsar–companion star separations, while containing companion stars with masses separated by nearly an order of magnitude (Arzoumanian et al., 1994; van Kerkwijk et al., 2011; Stovall et al., 2014; Kaplan et al., 2013), providing the opportunity to investigate how this affects the eclipses. Table 5.1 lists the orbital parameters of these two binaries that are most pertinent to the following eclipse analyses.

B1957 was the first black widow to be discovered (Fruchter et al., 1988a), and is one of the most intensively studied. Optical observations revealed the inner face of the companion star to be strongly irradiated (Kulkarni et al., 1988; van Paradijs et al., 1988), and a subsequent study of the companion’s radial velocity suggested that the system harbours a massive NS – $M_{\text{PSR}} = (2.40 \pm 0.12)M_\odot$ – in an orbit inclined at 65° (van Kerkwijk et al., 2011). In the radio domain, regular eclipses have been observed over a range of frequencies > 300 MHz (Fruchter et al., 1990; Ryba & Taylor, 1991). Based on these observations, there have been attempts to model both the outflow from companion star (Tavani
5.2 Observations

& Brookshaw, 1991) and the mechanisms behind the eclipses (e.g. Thompson et al., 1994), however these have remained largely inconclusive. In Fig. B.2 we show a schematic of the expected orbit as viewed in the sky.

J1816, on the other hand, was only discovered much more recently, with its radio eclipses and pulse arrival delays leading it to be classified as a redback (Stovall et al., 2014). However, follow-up studies in the optical domain revealed the companion star to have unique properties among the other known redbacks, with an unusually high temperature and metallicity best resembling a proto-WD (Kaplan et al., 2013), which has since brought this classification into doubt (Istrate et al., 2014). Although not a ‘stereotypical’ redback – somewhat vague in this context as the number of well characterised redbacks is low (c.f. Strader et al., 2019) – it still represents the class in that the companion is roughly an order of magnitude larger than that in black widows. Interestingly, J1816 also appears to harbour a massive NS – $M_{\text{PSR}} \sin^3 i = (1.84 \pm 0.11)M_\odot$ – but the orbital inclination, $i$, of the orbit is relatively unconstrained (Kaplan et al., 2013), and as such its projection on the sky is not known.

In this chapter we begin by describing the observations and analysis techniques in Section 5.2, and, following this, present the measured eclipse properties for each system in Sections 5.4 and 5.5. The findings are then discussed in detail in Section 5.6, considering the properties of the eclipse material, mass loss rates and eclipse mechanisms in both systems.

5.2 Observations

Based on the successful application of simultaneous interferometric and beamformed observations to study eclipses in Chapter 3, we undertook a dedicated campaign, using the same capabilities of the LOFAR Core HBAs (110–188 MHz), to observe B1957 and J1816. Observations of each source were split into groups, separated by a few months, within which two eclipses were observed with intervals of a few days, as shown in Table 5.2. This schedule aimed to investigate the eclipses on different timescales. In addition, the schedule was designed so that the eclipse of each source was centred near the meridian, hence minimising the effects of telescope sensitivity variations that can occur for low-elevation beam pointings (see Section 2.3.1). Due to the relatively long orbital periods of the two sources, the observations were chosen to be 4.5 hrs in duration, corresponding to approximately half an orbit, ensuring sufficient coverage of out-of-eclipse phases to allow measurements of the baseline DMs, flux densities and timing parameters. Complementary to this dedicated project, in 2014-Oct we had already obtained a single full-orbit observation of J1816 utilising the same simultaneous interferometric and beamformed mode of the LOFAR Core, thus further aiding in the investigation of time-variable eclipse phenomena.

Many thorough studies of the eclipse phenomena of B1957 exist for observations at $>300$ MHz (e.g. Fruchter et al., 1990; Ryba & Taylor, 1991), hence these results can be used in our interpretation of the low-frequency data. On the other hand, no such in-depth
studies exist for J1816 – the eclipse and corresponding TOA delays are reported in Stovall et al. (2014), but not deeply investigated – thus we obtained a dedicated eclipse observation at higher-frequency to complement the LOFAR data. For this, we utilised the upgraded GMRT (Section 2.2.3) to make a 6.5 hr observation of J1816 with all available antennas in a 550–750 MHz band, breaking every $\sim 1.5$ hrs to phase calibrate the array for $\sim 10$ mins.

### 5.3 Analysis

#### 5.3.1 Beamformed data

The LOFAR beamformed data were automatically coherently dedispersed, folded and cleaned as part of PulP (Section 2.2.1). The resulting folded data consisted of 5 s duration sub-integrations, 384 frequency channels and 512 (256) pulse phase bins for J1816 (B1957). The schedule plan to observe with high-elevation beam pointings, and the lack of a need to attain absolute flux density measurements, meant that thorough flux calibration was not required. Similarly, as both sources have only small percentages of polarised flux, no polarisation calibration was performed. The wandering of orbital parameters that commonly occurs in spider pulsars (Sections 1.1.3 and 2.3) was corrected for in J1816 by fitting out-of-eclipse TOAs to the timing model available in the Pulsar Catalogue using TEMPO2, with the spin frequency derivative, $F_1$, orbital period, $P_B$, and time of ascending node, TASC, as free parameters. This task was much more problematic for B1957, which is known to exhibit large variations in its orbit (Arzoumanian et al., 1994), as the readily available timing solutions had become insufficient as a baseline model to allow for the relatively small number of TOAs from these observations to accurately correct the parameters. As such, we instead used a baseline model developed using TOAs obtained from GLOW (a network of LOFAR single stations in Germany) observations spanning 2014-Jan – 2019-Jan (Appendix D; Julian Donner priv. comm.). This was optimised for our set of observations by fitting to TOAs using TEMPO2, with the epoch of periastron,
5.3. Analysis

Table 5.3: Step sizes in DM and \( \tau \) used in the model fits to data observed at different centre frequencies. \( \Delta \tau \) is expressed in units of the pulse period, \( P \).

<table>
<thead>
<tr>
<th>PSR</th>
<th>Centre frequency (MHz)</th>
<th>( \Delta \text{DM} ) (pc cm(^{-3}))</th>
<th>( \Delta \tau )</th>
<th>( P ) (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1816+4510</td>
<td>149</td>
<td>( 1 \times 10^{-4} )</td>
<td>0.005( P )</td>
<td>3.19</td>
</tr>
<tr>
<td>J1816+4510</td>
<td>650</td>
<td>( 1 \times 10^{-3} )</td>
<td>0.005( P )</td>
<td>3.19</td>
</tr>
<tr>
<td>B1957+20</td>
<td>149</td>
<td>( 1 \times 10^{-3} )</td>
<td>0.01( P )</td>
<td>1.61</td>
</tr>
</tbody>
</table>

To, and projected semi-major axis of the orbit, \( A_1 \), as free parameters. In a similar vein, the DM of each observation was adjusted by applying \( \text{pdmp} \) to the out-of-eclipse data to obtain the ‘optimum’ value, and installing this with \( \text{pam} \) (see Section 2.3).

The higher-frequency uGMRT data for J1816 were pre-processed by the methods described in Section 2.2.3, and were folded into 5 s sub-integrations, 4096 frequency channels and 512 pulse phase bins using the DM and timing ephemeris optimised with the LOFAR data observed within the same month.

The results presented in the previous chapters of this thesis have demonstrated the value that can be gleaned from precise measurements of DM and scattering timescale, \( \tau \), as a function of the orbital phase. Consequently, the same model fitting method, described in Section 2.3.2, was utilised here to extract these quantities relative to the out-of-eclipse values. Taking into account the possible variations in the mean pulse profiles over the long timescales covered by our observations, separate two-dimensional template profiles were made for each widely spaced (> 1 week) set of observations. Prior to applying the fits the data were integrated over time to form sub-integrations of durations 10–30 s, depending on the signal-to-noise of the observation. The step sizes used for the grid search over \( \Delta \text{DM} \) and \( \Delta \tau \) are shown in Table 5.3.

5.3.2 Interferometric data

The LOFAR interferometric data were obtained and pre-processed as per the methods of Section 2.2.1. For these observations a short, \( \sim 10 \) min, scan of a dedicated flux calibrator source was performed immediately before and after the target observation. For B1957 these were 3C295 and 3C48, respectively, and for J1816, 3C295 was used for both pre- and post-target observations. The pre-processed data were calibrated using the LOFAR \text{prefactor} pipeline (Section 2.3.1), and images of the target field were made using \text{WSClean} in time integrations of 2.5 mins and 5 mins for B1957 and J1816, respectively.

The earlier, 2014-Oct, observation of J1816 was instead planned to interleave calibrator observations throughout the long session, consisting of a repeating cycle of 30 mins on target and 7 mins on the flux calibrator 3C295. The pre-processing and calibration followed the same methods as used for PSR J1810+1744 in Chapter 3, similarly using \text{CASA} to image the pulsar in integrations of 5 mins. The repeating cycle of target–calibrator observations unfortunately led to small gaps in our data in both the ingress and egress of the image-plane eclipse.

Analogous to Chapter 3, flux density measurements of the source were made using \text{PYBDSF} to fit two-dimensional Gaussians to the image pixel intensities at apparent source
locations. For each observation a high signal-to-noise ‘detection image’ was made by integrating all out-of-eclipse data, which was then used to initially identify the location of ‘islands’ of emission used by \texttt{PYBDSF} as indicators of source positions. These positions were then automatically used in \texttt{PYBDSF} to fit the model Gaussians in each short-integration image, and extract the mean flux density, and 1σ uncertainty, over the integration time.

5.4 PSR J1816+4510

For J1816, Fig. 5.1 shows the collective measurements of the un-pulsed flux density obtained from images, each integrated over 5 mins, and the pulsed flux density and deviation in DM output from the template fits to the beamformed data. Both the pulsed and un-pulsed flux densities have been normalised such that the mean out-of-eclipse flux densities are unity, allowing a clear comparison of the eclipse effects.

At first sight some of the apparently now common features of low-frequency spider eclipses are visible, with the eclipse centred to a later orbital phase than inferior conjunction of the companion – phase 0.25 – a relatively stable ingress with little excess DM and a much more erratic egress with large DM fluctuations. Such features are generally attributed to a ‘tail’ of material that is swept behind the companion by Coriolis forces as it moves around the orbit (e.g. Chapter 3; Fruchter et al., 1990), and it appears reasonable to infer that the same phenomenon is responsible here. Equally clear is the complete attenuation – at least by a factor of 5 based on the signal-to-noise of the out-of-eclipse detections – of the continuum, un-pulsed flux in the eclipse region. As far as we are aware this has been observed in all published low-frequency imaging observations of spider eclipses thus far, although this only amounts to four other systems (Chapter 3; Fruchter & Goss, 1992; Roy et al., 2015; Broderick et al., 2016). The duration of the eclipses shows significant frequency dependence (see Chapter 6), with the variable low-frequency eclipses lasting for ~ 9–12% of the orbit, while the higher-frequency eclipse covers only ~ 5%. Notably, if the, as yet unconstrained, inclination of the orbit is near 90° then the Roche lobe would span ~ 7% of the orbit, assuming the parameter values in Table 5.1, and as such the 650 MHz flux would penetrate this, suggesting that either the orbit is not edge-on or the companion does not fill its Roche lobe.

Under closer inspection a particularly interesting feature emerges: comparing the continuum eclipses to the pulsed eclipses it can be seen that the orbital phases of the ingress are regularly consistent with one another – also seen in PSR J1810+1744 (Chapter 3), however in all but one eclipse egress the pulsed eclipse extends to a significantly later phase than the corresponding continuum eclipse. This is more readily shown in Fig. 5.2, where the pulsed and corresponding un-pulsed flux density measurements are over-plotted for three of the eclipses. This provides clear evidence for the presence of an eclipse mechanism that removes pulsar flux from our line of sight, then upon approaching egress transitions to one that merely smears out pulsations while not removing flux from the line of sight. This is the first ever such observational evidence for any spider pulsar, and
5.4. PSR J1816+4510

Figure 5.1: Measurements of the radio emission of PSR J1816+4510 throughout the eclipse region from simultaneous beamformed and imaging observations at 149 MHz. Top: Un-pulsed flux densities from continuum images, with each normalised so that the out-of-eclipse mean flux density is unity. The horizontal dashed line corresponds to the detection limit of the telescope. Middle: Pulsed flux densities from beamformed observations, again normalised to unity. Bottom: Deviation from mean out-of-eclipse dispersion measures for the same set of observations. The grey curves in the middle and bottom panels are measured from beamformed data observed at 650 MHz. Colours are consistent between panels, and error bars represent $1\sigma$ uncertainties from the simultaneous DM and scattering fits, as explained in the main text.
is discussed further in Section 5.6.2.

The inset plot of Fig. 5.1 magnifies the egress DM deviations, which show that the excess material in the tail is not smooth on these scales, and often slowly undulating structures are present that suggest relatively large scale clumps. Interestingly, in simplified two-dimensional hydrodynamical models of the outflow in B1957, Tavani & Brookshaw (1991) show that time-dependent, large scale, density enhancements can indeed form in the tail of the outflow. The timescale of large variations in the tail material is constrained by our observations to be < 4 days (∼10 orbits); notably the early-exiting egress, with relatively little DM fluctuations, on 2018-Sep-02 shows no similarities to that observed just 5 days previously. Comparing the eclipses observed in 2018 to that in 2014, we see no significant difference that could suggest long-term variability, although the extremely sparse sampling of eclipses over this time-span means that it cannot be ruled out.

At 650 MHz, the DMs are still highly asymmetric and no significant increase is seen in the ingress prior to loss of flux. This appears to be consistent with the TOAs presented in Fig. 10 of Stovall et al. (2014), where a sharp rise in ingress DM is only detected at 820 MHz and 1500 MHz, probing further into the eclipse. In addition, the general shape of the ∆DM pattern, which is relatively smooth on these magnitudes, is very well replicated by those seen in B1957 at a similar frequency (Ryba & Taylor, 1991).
5.5 PSR B1957+20

Fig. 5.3 presents the same measurements of un-pulsed flux density, pulsed flux density and deviation of DM, now for B1957 as a function of its orbit. The results are shown for four 149 MHz eclipses, with intervals between observations ranging from a few days to 5 months. Given the higher signal-to-noise of B1957 observations relative to those of J1816, the integration time of each image was reduced to 2.5 mins, allowing ~ 5 flux density samples in each eclipse ingress and egress. This increased resolution permits stringent tests on the orbital phases of pulsed versus un-pulsed eclipses, and shows that the two are closely matched in both the times of ingress and of egress, suggesting that the low-frequency eclipse occurs solely as a result of removal of flux from the line of sight. On the other hand, in the 2018-Aug-06 and 2019-Jan-09 egresses – where ΔDM is largest – there is some reduction in pulsed relative to un-pulsed flux density part way through the egress. This is likely explained by low-level scattering causing broadening of the pulsations. Indeed, our fits of ΔDM and Δτ are consistent with this being the case, however the full pulsed flux density is not accounted for here as the pulse profile at 149 MHz has a duty cycle of ~ 100%, thus any scatter-broadening of the profile effectively smears the flux into the arbitrary baseline level, which is automatically subtracted in pre-processing of the data. It could well be the case that a more severe effect of the same mechanism is responsible for the extended egresses in J1816, as this pulsar too has a ~ 100% duty cycle. Taking into account the typical signal-to-noise of the out-of-eclipse images, the flux density during eclipse is reduced by at least a factor of ~ 25 and is consistent with zero flux. This is in agreement with the observation at 330 MHz in Fruchter & Goss (1992), whereby a single image integrated over the entire eclipse region constrained the flux density of B1957 to (1 ± 3) mJy, whereas this value was found to be (38 ± 3) mJy when integrated over the full observation.

The patterns in ΔDM that we measure are consistent with the measurements at > 300 MHz made in the few years following the initial discovery (Fruchter et al., 1990; Ryba & Taylor, 1991), and the corresponding interpretations of a swept back, low-density tail of material trailing behind the companion still appear to be applicable. Similar to J1816, and at higher frequencies in B1957, there are slowly undulating patterns in the DM, however our high signal-to-noise measurements also reveal rapid fluctuations of the order of 10^{-3} \text{ pc cm}^{-3} on 20 s timescales. This contrasts the ~ 10^{-5} \text{ pc cm}^{-3} fluctuations on 2 s timescales reported in Main et al. (2018), for which the corresponding eclipse, observed at 325 MHz in 2014-Jun, is over-plotted on our observations in grey in the bottom panel of Fig. 5.3. The most remarkable feature of this is the apparent shift in eclipse location of ~ 1–2% over 4 yrs, suggesting significant bulk motion of the eclipse medium. Noting that the eclipses presented here appear more consistent with those in Ryba & Taylor (1991), it is not clear if the 2014-Jun eclipse represents a more isolated case, or if such shifting of the eclipse is a continuous, slowly-varying function of time – c.f. bulk DM variations in Chapter 4 on timescales of years.
Figure 5.3: Measurements of the radio emission of PSR B1957+20 throughout the eclipse region from simultaneous beamformed and imaging observations at 149 MHz. Top: Un-pulsed flux densities from continuum images, with each normalised so that the out-of-eclipse mean flux density is unity. The horizontal dashed line corresponds to the detection limit of the telescope. Middle: Pulsed flux densities from beamformed observations, again normalised to unity. Bottom: Deviation from mean out-of-eclipse dispersion measures for the same set of observations. Overplotted in grey is that observed at 335 MHz as published in Main et al. (2018), which appears to have an ingress and egress shifted to earlier orbital phases (see main text). Colours are consistent between panels, and error bars represent 1σ uncertainties from the simultaneous DM and scattering fits, as explained in the main text.
5.5.1 Out-of-eclipse variability

As for all of the observations used in this thesis, we measured pulse TOAs to fit to a timing model of the pulsar in order to refine the orbital parameters (see Section 2.3). Upon inspection of the TOA residuals – the discrepancies between the expected TOAs from the model, and the measured TOAs from the data – there was unusual structure with magnitudes of $\sim 20 \mu s$, and timescales of minutes–hours that could not be accounted for with the usual pulsar rotation and orbital parameters (see Sections 1.1.3 and 1.1.3). To investigate the possibility of a frequency-dependent mechanism being responsible for the variations – e.g. scattering or DM – we split the LOFAR band into 3 sub-bands and obtained TOAs for each. The TOA residuals relative to the timing model are shown in Figs. 5.4, 5.5, 5.6 and 5.7 for the four observations. The TOA measurements alone are not conclusive, but do appear to show frequency structure in some of the larger delays. Taking this further, the DM and $\tau$ template fitting method (Section 2.3.2) was applied with increments of $\Delta DM$ and $\Delta \tau$ small enough to allow multiple grid search elements across the observed $\sim 20 \mu s$ delays. Two templates were generated, one for the 2018-Aug observations, and one for the 2019-Jan observations, integrating over $\sim 30$ mins of data to gain signal-to-noise while avoiding integrating over too much of the delays that would act to broaden the template profiles. In addition to the standard template fitting method, a third grid search dimension was included to allow positive or negative phase shifts of the template, simultaneously in all frequency channels, in order to model frequency-independent TOA structure.

Unfortunately, the results of the fits suggest unrealistic interchanges between phase shifts,
Chapter 5. Class Segregation – Comparing Eclipses for Widely Separated Companion Masses

**Figure 5.5:** Top: Measured time-of-arrival of pulses in 3 non-overlapping sub-bands relative to the timing model for the observation of PSR B1957+20 on 2018-Aug-06. Data from the eclipse region has been removed for clarity. Middle/Bottom: Pulse profiles integrated over the full frequency band and 10 mins (black) at the indicated times. The grey, dashed profiles represent the baseline profile, and the orange profiles show the template after the best-fit values of phase shift, $\Delta D$M and $\Delta \tau$ have been applied.

**Figure 5.6:** Top: Measured time-of-arrival of pulses in 3 non-overlapping sub-bands relative to the timing model for the observation of PSR B1957+20 on 2019-Jan-07. Data from the eclipse region has been removed for clarity. Middle/Bottom: Pulse profiles integrated over the full frequency band and 10 mins (black) at the indicated times. The grey, dashed profiles represent the baseline profile, and the orange profiles show the template after the best-fit values of phase shift, $\Delta D$M and $\Delta \tau$ have been applied.
5.6. Discussion

As an indication into the volume of excess material in these two systems we can draw comparisons between the $\Delta$DM measurements. Beginning with the trailing tail of material post-eclipse, our LOFAR observations show $\Delta$DM $\sim$ 0.01 pc cm$^{-3}$ for both near
Chapter 5. Class Segregation – Comparing Eclipses for Widely Separated Companion Masses

orbital phase $\phi = 0.32$. Probing closer to the companion, the 650 MHz observation of J1816 shows $\Delta DM$ is around a factor of 10 larger than the above LOFAR measurements by $\phi = 0.275$. Similarly, the observations of B1957 presented by Ryba & Taylor (1991) show TOA delays of $\sim 200 \mu s$ at 1400 MHz at this orbital phase, also corresponding to $\Delta DM \sim 0.1$ pc cm$^{-3}$. Prior to the eclipse, in J1816 the ingress $\Delta DM$ appears to be negligible until slightly closer to companion inferior conjunction relative to B1957, although the TOA measurements in Stovall et al. (2014) suggest a sharp increase in DM in ingress, just beyond the beginning of the eclipses at 650 MHz observed here, again comparable with that in B1957 (Ryba & Taylor, 1991).

Considering that the orbital separations for both systems are much the same (see Table 5.1), and assuming that the material resides in close proximity to the orbits, then the implied physical widths spanned by the material are similar. Taking the common approximation that the material depth is equivalent to the eclipse width, then the implied density profiles for the two systems are also similar.

The comparable eclipse material densities, volumes and therefore masses that are inferred from the $\Delta DM$ measurements alone has interesting connotations when the vast differences between the nature of the companion stars are considered. On the one hand, these observations may arise out of a coincidence in the balance of competing effects caused by differences in the companion stars other than just their masses, e.g. density of the star and its size relative to the Roche lobe, strength of a stellar magnetic field etc., which may result in similar amounts of ablated material. With this in mind, we note that if both companions fill their respective Roche lobes, then the implied total pulsar wind energies incident on the stars are approximately equal, i.e. $U_{E,B1957}R_{L,B1957}^2 \approx U_{E,J1816}R_{L,J1816}^2$ (Table 5.1), in the case of isotropic winds.

Alternatively, if the eclipse material instead originates from electron-positron pairs in the pulsar wind becoming trapped in a magnetosphere (e.g. Khechinashvili et al., 2000; Li et al., 2019), then the magnetic fields of the companions would dictate the mass and volume of eclipse material rather than the companion masses. However, a study into the radio emission from B1957 presented in Li et al. (2019) appears to cast doubt on the latter scenario, as the observed polarisation properties did not agree with those theoretically predicted for propagation of the radio emission through a magnetised pair plasma. The authors do directly state that this could still be a promising scenario for J1816, for which ablation of material from the companion would be difficult to explain given its expected degenerate nature (Kaplan et al., 2013). Irrespective of its origin, the suggested similarities between the material around the companion stars in these systems mean that J1816 would make an interesting candidate for lensing of pulsar radio emission pre- and post-eclipse by the clumpy material, as recently observed in B1957 (Main et al., 2018).

Regarding the timing irregularities in B1957 presented in Section 5.5.1, neither the source nor the mechanism are clear, though broadening of the tail of pulses is indicative of scattering and/or dispersion. The precision with which we can measure TOAs in J1816 is not as high – due to the lower flux density of the pulsar – however we see no evidence for structure of a similar order of magnitude in the TOA residuals. Further long duration
observations of B1957, covering all orbital phases, would provide the opportunity to test for correlation between the TOA variations and orbital phase, which, if found, would strongly suggest that the origin lies within the binary system, and likely a result of propagation effects in excess material. The globular cluster eclipsing pulsar, PSR B1744–24A (Ter5A), is a well studied example of a binary system which demonstrates propagation delays that are caused by the ablated material from the companion unusually overcoming the pulsar wind, and flowing all around the orbit (Lyne et al., 1990). The propagation effects are much more significant in Ter5A, and are often accompanied by eclipses of variable durations occurring at all orbital phases, however it may be the case that the outflow geometry in B1957 bears some similarities to Ter5A, albeit with less material flowing around the orbit. Indeed, Tavani & Brookshaw (1991, 1993) model the outflows in both B1957 and Ter5A using two-dimensional hydrodynamical simulations, and by balancing their model parameters – mass loss rate, gas injection temperature, Mach number, effective cross-section and pulsar luminosity – can qualitatively reproduce the basic observable properties of the two. There is significant flexibility in these model parameters as they are largely unconstrained by independent observations, thus it would be interesting to investigate if realistic tweaking of the parameters could allow some of the ablated material in B1957 to also flow around the orbit.

5.6.1 Mass loss

The previous chapters in this thesis have made use of the method presented in Thompson et al. (1994) in order to estimate mass loss rates from the systems. As explained in Chapter 3, this assumes that the material leaves the system through a projected circle of diameter equal to the eclipse width, perpendicular to the orbital plane. The velocity of the material is determined by equating the energy density of the pulsar wind at the companion distance to the momentum flux of the eclipse material, i.e. \[ V_W = \left( \frac{U_E}{n_e m_p} \right)^{1/2}. \]

Then the mass loss rate is given by \[ \dot{M}_C \sim \pi R_E^2 m_p n_e V_W, \] where \( R_E \) is the half-width of the eclipse.

In Thompson et al. (1994) the authors specifically focussed on the case of B1957, estimating \( \dot{M}_C \sim 3 \times 10^{-13} M_\odot \) yr\(^{-1}\). For consistency with the rest of the pulsars studied in this thesis, we can make a new approximation for this based on the 149 MHz observations, and taking into account the expected orbital inclination. Using the values in Table 5.1 the equivalent eclipse width at the companion’s orbit is \( 2\pi a_C \phi_{\text{ecl}} \approx 1.64 R_\odot \), for \( a_C = a_p M_{\text{PSR}}/M_C, \) \( a_p \sin i = 0.089 \) lt-s (Arzoumanian et al., 1994), \( M_{\text{PSR}} = 2.4 M_\odot \) and \( M_C = 0.035 M_\odot \) (van Kerkwijk et al., 2011). When viewed at an inclination of 65° this corresponds to a chord across the assumed circle with diameter \( 2.98 R_\odot \). Taking the 149 MHz \( \Delta DM = 0.01 \) pc cm\(^{-3}\) to be distributed over a depth similar to the eclipse radius gives an implied density, \( n_e = 1.5 \times 10^5 \) cm\(^{-3}\). This gives an expected mass loss rate, \( \dot{M}_C \sim 10^{-12} M_\odot \) yr\(^{-1}\). For J1816 the inclination of the orbit is not yet constrained (Kaplan et al., 2013), and as such we assume here that \( i = 90^\circ \). Again using values from Table 5.1, and an eclipse
duration of 11% of the orbit, the estimated eclipse width is $2\pi a_C\phi_{\text{ecl}} \approx 1.70R_\odot$, for $a_C = a_p M_{\text{PSR}} / M_C$, $a_p \sin i = 0.60$ lt-s (Stovall et al., 2014), $M_{\text{PSR}} = 1.84M_\odot$ and $M_C = 0.193M_\odot$ (Kaplan et al., 2013). For $\Delta D_M = 0.01$ pc cm$^{-3}$, the implied density of eclipse material is $n_e = 2.6 \times 10^5$ cm$^{-3}$ if the depth is taken to be comparable to the eclipse width. This gives an estimated mass loss rate for J1816 of $M_C \sim 2 \times 10^{-13}$ M$_\odot$ yr$^{-1}$.

These estimated values are of a similar order of magnitude to those found for black widow pulsars PSR J1810+1744 and PSR J2051$-$0827 in Chapters 3 and 4, respectively, and the same caveats apply, in that the initial assumptions of the mass loss process heavily dominate the estimated values. Considerations such as a companion magnetosphere trapping the material, or widening of the orbit as mass is lost could lead to much lower, or continually decreasing, mass loss rates. On the other hand, if the material has a large neutral component then the mass loss could be much larger, as the DM measurements are only sensitive to ionised material. Assuming that the latter case is unlikely, bearing in mind the expected high energies incident upon the material (Thompson et al., 1994), it would appear that these estimates are more appropriately considered as upper limits, suggesting that complete evaporation of the companion stars does not appear realistic within typical timescales of evolution, especially for the more massive companion of J1816.

5.6.2 Mechanisms

As the ‘original’ black widow, B1957 has been subject to many in-depth scrutinies, and the mechanisms behind the observed eclipses have been of particular interest. Thompson et al. (1994) reviewed many of the previously proposed mechanisms, and also examined some seemingly promising alternatives (see Section 1.3.4). The authors found smearing out of the pulsations to be most consistent with the observational evidence for eclipses at 1400 MHz, and suggested that cyclotron-synchrotron absorption in either a companion star magnetosphere, or material entrained in the pulsar wind, was most likely at lower-frequencies. However, nonlinear Raman scattering (Section 1.3.4) also provided a feasible alternative at low-frequencies, should the plasma conditions allow growth of induced turbulence to a magnitude large enough to remove pulsar flux from the line of sight. Later, Khechinashvili et al. (2000) presented a different model of cyclotron damping of the radiation, considering a companion magnetosphere filled with electron-positron pairs from the pulsar wind, which was again consistent with the available observations. Recently some difficulties have arisen for both of the proposed cyclotron models, as new observations of lensing, and polarisation, in B1957 have led to tight upper limits on the strength of magnetic fields near the eclipse edges ($B_\parallel = 0.02 \pm 0.09$ G; Li et al., 2019), which are seemingly lower than those required for either model. Although this constraint is many magnitudes more precise than the limit found for PSR J2051$-$0827 in Chapter 4 ($B_\parallel = 20 \pm 120$ G), their observations do not strongly constrain the field strength actually within the eclipses where the absorption occurs. No such constraints are available for J1816 due to its low fractional polarisation in the pulsed radio emission.

Our observations conclusively show that flux is removed from the line of sight during
the low-frequency eclipses of both pulsars, consistent with the eclipse mechanisms suggested above. In addition, in Chapter 6 we show that the frequency dependence of the duration of eclipses in J1816 is consistent with the $\nu^{-0.4}$ relation found for B1957 over a wide range of frequencies (Fruchter et al., 1990; Ryba & Taylor, 1991), suggesting that a similar mechanism could be responsible for both.

For J1816, and to a lesser extent B1957, our observations show that the pulsed emission can sometimes remain undetected in the variable tail of material, while the continuum flux density recovers to the out-of-eclipse level, strongly suggesting that the propagation through the material causes the pulsations to become smeared in time. As considered in both Chapters 3 and 4, rapid fluctuations in DM can smear out pulsations if the change in induced delays within a single time-integration significantly exceeds the pulse width. For J1816, with a pulse width approximately half of the 3.19 ms pulse period, the necessary change in DM within an integration would need to exceed $\sim 0.01$ pc cm$^{-3}$ at 149 MHz. The 650 MHz observation offers a probe into the smearing region, and shows the DM variation to in fact be relatively slow, with a gradient significantly below that required to smear out the 149 MHz pulsations within a 30 s integration.

An alternative to DM smearing regards an increase in scattering causing the pulsations to become broadened in time. As the 149 MHz pulsed flux density recovers immediately after the smearing region, our fits of $\Delta$DM and $\Delta\tau$ are consistent with a rise in scattering timescale relative to the out-of-eclipse level, but this is loosely constrained to be $\lesssim 0.2P$, where $P$ is the pulse period. As such, for scattering to cause the loss of pulsations, a relatively sharp boundary must be present where $\Delta\tau$ increases to $> 0.5P$ within a 30 s integration. Again utilising the 650 MHz observation to directly probe the smearing region, our model fits constrain $\Delta\tau \lesssim 0.03P$ at 650 MHz. Taking the scattering timescale to scale with frequency as $\tau \propto \nu^{-4}$, this corresponds to roughly 10 times the pulse period at 149 MHz, and so is entirely consistent with scatter-broadening causing the loss of pulsations during egress.

Should scattering be the root cause of the variable J1816 egresses, this implies differences in the tail material of the two pulsar systems that is not noticeable from the DM variations alone. As B1957 has a similar pulse profile to J1816, but with a pulse period approximately half as long, the threshold scattering timescale to smear out the pulsations would also half. As a consequence, if the properties of the tail material were to be similar in both systems, the pulsations in B1957 should also undergo smearing beyond the pulse period. Although there is some evidence of pulse smearing in the B1957 egresses, this is to a much lesser extent than that seen for J1816.

5.7 Conclusion

In this chapter we present a direct comparison of the eclipses in two binary pulsars which have similar orbital parameters, but with companion star masses differing by an order of magnitude, namely, PSR B1957+20 and PSR J1816+4510. Both systems show comparable eclipse durations, with DM variations of a similar order of magnitude at orbital phases
near eclipse. The DM variations are shown to be highly asymmetric about the eclipses and fluctuate rapidly, indicative of a clumpy, swept back tail of material in both systems. The similar eclipse properties, regardless of the companion star type and mass, are discussed, and we consider that the eclipses may be independent of companion mass, or the effect of mass may be fortuitously cancelled out by other factors.

Estimated mass loss rates for the two systems lie in the range $10^{-13} - 10^{-12} \, M_\odot \, yr^{-1}$, similar to those predicted for PSR J1810+1744 and PSR J2051−0827 in Chapters 3 and 4, again suggesting that the companions will not be fully evaporated on any reasonable timescale of evolution.

Simultaneous observations of the pulsed flux, and the continuum, unpulsed flux show that total removal of flux from the line of sight occurs during the main eclipse, which now appears to be common at low-frequencies. The observations are consistent with the expected effects of cyclotron-synchrotron absorption, or stimulated nonlinear scattering, as the primary causes of the eclipses.

For PSR J1816+4510 we present the first direct detection of an eclipse mechanism transferring between removal of flux, and smearing of pulsations in a single eclipse. We attribute this to scattering in the extended tail of material, and infer that the properties of this material must differ in PSR B1957+20 as no such scattering is detected. Additionally, another potential difference between the two systems is presented, whereby measured pulse time-of-arrivals in PSR B1957+20 appear to result from time-variable broadening of the pulses throughout the orbit, indicative of scattering or dispersion in what may be excess material extending around the orbit.
Chapter 6

Frequency Dependence of the Eclipses

“We are not lost. We’re locationally challenged.”

John M. Ford

In this chapter we present measurements of the eclipse durations over a wide range of frequencies \( \lesssim 1 \) GHz for five spider pulsar systems. For each pulsar we fit power law functions to model the relationship between the eclipse durations and the frequency of the radiation. We find these to generally give good fits, however temporal variability in the eclipse durations can affect the apparent relationship, thus we attempt to address this where multiple observations at a given frequency are available. For all pulsars the dependence on frequency is significant, with wider eclipses at lower-frequencies. These results provide a marked improvement in the observational data available for theoretical studies of the eclipse mechanisms.

Contributions of others: General guidance and discussions by R. P. Breton. LOFAR single station observations of PSR J1810+1744 planned/performed by C. Tiburzi, J. Donner and J. P. W. Verbiest. uGMRT observations for PSR J1810+1744 and PSR J2215+5135 were performed by B. Bhattacharyya. All other observations provided as acknowledged in previous chapters.

6.1 Introduction

Measuring the eclipse durations as a function of observing wavelength, in an individual spider pulsar system, has the potential to discriminate between eclipse mechanisms, conditional on the assumptions made about the electron density and temperature distributions and magnetic properties of the eclipse medium. Alternatively, by assuming a given eclipse mechanism, certain properties of the eclipse medium can be inferred through the frequency dependence of the observed eclipses.
In the thorough critique of possible eclipse mechanisms for PSR B1957+20 and PSR B1744−24A (Ter5A), Thompson et al. (1994) directly refer to the observed degree of frequency dependence of the eclipse durations to provide evidence against a refractive mechanism. Here the authors showed that it is not plausible for both the small measured pulse arrival time delays at eclipse edges, and the relatively strong sensitivity of eclipse duration on frequency, to be simultaneously observed for a refractive mechanism with realistic density distributions for the eclipse material. Further, both Thompson et al. (1994) and Khechinashvili et al. (2000) cite the consistency of the predicted frequency dependence from cyclotron-synchrotron absorption with those observed in PSR B1957+20 as evidence in favour of such a mechanism being responsible for the eclipses.

However, there are significant problems associated with the reliable measurement of eclipse durations as a function of frequency. Generally the eclipse durations are of the order of 1 hr, and the change in duration with frequency tends to be \(\lesssim\) few mins for typical observing bandwidths. As such, long duration observations with large fractional frequency coverage are required in order to make precise measurements, which can be difficult to achieve with limited availability of telescope time. Furthermore, the very definition of eclipse duration is not robust, and depends on the signal-to-noise detection of the pulsar away from the eclipse. As the disappearance and re-emergence of flux at eclipse edges occurs over a finite time (see earlier chapters), a higher signal-to-noise observation of a pulsar, at a given frequency, will probe deeper into the eclipse region than an equivalent observation with lower signal-to-noise. A third problem arises from the time-variable nature of the eclipses. Due to the necessity for wide-frequency coverage, observations must often be performed with different telescope facilities, which can lead to large temporal separations between measurements of the eclipse durations at different frequencies, in which time the eclipse medium may have significantly changed. Stappers et al. (2001a) highlight the latter in their attempt to measure the frequency dependence for PSR J2051−0827, whereby the variability in eclipse durations at each individual frequency completely masks any genuine dependence on frequency. The collective effect of these issues has been to allow measurements of significant frequency dependencies of eclipse durations for only a few pulsar systems (Nice et al., 1990; Ryba & Taylor, 1991; Broderick et al., 2016) – at least to our knowledge, some may have been missed due to only sporadic reporting of these measurements over the last \(\sim\) 30 yrs.

As a result, to vastly increase the observational samples available for future studies, we bring together here our observations on all of the spider pulsars studied so far in this thesis. This includes PSR J1810+1744, a BW in a 3.6 hr orbit (Chapter 3); PSR J1816+4510, a RB-type pulsar in a 8.7 hr orbit (Chapter 5); PSR B1957+20, the ’original’ BW in a 9.2 hr orbit (Chapter 5); and PSR J2051−0827, a BW in a tight, 2.4 hr orbit (Chapter 4). Where possible we incorporate previously published eclipse duration data for the same sources. In addition to the above sources we also include observations of PSR J2215+5135; a RB pulsar, discovered in a radio-frequency search of \(\gamma\)-ray Fermi-LAT sources (Hessels et al., 2011). The pulsar radio emission is typically eclipsed for around half of the orbit, with image-plane observations showing the pulsar flux to be removed from the line of sight.
6.2. Observations

The observations used in this chapter have largely already been introduced earlier in this thesis. We bring together all of our datasets on five spider pulsars in order to get as wide a frequency coverage as possible, and these are listed in Table 6.1. For a number of these sources there has been previously published eclipse durations, and we include these in our analysis for comparison.

The low-frequency data for PSR J1810+1744 from Chapter 3, consisting of multiple LOFAR observations at 149 MHz and a single WSRT observation at 345 MHz, have been expanded on with a recently acquired simultaneous dual-frequency GMRT observation,
with half of the available antennas observing in a 200 MHz band centred at 400 MHz, and the other half in a 200 MHz band centred at 750 MHz. The observation was 5 hrs in duration, catching two full consecutive eclipses, with short \( \sim 10 \) min breaks occurring every 1.5 hrs in order to re-calibrate the phases between separate antennas. Total intensity data were recorded with a sampling time of 81.92 \( \mu s \), which were then folded with the most recently available ephemeris into 4096 frequency channels, 256 pulse phase bins and 20 s sub-integrations for analysis. Small DM and orbital timing corrections were made following the methods of Section 2.3.

In Chapter 5 a series of LOFAR observations of PSR J1816+4510 and PSR B1957+20 were studied. Here we make use of the same data, including both beamformed and imaging data for PSR B1957+20, whereas including only the beamformed data for PSR J1816+4510, as the long integration times of the imaging data would mask any small frequency dependent eclipse phenomena. In addition, the 650 MHz GMRT observation of PSR J1816+4510, also from Chapter 5, has been included in this work.

PSR J2051−0827 was the subject of investigations in Chapter 4. As previously noted in Stappers et al. (2001a) the temporal variations in the eclipses are of a large enough magnitude to mask any clear frequency dependence. As such, we undertook a dedicated campaign to observe the pulsar’s eclipses over an extremely wide frequency range, within just a 2 week period – shorter than the timescales of significant eclipse variability presented in Chapter 4. These observations, used as part of the earlier study, consisted of a 2 hr LOFAR observation at 149 MHz, a 2 hr GMRT observation at 400 MHz and 3 hr Parkes observation covering 705–4032 MHz. Note however that eclipses in this pulsar usually only occur for observing frequencies \( \lesssim 1 \) GHz.

Finally, we obtained a single, simultaneous dual-frequency observation of the RB pulsar PSR J2215+5135, not yet presented in this thesis. This was a 5 hr observation – more than a full orbit – using the GMRT with half of the antennas centred at 650 MHz and half at 1360 MHz. The data were recorded with a 40.96 \( \mu s \) sampling time, and \( \sim 10 \) min breaks occurred every 1.5 hrs for phase calibration of the array. These raw data were folded into 2048 frequency channels, 256 pulse phase bins and sub-integrations of either 60 s (650 MHz) or 4 mins (1360 MHz) to ensure high enough signal-to-noise for eclipse analyses.

### 6.3 Analysis

The primary goal of the work presented in this chapter was to measure the eclipse widths as a function of observing frequency. To achieve this the same method from Chapter 3 was applied here, whereby the eclipse ingress (egress) flux densities, \( f \), as a function of orbital phase, \( \phi \), were fit to a Fermi-Dirac type function, \( f = \left[ e^{\frac{\phi - p_1}{p_2}} + 1 \right]^{-1} \), with orbital phase of half-flux density, \( p_1 \), and slope, \( p_2 \), as free parameters, via the method of least squares. To perform the least squares fit we made use of the \texttt{curve_fit} function
from SciPy’s\footnote{https://www.scipy.org/} optimize package. Prior to the fits, the measured flux densities were normalised so that the mean out-of-eclipse flux density was unity. The normalisation was applied to ingress and egress data separately as often the out-of-eclipse means differed pre- and post-eclipse due the majority of the data having not been formally flux calibrated, meaning that slowly varying trends as a result of, for example, telescope pointing elevation, could still remain. As the functional form used to model each eclipse edge was a one-sided ‘step-like’ function, we were required to mask the opposite side of the eclipse while fitting an individual ingress or egress to avoid this biasing the residuals between the data and model in the least squares fits. Examples of the fits for PSR J2051−0827 are shown in Fig. 6.5.

Using the fitted parameters, we defined the eclipse duration as the full-width at half of the out-of-eclipse flux density, i.e. \( \Delta \phi_{\text{eclipse}} = p_{1,\text{eg}} - p_{1,\text{in}} \) where the subscripts ‘in’ and ‘eg’ refer to fits to eclipse ingress and egress, respectively. To avoid eclipse-to-eclipse variability from contaminating an individual eclipse duration measurement, we only calculated this metric for those observations that cover entire eclipses. Further, due to the observed asymmetry in many low-frequency eclipses (see Chapter 3) we also measured durations for the eclipse ingresses and egresses separately; defined as \( \Delta \phi_{\text{in/eg}} = |0.25 - p_{1,\text{in/eg}}| \), i.e. the orbital phase difference between ingress or egress and inferior conjunction of the companion, \( \phi = 0.25 \).

Uncertainties in these metrics were taken to be the 1\( \sigma \) uncertainty in \( p_1 \) from the least squares fit for the ingress and egress durations, and the quadrature sum of the 1\( \sigma \) uncertainties in \( p_{1,\text{in}} \) and \( p_{1,\text{eg}} \) for the full eclipse duration. Unless otherwise stated – see Section 6.3.5 for PSR J2215+5135 – these formal uncertainties were assumed throughout further analyses, meaning that each individual measurement made no attempt to account for temporal variability in the eclipses.

As in previous analyses (Chapter 3; Nice et al., 1990; Fruchter et al., 1990; Ryba & Taylor, 1991; Broderick et al., 2016) we attempted to glean insight from these results by fitting power law curves to the measured durations of the form \( \Delta \phi = A (\nu/150)^{-\alpha} \), where \( \nu \) is the observing frequency and \( A \) and \( \alpha \) are free parameters to be fit, representing the effective location and steepness of the curve, respectively. Similarly to the Fermi-Dirac fits explained above, we utilised the curve_fit function from SciPy.optimize to perform least squares fits. Separate power laws were fit in the case that clear temporal variability between eclipses was present – see Section 6.3.2 for PSR J1816+4510. It is the resulting \( \alpha \) parameters that we consider here – the \( A \) parameter accounts only for systematic variation of the eclipse width at 150 MHz between different pulsar systems – and these are presented in Table 6.3. In Appendix E the measured eclipse durations, fitted power law coefficients and corresponding uncertainties are given, with the intention for these to be utilised in future studies.
6.3.1 PSR J1810+1744

The measured eclipse durations and corresponding best-fit power law for PSR J1810+1744 are shown in the top panel of Fig. 6.1. Also plotted here are the data from Chapter 3, with the fitted power law shown by the grey, dashed line. With different coloured points representing separate eclipses, the strong influence of temporal variability of the eclipse properties on their apparent frequency dependence is immediately obvious for the measurements near 350 MHz. Shown in the bottom panel are the separate ingress and egress durations, relative to inferior conjunction of the companion. This provides further information on the eclipse variability, revealing that the duration change near 350 MHz is primarily caused by a significant shift in the ingress location, whereas the egress is consistent between the two observed eclipses.

The WSRT 345 MHz observation (red points) took place in 2011-Jun, more than a year prior to the earliest 149 MHz observation, and \( \sim 7 \) yrs prior to the recently observed GMRT eclipse at a similar frequency (blue points), thus the timescale of the ingress shift can only be loosely constrained. We note that there is little variability in the 149 MHz eclipses over 2012-Dec – 2015-Feb (although only sparsely sampled). In addition, we obtained 69 single station LOFAR (149 MHz) observations spread over 2017-Jul – 2018-Aug. These had too low signal-to-noise to split into sub-bands, but the full bandwidth eclipses were analysed and the vast majority of ingress durations laid in the range \( 0.052 < \Delta \phi_{\mathrm{in}} < 0.057 \), with extremes at \( \Delta \phi_{\mathrm{in}} \approx 0.047 \) and \( \Delta \phi_{\mathrm{in}} \approx 0.058 \). On the other hand, the majority of egress durations were found to lie within \( 0.068 < \Delta \phi_{\mathrm{eg}} < 0.085 \), with extremes at \( \Delta \phi_{\mathrm{eg}} \approx 0.065 \) and \( \Delta \phi_{\mathrm{eg}} \approx 0.095 \), demonstrating much larger variability in the eclipse egress relative to ingress at these low-frequencies. The high signal-to-noise LOFAR Core observations plotted in Fig. 6.1 are consistent with the most common range of the single station observations for both ingress and egress.

Taking into account the implied higher variability in the eclipse egress from the LOFAR single station observations, and also noting the consistency of the plotted 149 MHz and GMRT 400 MHz ingress durations with a single power law – reduced \( \chi^2 = 1.6 \) as opposed to a reduced \( \chi^2 = 8.6 \) for the LOFAR and WSRT fit from Chapter 3 – suggests that WSRT observation may have caught a relatively rare event, or that the higher density inner material is more variable than the tenuous outer material responsible for 149 MHz eclipse boundaries. In either case, we believe that the new fitted power laws presented here give a more reliable representation of the system over this range of frequencies.

Moving to higher frequencies, the eclipse simultaneously observed at 400 MHz and 750 MHz interestingly does not appear to follow a simple power law – although the uncertainty is relatively large on the 750 MHz observations – which could be a result of the eclipse medium not being smoothly varying over this range, or possibly different mechanisms. Although we observed two consecutive eclipses at these frequencies, only one eclipse egress is plotted due to unusual behaviour in the second egress, whereby the flux density at both 400 MHz and 750 MHz initially began to re-emerge at the same phase as the previous eclipse, then sharply disappeared for the remainder of the observation – only a few minutes. Such ‘mini-eclipses’ with durations on the order of a few minutes, close to
6.3. Analysis

Figure 6.1: Eclipse durations versus frequency for PSR J1810+1744. Data points < 200 MHz, and points in red near 350 MHz are taken from Chapter 3. Colours are consistent between plots and represent separate eclipses. Top: Full eclipse durations. Fitted power law lines have slopes $\alpha_{\text{full}} = 0.22$ (solid) – fit to blue GMRT and green LOFAR points; $\alpha_{\text{full}} = 0.41$ (grey, dashed, Chapter 3) – fit to red WSRT and green LOFAR points. Bottom: Ingress and egress durations. Fitted power law lines have slopes $\alpha_{\text{in}} = 0.09$ (solid) – fit to all LOFAR and blue and orange GMRT points; $\alpha_{\text{in}} = 0.41$ (grey, dashed, Chapter 3) – fit to all LOFAR and red WSRT points; $\alpha_{\text{eg}} = 0.29$ (black, dash-dot) – fit to all egress points; $\alpha_{\text{eg}} = 0.35$ (grey, dashed, Chapter 3) – fit to all LOFAR and red WSRT points. The poor fit of the 750 MHz ingress points (blue, orange) suggests a step change in the eclipse medium properties, or a change in eclipse mechanism (see main text).
Table 6.2: Best-fit power law exponents for eclipse durations in PSR J1816+4510, when fit to LOFAR data only, i.e. $\Delta \phi_{\text{eclipse}} \propto \nu^{-\alpha}$, for $100 < \nu < 200$ MHz. The weighted means of $\alpha_{\text{full}}$ and $\alpha_{\text{eg}}$ are given in the bottom row.

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<td>$0.10 \pm 0.02$</td>
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<td></td>
<td>$0.12 \pm 0.02$</td>
<td>$0.11 \pm 0.02$</td>
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eclipse edges, were also observed in the BW pulsar PSR J1544+4937, and were attributed to clumps of plasma surrounding the main eclipse material (Bhattacharyya et al., 2013). In cases where the flux is not detected to briefly re-emerge, these clumps could be responsible for the variable eclipse durations that we observe.

### 6.3.2 PSR J1816+4510

In Fig. 6.2 the measured full eclipse, ingress and egress durations for PSR J1816+4510 are plotted, along with the corresponding fitted power laws. The large variability in the egress durations at low-frequency was discussed in Chapter 5, with the analysis suggesting that different mechanisms were responsible for the latter part of the eclipse in comparison to the ingress and main duration, particularly for the extended egresses. It appeared to be most likely that scattering of the pulsed emission in a tenuous tail of material caused the eclipses to be extended, which would have much less influence on higher-frequency emission for which scattering would be less prominent. This picture is supported by the observed stability in the eclipse ingress, which would be unaffected by a trailing tail of material.

The ingress power law gives a good fit across all four 149 MHz eclipses and the single 650 MHz eclipse, suggesting that any effect of time variability is negligible here. Alternatively, for the more complex egress we take the most shallow power law to give the most reliable indicator of the main bulk of the eclipse medium, for which the pulsed and unpulsed eclipses were consistent in duration, suggesting only a small amount of eclipse extension due to scattering (Chapter 5). Indeed, this gives a much better fit across both the LOFAR and GMRT bandwidths (reduced $\chi^2 = 2$) relative to the extended eclipses, for which a single power law is evidently not sufficient (reduced $\chi^2 = 34$ and 80 for the dashed and dotted power laws, respectively).

As a consequence of the inconsistency of the egress frequency dependence across the low-frequencies with that of the high-frequencies, we also performed fits to the data $< 200$ MHz only. As for the full frequency coverage data, we fitted 3 separate power laws, using the two eclipses in blue and red in a single fit. The resulting power law exponents are presented in Table 6.2, along with their weighted mean, and are discussed further in the context of PSR B1957+20 below.
6.3. Analysis

Figure 6.2: Eclipse durations versus frequency for PSR J1816+4510. Colours are consistent between plots and represent separate eclipses. **Top:** Full eclipse durations. Fitted power law lines have slopes $\alpha_{\text{full}} = 0.34$ (dash-dot) – fit to orange LOFAR and purple GMRT points; $\alpha_{\text{full}} = 0.42$ (dashed) – fit to red and blue LOFAR and purple GMRT points; $\alpha_{\text{full}} = 0.49$ (dotted) – fit to green LOFAR and purple GMRT points. **Bottom:** Ingress and egress durations. Fitted power law lines have slopes $\alpha_{\text{in}} = 0.16$ (solid) – fit to all ingress points; $\alpha_{\text{eg}} = 0.46$ (dash-dot) – fit to orange LOFAR and purple GMRT points; $\alpha_{\text{eg}} = 0.58$ (dashed) – fit to red and blue LOFAR and purple GMRT points; $\alpha_{\text{eg}} = 0.68$ (dotted) – fit to green LOFAR and purple GMRT points. The low-frequency egress points appear to follow a different power law to those at high-frequency (see main text).
6.3.3 PSR B1957+20

In Fig. 6.3 the measured eclipse durations for PSR B1957+20 are shown, along with the power laws fit to our data (< 200 MHz). For comparison we also over-plot previously published higher-frequency measurements from Ryba & Taylor (1991) (grey points), and more recent approximate durations taken from observations with the Arecibo telescope (black points; Robert Main priv. comm.) which were only informally measured, without the use of a model fit. The larger uncertainties on the Ryba & Taylor (1991) measurements, relative to ours at low-frequency, are primarily a result of temporal variability in the eclipses which has been averaged over, and the plotted errorbars span the regions containing ~ 68% of the observed eclipses. This is also the case with the Arecibo data, however the informal ‘measurement’ method led to us assigning somewhat arbitrary uncertainties that reflected our confidence.

For the few eclipses at low-frequency that we have analysed, the measured durations are generally consistent with one another, and like PSR J1810+1744, do not display the egress instability that we observe in PSR J1816+4510. Although the higher-frequency points from Ryba & Taylor (1991) are displaced relative to our LOFAR measurements, we believe that this is likely a consequence of temporal variability or lower signal-to-noise causing a systematic apparent lengthening of the eclipses, and are not representative of the eclipses actually being as long as those at low-frequency. This argument is consistent with the more recent Arecibo data, whereby the eclipse durations > 300 MHz are shorter than those < 200 MHz, as expected.

Taken on their own, ignoring the systematic shift relative to our data, the egress measurements > 300 MHz suggest a steeper frequency relationship than our measurements < 200 MHz. On the other hand, the ingress eclipses appear more consistent with a single power law component. These are similar trends to those observed for PSR J1816+4510, and Table 6.3 shows both that the ingress power laws for both pulsars are consistent within 1σ, and that the egress power laws for the pulsars are significantly closer when fit to the low-frequency data only (Table 6.2). Furthermore, through power law fits to their higher-frequency data, Ryba & Taylor (1991) measured the full eclipse duration for PSR B1957+20 to scale with α ≈ 0.4; entirely consistent with our measured α_{full} for PSR J1816+4510 when considering the high-frequency data (Table 6.3). These similarities further highlight the ‘twinned’ nature of the eclipses between these two pulsars, regardless of the vastly different companion stars, as discussed in Chapter 5.

6.3.4 PSR J2051−0827

PSR J2051−0827 is a well studied pulsar and has been observed over a wide range of frequencies for multiple decades (see Chapter 4). However, its relatively short duration eclipses mean that even small amounts of temporal variability can completely mask any genuine dependence of the eclipse duration on frequency, as was found to be the case in the only previous attempt to measure the frequency dependence (Stappers et al., 2001a). To try and overcome this problem, we undertook a campaign to perform coordinated
6.3. Analysis

Figure 6.3: Eclipse durations versus frequency for PSR B1957+20. Grey points are taken from Ryba & Taylor (1991), and black points from Arecibo observations in 2014 and 2018 (Robert Main priv. comm.). Colours are consistent between plots and represent separate eclipses. Top: Full eclipse durations. The fitted power law line has slope $\alpha_{\text{full}} = 0.18$ – fit to all LOFAR points; Bottom: Ingress and egress durations. Fitted power law lines have slopes $\alpha_{\text{in}} = 0.18$ (solid) – fit to all LOFAR points; $\alpha_{\text{eg}} = 0.21$ (dashed) – fit to all LOFAR points. Grey and black ingress and egress points have each been offset marginally in frequency for clarity.
Chapter 6. Frequency Dependence of the Eclipses

multi-frequency observations of the eclipses over just a two week period. The results of these observations are shown in Fig. 6.4, along with the power law curves fit to our data. Over-plotted in grey are the measured durations at 325 MHz, 430 MHz and 660 MHz taken from Stappers et al. (2001a), with the uncertainties representing the variability observed in 7, 22 and 10 eclipses, respectively, over the dates 1994-May – 1997-Sep.

An additional difficulty arose with our observations, in that the ‘eclipse’ at 933 MHz did not fully remove the pulsed flux density, and instead only reduced it to \( \sim 40\% \) of the out-of-eclipse level. The eclipse was also somewhat irregular, appearing to occur in two stages, with an initial drop down to \( \sim 70\% \) of the out-of-eclipse level where it remained in an intermediate plateau, before dropping a second time; conversely, the egress appeared to be more regular. In an attempt to model this eclipse we fitted two separate ingress functions, with the ‘outer-eclipse’ fit to the initial flux decrease, while masking the plateau data points, and the ‘inner-eclipse’ fit to the 2nd flux decrease, taking the plateau as the effective out-of-eclipse level. The observed eclipses are shown in the top panel of Fig. 6.5, over-plotted with the fitted model functions.

In the top panel of Fig. 6.4 we plot the effective eclipse durations for both the inner- (green) and outer-eclipses (red) at 933 MHz, showing only the outer-eclipse to be consistent with a single power law across all the measured frequencies. Irrespective of this observation, the lower-frequency data show a clear frequency dependence of the eclipse duration, allowing us to successfully measure a power law relationship for this pulsar for the first time.

Comparing the eclipse durations from Stappers et al. (2001a) with ours, it can be seen that at 325 MHz and 430 MHz both sets are consistent, however their duration at 660 MHz is far longer than predicted by our power law fit. To investigate this one can refer to the DM measurements across the eclipse region, which are representative of the material density distribution. In the bottom panel of Fig. 6.5 the measured \( \Delta \)DM profile corresponding to the time of the observing campaign is shown. The profile is asymmetric about companion inferior conjunction, with a brief peak in density (\( \Delta \)DM \( \sim \) 0.05 pc cm\(^{-3}\)) occurring only over the phase range \( \approx 0.25–0.275 \), coincident with the 933 MHz inner-eclipse. Conversely, in Fig. 6 of Stappers et al. (2001a) their measured DM profile has a peak that, although of a similar order of magnitude, persists for much longer, covering \( \phi \approx 0.22–0.29 \). If we assume this to be representative of the DM profile for most of their observed 660 MHz eclipses – in Chapter 4 similar DM structures are shown to persist for months-to-years – then this suggests that the higher-frequency eclipses are sensitive only to the most dense regions of the eclipse material, which is shown in Chapter 4 to be highly variable over multiple years. On the other hand, the low-frequency eclipses appear to be more stable (Chapter 4) and less sensitive to the peaks of the density profile close to the companion, which they do not directly probe. This highlights the susceptibility of eclipse duration measurements to become erratic in the presence of irregular material density distributions. With the low inclination angle of the orbit of PSR J2051−0827 implying that our line of sight cuts across the outer edge of the ablated material, this pulsar in particular may be at risk of asymmetric and irregular density distributions, which is
Figure 6.4: Eclipse durations versus frequency for PSR J2051−0827. Grey points are taken from Stappers et al. (2001a). Colours are consistent between plots and represent separate eclipses. Top: Full eclipse durations. The fitted power law line has slope $\alpha_{\text{full}} = 0.41$ - fit to all LOFAR and GMRT points and red Parkes point; Bottom: Ingress and egress durations. Fitted power law lines have slopes $\alpha_{\text{in}} = 0.37$ (solid) - fit to all ingress points; $\alpha_{\text{eg}} = 0.51$ (dashed) - fit to all egress points. Red Parkes ingress and egress points have each been offset marginally in frequency for clarity.
Chapter 6. Frequency Dependence of the Eclipses

Figure 6.5: Top: Measured pulsed flux densities (dashed) for PSR J2051−0827, normalised so that the mean out-of-eclipse levels are unity, taken from Chapter 4. Solid lines show the best-fit Fermi-Dirac functions for each ingress and egress (see main text). The half-flux density level is represented by the thin horizontal dashed line. Bottom: DM relative to mean out-of-eclipse value measured from a single eclipse observation spanning 705–4032 MHz (Chapter 4).

also implied by the work in Chapter 4.

6.3.5 PSR J2215+5135

For the final pulsar in the study, we have observed a single eclipse simultaneously in two relatively high frequency bands. The measured eclipse durations are shown in Fig. 6.6, along with low-frequency data from LOFAR imaging observations published in Broderick et al. (2016). The black power law curves resulted from fits to all of the available data, including that of Broderick et al. (2016), while the grey, dash-dot line shows the published power law fit to the LOFAR data only. The errorbars assigned to our measurements have been increased from the formal $1\sigma$ fits in order to better reflect our confidence in the model fits due to the presence of large gaps ($\Delta\phi \sim 0.04$) in the data masking the beginning of both the ingress and egress, when phase calibration of telescope unfortunately fell.

It can be seen the eclipses in PSR J2215+5135 cover huge fractions of the orbit relative to the previous pulsars in this study. This is typical of RB pulsars, and especially those that are known to transition between RB states and accretion states (e.g. Archibald et al., 2009). These long eclipse durations mean that their frequency dependence is generally easier to detect, even though the power law fit to our data is relatively shallow (see Table 6.3). The implied frequency dependence, with $\alpha_{\text{full}} = 0.21 \pm 0.04$, is at odds with the
6.3. Analysis

![Graph](image)

**Figure 6.6**: Eclipse durations versus frequency for PSR J2215+5135. Grey points < 200 MHz are taken from Broderick et al. (2016). Colours are consistent between plots and represent separate eclipses. Top: Full eclipse durations. Fitted power law lines have slopes $\alpha_{\text{full}} = 0.21$ – fit to all points; $\alpha_{\text{full}} = 0.42$ (grey, dash-dot, Broderick et al., 2016) – fit to LOFAR points only; Bottom: Ingress and egress durations, grey points < 200 MHz represent equal ingress and egress durations as Broderick et al. (2016) assumed symmetric eclipses. Fitted power law lines have slopes $\alpha_{\text{in}} = 0.26$ (solid) – fit to all ingress points; $\alpha_{\text{eg}} = 0.19$ (dashed) – fit to all egress points. Blue GMRT ingress and egress points have each been offset marginally in frequency for clarity.
significantly steeper one measured across frequencies < 200 MHz, with $\alpha = 0.42 \pm 0.11$ (Broderick et al., 2016), however is still consistent with all of the data (reduced $\chi^2 = 0.8$). It is worth noting that as we have only observed a single eclipse at higher frequencies, there is no indication of the magnitude of temporal variability in the eclipses, and this may play a role in the discrepancy between the two measured power law exponents.

6.4 Discussion

In Table 6.3 we show the measured frequency power law exponents along with the properties of binary systems. Also included are previously published measurements for Ter5A, whereby Nice et al. (1990) find an apparently steep eclipse duration dependence on frequency of $\Delta \phi \propto \nu^{-0.63 \pm 0.18}$.

All of the pulsars studied here exhibit a clear frequency dependence of the eclipse duration, with the measured full eclipse duration exponents spread over $0.18 \lesssim \alpha_{\text{full}} \lesssim 0.63$, ingress durations between $0.09 \lesssim \alpha_{\text{in}} \lesssim 0.37$ and egress durations between $0.19 \lesssim \alpha_{\text{eg}} \lesssim 0.68$. For two of the pulsars – PSR J1816+4510 and PSR B1957+20 – a single power law does not appear sufficient to model the eclipse egress durations across both frequencies < 200 MHz and > 200 MHz, which we interpret as a consequence of a tenuous swept-back tail of material (Fruchter et al., 1990) that has less influence on the propagation of higher-frequency emission due to its likely low-density. This could cause a break in the power law if the eclipse mechanism in the tail material differed to that caused by the main bulk of the medium, or if the properties of the tail material vary with orbital phase at a different rate relative to the main bulk of the medium. For those pulsars where we have wide frequency coverage, namely, PSR J1810+1744, PSR J1816+4510 and PSR J2051−0827, the eclipses become continuously more symmetric about companion inferior conjunction towards higher observing frequencies. This is also seen in PSR B1957+20 if we consider the higher-frequency measurements from Ryba & Taylor (1991) along with our own. This is further consistent with the idea of a tenuous swept-back tail of material, having increasing influence on the wave propagation towards lower-frequencies.

Comparing the properties of the pulsars’ orbits with their respective $\alpha$ values, we see no clear correlation with any individual parameter, although there is a hint of a trend of decreasing steepness of the power law for increasing pulsar wind energy density at the companion star, i.e. $\alpha(U_E)$. However with only 6 samples, and possibly inaccurate or time-dependent estimates of $U_E$ and $\alpha$, this is currently inconclusive. Future optical observations can better constrain the pulsar wind flux incident on the companion stars (e.g. Linares et al., 2018) and further measurements of the eclipse durations can provide information on the magnitude of temporal variability, thus paving the way to being able to robustly determine the presence of correlations.

Some of the differences between the measured frequency dependencies may be due to different eclipse mechanisms, for example Thompson et al. (1994) find the predictions of stimulated Raman scattering to best match the observed eclipse properties in Ter5A, whereas absorption is favoured in PSR B1957+20. However, equally important are the
### 6.4. Discussion

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<th>$M_C$ ($M_\odot$)</th>
<th>$R_C$ ($R_\odot$)</th>
<th>$P_b$ (hr)</th>
<th>$a$ ($R_\odot$)</th>
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Table 6.3: Parameters of spider systems along with best-fit power law exponents for eclipse full-width half-maxima, $\alpha_{\text{full}}$, ingress duration, $\alpha_{\text{in}}$, and egress duration, $\alpha_{\text{eg}}$, against observation frequency, i.e. $\Delta t_{\text{eclipse}} \propto \nu^{-\alpha}$. Three $\alpha_{\text{full}}$ and $\alpha_{\text{eg}}$ are listed for PSR J1816+4510 due to the observed high eclipse-to-eclipse variability in the egress phase. The pulsar binary parameters are: companion mass, $M_C$, and radius, $R_C$, orbital period, $P_b$, orbital separation, $a$ – calculated from published projected semi-major axis, $a_p \sin i$, orbit inclination, $i$, and mass ratio as $a = a_p + a_p M_{\text{PSR}}/M_C$ – and energy density of pulsar wind at the companion distance, $U_E = \dot{E}/4\pi c a^2$. Also included for comparison are the parameters for globular cluster PSR B1744−24A (Ter5A), not measured in this work. $^a$ Breton et al. (2013); $^b$ Minimum mass assuming $M_{\text{PSR}} = 1.4M_\odot$ and $i = 90^o$; $^c$ Assuming 80% Roche lobe filling factor (Breton et al., 2013); $^d$ Hessels et al. (2011); $^e$ Kaplan et al. (2013); $^f$ Stovall et al. (2014); $^g$ van Kerkwijk et al. (2011); $^h$ Arzoumanian et al. (1994); $^i$ Thompson et al. (1994); $^j$ Lazaridis et al. (2011); $^k$ Shaifullah et al. (2016); $^l$ Stappers et al. (2001b); $^m$ Linares et al. (2018); $^n$ Abdo et al. (2013); $^o$ Optical observations by Linares et al. (2018) suggest that this could be a factor of 3 larger; $^p$ Fit included LOFAR data from Broderick et al. (2016); $^q$ Nice & Thorsett (1992); $^r$ Approximate Roche lobe radius assuming $i = 90^o$ (Nice & Thorsett, 1992); $^t$ Nice et al. (1990).
different electron density distributions in the eclipse media between systems. The influence of different electron distributions will depend on both the properties of the material as a whole and the particular lines of sight that we sample, given the different orbit inclinations. Notably, in PSR J2051−0827 we appear to be sampling the ‘upper-edge’ of the material (Chapter 4) with its relatively low inclination angle, thus the density distribution may be significantly different here to that crossed by a line of sight passing closer to the companion. Indeed, the DM measurements throughout the eclipse region in PSR J2051−0827, presented in Chapter 4, often show that stochastic clumpy structure can dominate any smooth density profile that may be present. Furthermore, in Section 6.3.4 it is suggested that the stochastic peaks in electron column density may determine the orbital phase and duration of the high-frequency (> 600 MHz) eclipses. Bearing this in mind, we note that much care must be taken when interpreting the relationship between eclipses and observing frequency, and suggest that higher-inclination systems may provide the best opportunity for theoretical modelling, in which the density distribution of the eclipse material sampled by the line of sight is likely to be less dominated by erratic clumpy structures. However, most eclipsing pulsars with reasonably constrained inclination angles appear to be far from being orientated edge-on (Table 6.3; Breton et al., 2013; Crawford et al., 2013; Bellm et al., 2016) suggesting that there may be a selection effect against the ‘ideal’ inclination of ∼ 90°. Thus, at the very least, attempts should consider the measured DM profile through the eclipse at the time of the observations.

### 6.5 Conclusion

In this chapter we present measured eclipse durations at a range of radio-frequencies for five spider pulsars, significantly increasing the volume of observational data available to constrain theoretical models. Out of the five pulsars, two had no previously measured frequency dependencies of the eclipse durations (PSR J1816+4510 and PSR J2051−0827), and for the remaining three we have increased the observed frequency coverage (PSR J1810+1744, PSR B1957+20 and PSR J2215+5135).

For all of the pulsars there is a significant dependence of the eclipse durations on frequency, with low-frequencies corresponding to wider eclipses. We find that commonly used power law functions generally give good fit to the data, but temporal variability of the eclipses can be a hindrance, thus (near-)simultaneous multi-frequency observations are the most ideal. Our results strengthen previous suggestions that, at higher-frequencies, the eclipses become gradually more symmetric about inferior conjunction of the companion. We attribute this to a low-density tail of material trailing behind the companion in its orbit. However, in some cases (e.g. PSR J2051−0827) it appears that the stochastic nature of the electron density profile sampled by the line of sight can be the dominant effect in determining the location and duration of high-frequency eclipses. Following on from the previous chapter, we find further similarities between PSR J1816+4510 and PSR B1957+20, whereby a single power law does not appear to be sufficient over the full range of frequencies < 1 GHz. When split across a threshold frequency of ∼
200 MHz, the individual power law fits to each of the low- and high-frequency sets give near consistent values between the two pulsars. Finally, the results suggest a hint of correlation between the pulsar wind energy density at the distance of the companion star and the steepness of the power law. However, the relatively small amount of data and its limited reliability mean that this will need to be revisited when there is an improved knowledge of the incident pulsar wind energy and of the temporal variability of eclipse durations.
Chapter 7

Conclusion

“We are at the very beginning of time for the human race. It is not unreasonable that we grapple with problems. But there are tens of thousands of years in the future. Our responsibility is to do what we can, learn what we can, improve the solutions, and pass them on.”

Richard Feynman

The highly compact and energetic nature of pulsars means that they can reside in extremely tight binary systems, in which the companion star orbits close to the source of an intense pulsar wind. Such systems are thought to be the successors of a recycling phase involving significant mass transfer, potentially leading to unusual properties for both the pulsar and the companion, especially in the presence of continuous pulsar wind irradiation. Monitoring of the regular, pulsed radio emission from the pulsars in these systems often reveals propagation delays occurring immediately before and after prolonged disappearances of the pulsations – eclipses – generally coincident with inferior conjunction of the companion star. However, the duration of the eclipses and surrounding propagation delays are inconsistent with the responsible medium being enclosed within the companions’ Roche lobes, suggesting that it cannot be gravitationally bound to the star and must be continuously replenished, presumably by a wind driven from the irradiated star. These so-called spider pulsar systems are unique natural laboratories providing insights into the response of plasma, and even entire stars, to strong irradiation.

Even though the first spider pulsar was discovered more than 30 years ago, the eclipse mechanism(s) and the properties of the plasma responsible for the eclipses, its origin and departure rate from the system are very poorly understood. Although precise measurements of the propagation effects offer the opportunity to better understand these properties, there has thus far only been a handful of dedicated studies, focussing on a small number of spider pulsars. Consequently, a lack of observational constraints has meant that inferences about the various phenomena typically rely on strong, likely simplified assumptions about the eclipse medium, orbit geometry and pulsar wind. As more data are collected for spider pulsars it is becoming ever more clear that the systems are much more complex than this, showing temporal variability within individual systems, and key differences between systems.
The overarching output of this work has been to provide a marked increase in the observational constraints available for radio-frequency eclipse phenomena in spider pulsars. We have undertaken a programme of observations at low-radio-frequencies (<200 MHz), a near-unexplored region of the spectrum for eclipses, utilising the capabilities of the Low-Frequency Array to offer higher sensitivities than has previously been possible. In performing such observations for four spider pulsars – PSR J1810+1744 (Chapter 3), PSR J1816+4510 (Chapter 5), PSR B1957+20 (Chapter 5) and PSR J2051−0827 (Chapter 4) – we showed the low-density outer regions of the eclipse media in these pulsars to be variable on timescales of hours, and have precisely measured small column density fluctuations and scattering of the pulsed radiation. Furthermore, we performed simultaneous imaging and beamformed observations of the eclipses for PSR J1810+1744, PSR J1816+4510 and PSR B1957+20 with unprecedented temporal resolution. This allowed direct discrimination between subsets of feasible eclipse mechanisms, and showed that only those mechanisms that predict complete removal of pulsar flux from the line of sight, as opposed to those that predict smearing out of the pulsed nature of the radiation, can be responsible for the primary extent of eclipses of low-frequency emission in these systems. In the case of PSR J1816+4510, and to a lesser extent PSR B1957+20, the high-temporal resolution observations suggest that the low-frequency eclipse mechanism can switch to one that smears out the pulsations while not attenuating the total flux in the latter stages of the eclipse, implying that the properties of the eclipse medium probed by the line of sight must cross some threshold level; this is the first detection of this phenomenon to-date.

The low-densities of the eclipse media implied by DM measurements for all four of the above pulsars suggests that neither refraction nor free-free absorption can reasonably account for the observed eclipses, in agreement with previous studies for PSR B1957+20 and PSR J2051−0827. Our extensive data sets for PSR J1810+1744 and PSR J2051−0827 permitted more in-depth scrutinisation of plausible eclipse mechanisms; in Chapter 3 we find that only cyclotron-synchrotron absorption, or non-linear scattering mechanisms, provide inferred eclipse properties that are consistent with the frequency dependence and total flux disappearance observed for PSR J1810+1744. For PSR J2051−0827 – Chapter 4 – we did not have the luxury of high signal-to-noise imaging observations to simply rule out pulse smearing eclipse mechanisms, however by comparing the measured DMs at a range of frequencies near the eclipse boundaries we confidently ruled out DM smearing as a plausible eclipse mechanism. The possibility of scattering of the pulsations beyond the pulse period – such as that seen in PSR J1816+4510 – was shown to remain consistent with observations, while cyclotron-synchrotron absorption also provides a reasonable explanation, being consistent with the magnetic field constraints that we determined from the polarisation properties of the pulsar’s emission; our results showed that the linearly polarised component becomes attenuated in the eclipse region while the circularly polarised component is largely unaffected, suggesting the presence of a rapidly varying magnetic field in the eclipse medium. A lack of a detectable delay between the left- and right-hand circular polarisation components allowed us to place loose upper limits on
the strength of the field in this system for the first time, finding the parallel component \( B_{||} = (20 \pm 120) \text{ G} \). Alternatively, if the magnetic field were directed near-perpendicular to the line of sight, then its maximum strength is constrained to be \( B_{\perp} \lesssim 0.3 \text{ G} \). Measurements of the RM show it to remain largely consistent with a constant value throughout the orbit, although two discrepant measurements in the low-frequency eclipse egress imply \( B_{||} \gtrsim 0.9 \text{ mG} \), if they result entirely from magnetic fields within the binary.

The observation that there exists a relatively large population of isolated MSPs in the Galactic plane has long been problematic for theories of pulsar evolution (Sections 1.2.2 and 1.3.1). One of the more long-standing theories proposes that spider pulsars are a progenitor to isolated MSPs, whereby the companion star is eventually completely destroyed by the pulsar wind driven irradiation. While an attractive idea, empirical estimates have since cast doubt on its feasibility due to only low mass loss rates implied by observations of a small number of spider pulsars, however these estimates relied on strong assumptions about the properties of the out-flowing plasma. In this thesis we have extended similar empirical estimates to a number of different spider systems, finding low implied mass loss rates of \( 10^{-13} - 10^{-12} \text{ M}_\odot \text{ yr}^{-1} \) that would likely require more than the age of the Universe to fully remove the total mass of the companion stars. Unfortunately, we still relied on significant assumptions about the outflow mechanism and geometry, thus although adding further weight to the rejection of this theory, our results are not conclusive in this regard.

Knowledge of the temporal variability of the eclipse medium in an individual system can provide information on both its average and extreme properties; such information can allow tighter and more accurate constraints on the eclipse mechanisms, mass loss and the governing forces in the medium. To this end, in Chapter 4 we performed eclipse monitoring of PSR J2051−0827 with observations spanning over a decade, and observation intervals ranging from hours to weeks to years, in order to probe different timescales of variability. This pulsar proved to be particularly useful for such a study as the pulsar emission > 1 GHz is generally not eclipsed, providing the means to measure the column density of the material throughout the entire eclipse region. Our results showed that the previously observed small scale variations acting on timescales of hours were in fact modulated by large trends in the eclipse density, on timescales of months to years. As discussed in Chapter 3 for PSR J1810+1744 – and also applicable to the other pulsars studied in this thesis – the density fluctuations occurring within orbital timescales can be justified if the material travels at velocities near to or above the escape speed of the companion star – typically a few 100 km s\(^{-1}\) – as this is near an order of magnitude larger than the necessary velocity to travel the typical eclipse and orbit sizes within the orbital periods of the pulsars. However, the long-timescale modulations are not consistent with such a simplified picture, which raises interesting questions into the mechanisms driving the behaviour, with magnetic fields providing a crude, but attractive explanation. We also pose a question as to whether or not there is a physical link between the eclipse medium variations detected here, and previously measured orbital period modulations that act on similar timescales.
The existence of ‘mini-eclipses’ – typically short duration disappearances of pulsar flux, away from the regular eclipse phase – is more commonly associated with RBs, and in particular transitional pulsars, where the wind driven from the non-degenerate companion star is expected to be stronger than in BWs, resulting in material potentially spreading all around the orbit. However, in Chapters 3 and 6 we show that mini-eclipses also occur in PSR J2051−0827 and PSR J1810+1744, respectively, and in Chapter 5 we detect delays in pulse arrival times from PSR B1957+20 that are indicative of propagation delays in excess material along the line of sight. These three systems represent the entire sample of BWs observed in this thesis, strongly suggesting that clumps of material spreading beyond the typical eclipse region is also relatively common in BWs.

As comparable studies are performed on more spider pulsars, population wide properties of the irradiation and eclipse phenomena will begin to emerge. In Chapter 5 we investigated the seemingly peculiar eclipsing pulsar PSR J1816+4510, which has a companion star with mass akin to the redback class, but appears to be a proto-WD in which mass loss arising through ablation would be puzzling. We show here that its eclipses in fact share many properties with that of the ‘original’ black widow, PSR B1957+20, which has a companion almost an order of magnitude less massive. As a result, we suggest that PSR J1816+4510 makes an interesting candidate for identifying pulse lensing in the eclipse medium, which has recently been observed in PSR B1957+20, offering an alternative insight into the properties of the medium. Furthermore, in Chapter 6 we brought together observations of five spider pulsars to report on the dependence of the eclipses on radiation frequency. It was shown that for all of the systems the eclipse duration scales inversely with frequency, but the strength of the relationship varies between each, and we highlight a possible correlation of the frequency dependence with the magnitude of the pulsar wind energy density at the companion, but require more pulsar systems for a robust test.

The requirement for studies of more pulsar systems to reach reliable conclusions is a recurring theme for the spiders. However, the rate at which new spiders are being discovered is now heavily out-weighing the rate at which their eclipse properties are being measured, meaning that there are growing opportunities to fill gaps in the sample spaces of orbit inclinations and separations, phases of evolution and companion star properties. Comparing the eclipses and induced propagation effects in different spiders over this sample space will shed light on the parameters that determine the properties of eclipse medium. Some interesting questions that we are becoming ever-closer to answering are: what exactly are the different eclipse mechanisms, and what determines the most prominent mechanism in each system? Why do some systems show common, and highly variable ‘mini-eclipses’, yet others don’t? Why do most known eclipsing systems appear to have moderate orbit inclination angles; is there a sweet spot? Is there a selection effect against edge-on systems, such as the pulsar being fully enshrouded? Could this mean much larger mass loss than we currently infer?

To this end, we plan to publish the various works in this thesis, allowing the results to
be used in future studies. In addition, we have scheduled more ultra-wide band observations with the Parkes telescope in order to increase the reliability of the polarisation measurements in PSR J2051−0827, and apply similar analyses to a wider set of spider pulsars.
# Appendix A

## PSR J1810+1744 Baseline Timing Ephemeris

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<th>Formal uncertainty</th>
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Table A.1 – *Continued from previous page*

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Appendix B

Schematics of Binary Geometries

In Figs. B.1, B.2, B.3 and B.4 we present schematics of the orbits for four of the five pulsars studied in this thesis, as they are seen projected on the sky. No schematic is drawn for PSR J1816+4510 as there is no published constraint on the inclination of the orbit. For each pulsar we use the latest published pulsar timing parameters, stellar masses and radii, and orbit inclinations.
**Appendix B. Schematics of Binary Geometries**

**Figure B.1:** Expected projection of the PSR J1810+1744 system on the sky, assuming an inclination angle of 50° (Breton et al., 2013; Schroeder & Halpern, 2014). The schematic shows 5 snapshots of the system at the labelled orbital phases, with the small black dots representing the pulsar, blue circles representing the expected size of companion star ($R_C \approx 0.15 \, R_\odot$; Breton et al., 2013), and small red dots marking the centre point of the night-side of the companion star (i.e. the furthest point from the pulsar). The companion star and orbit are approximately to scale assuming the radio timing orbital parameters of Hessels et al. (2011), pulsar and companion masses of $1.4 \, M_\odot$ and $0.045 \, M_\odot$, respectively, and without accounting for gravitational deformation of the companion. The companion passes closest to our line-of-sight towards the pulsar – directed out of the page – at an orbital phase of 0.25.

**Figure B.2:** Expected projection of the PSR B1957+20 system on the sky, assuming an inclination angle of 65° (van Kerkwijk et al., 2011). The schematic shows 5 snapshots of the system at the labelled orbital phases, with the small black dots representing the pulsar, blue circles representing the expected size of companion star ($R_C \approx 0.25 \, R_\odot$; van Kerkwijk et al., 2011), and small red dots marking the centre point of the night-side of the companion star (i.e. the furthest point from the pulsar). The companion star and orbit are approximately to scale assuming the radio timing orbital parameters of Arzoumanian et al. (1994), and pulsar and companion masses of $2.4 \, M_\odot$ and $0.035 \, M_\odot$, respectively. The companion passes closest to our line-of-sight towards the pulsar – directed out of the page – at an orbital phase of 0.25.
Appendix B. Schematics of Binary Geometries

Figure B.3: Expected projection of the PSR J2051−0827 system on the sky, assuming an inclination angle of 40° (Stappers et al., 2001b). The schematic shows 5 snapshots of the system at the labelled orbital phases, with the small black dots representing the pulsar, blue circles representing the companion star Roche lobe, and small red dots marking the centre point of the night-side of the companion star (i.e. the furthest point from the pulsar). The companion star and orbit are approximately to scale assuming the radio timing orbital parameters of Shaifullah et al. (2016), pulsar and companion masses of 1.8 $M_\odot$ and 0.05 $M_\odot$, respectively, and companion Roche lobe radius of 0.15 $R_\odot$ as assumed in Lazaridis et al. (2011). The companion passes closest to our line-of-sight towards the pulsar – directed out of the page – at an orbital phase of 0.25.

Figure B.4: Expected projection of the PSR J2215+5135 system on the sky, assuming an inclination angle of 63.9° (Linares et al., 2018). The schematic shows 5 snapshots of the system at the labelled orbital phases, with the small black dots representing the pulsar, blue circles representing the expected size of companion star ($R_C \approx 0.39 R_\odot$; Linares et al., 2018), and small red dots marking the centre point of the night-side of the companion star (i.e. the furthest point from the pulsar). The companion star and orbit are approximately to scale assuming the radio timing orbital parameters of Abdo et al. (2013), pulsar and companion masses of 2.27 $M_\odot$ and 0.33 $M_\odot$, respectively, and without accounting for gravitational deformation of the companion. The companion passes closest to our line-of-sight towards the pulsar – directed out of the page – at an orbital phase of 0.25.
## Appendix C

### LOFAR Observations for PSR J2051−0827

Table C.1: List of LOFAR observations with the corresponding \texttt{rmfit} measured rotation measures and estimated ionosphere-induced rotation measures using \texttt{ionFr} (Sotomayor-Beltran et al., 2013). *No significant RM detection.* \(^b\)Observation duration split into two halves to allow for separate RM measurements.

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<td>2.82 ± 0.19</td>
</tr>
<tr>
<td>17:07 2014-12-04</td>
<td>LC2_039</td>
<td>L253011b(^b)</td>
<td>−29.83 ± 0.10</td>
<td>2.82 ± 0.19</td>
</tr>
<tr>
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<td>LC2_039</td>
<td>L253015</td>
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*Continued on next page*
Table C.1 – Continued from previous page

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<tr>
<td>21:25 2015-09-04</td>
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<td>1.01 ± 0.10</td>
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<td>21:26 2016-09-03</td>
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<td>19:36 2016-10-01</td>
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<td>–31.59 ± 0.07</td>
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Appendix D

PSR B1957+20 Baseline Timing Ephemeris

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</tr>
<tr>
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Table D.1 – Continued from previous page

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Appendix E

Eclipse Versus Observation Frequency Data
### Table E.1: Measured eclipse durations for PSR J1810+1744 in Chapter 6, for full eclipse, $\Delta \phi_{\text{eclipse}}$, ingress, $\Delta \phi_{\text{in}}$, and egress, $\Delta \phi_{\text{eg}}$, along with formal 1\(\sigma\) uncertainties from the least squares fits.

<table>
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<tr>
<th>PSR</th>
<th>Telescope</th>
<th>$\nu$ (MHz)</th>
<th>$\Delta \phi_{\text{eclipse}}$</th>
<th>$\Delta \phi_{\text{in}}$</th>
<th>$\Delta \phi_{\text{eg}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1810+1744</td>
<td>LOFAR</td>
<td>118</td>
<td>0.140 $\pm$ 0.002</td>
<td>0.0527 $\pm$ 0.0010</td>
<td>0.0829 $\pm$ 0.0015</td>
</tr>
<tr>
<td></td>
<td></td>
<td>134</td>
<td>0.131 $\pm$ 0.002</td>
<td>0.0522 $\pm$ 0.0010</td>
<td>0.0788 $\pm$ 0.0015</td>
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<tr>
<td></td>
<td></td>
<td>154</td>
<td>0.125 $\pm$ 0.002</td>
<td>0.0517 $\pm$ 0.0010</td>
<td>0.0744 $\pm$ 0.0015</td>
</tr>
<tr>
<td></td>
<td></td>
<td>176</td>
<td>0.121 $\pm$ 0.002</td>
<td>0.0505 $\pm$ 0.0010</td>
<td>0.0689 $\pm$ 0.0015</td>
</tr>
<tr>
<td></td>
<td>WSRT</td>
<td>321</td>
<td>0.090 $\pm$ 0.002</td>
<td>0.033 $\pm$ 0.001</td>
<td>0.057 $\pm$ 0.002</td>
</tr>
<tr>
<td></td>
<td></td>
<td>344</td>
<td>0.091 $\pm$ 0.002</td>
<td>0.033 $\pm$ 0.001</td>
<td>0.058 $\pm$ 0.002</td>
</tr>
<tr>
<td></td>
<td></td>
<td>369</td>
<td>0.088 $\pm$ 0.002</td>
<td>0.031 $\pm$ 0.001</td>
<td>0.057 $\pm$ 0.002</td>
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<td></td>
<td>GMRT</td>
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<td>0.0480 $\pm$ 0.0006</td>
<td>0.0594 $\pm$ 0.0012</td>
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<td>389</td>
<td>0.105 $\pm$ 0.001</td>
<td>0.0469 $\pm$ 0.0006</td>
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<td>461</td>
<td>0.102 $\pm$ 0.001</td>
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### Table E.2: Measured eclipse durations for PSR J1816+4510 in Chapter 6, for full eclipse, $\Delta \phi_{\text{eclipse}}$, ingress, $\Delta \phi_{\text{in}}$, and egress, $\Delta \phi_{\text{eg}}$, along with formal 1\(\sigma\) uncertainties from the least squares fits.

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<tr>
<th>PSR</th>
<th>Telescope</th>
<th>$\nu$ (MHz)</th>
<th>$\Delta \phi_{\text{eclipse}}$</th>
<th>$\Delta \phi_{\text{in}}$</th>
<th>$\Delta \phi_{\text{eg}}$</th>
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<td>144</td>
<td>0.1090 $\pm$ 0.0008</td>
<td>0.0360 $\pm$ 0.0003</td>
<td>0.0730 $\pm$ 0.0007</td>
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<tr>
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<td></td>
<td>171</td>
<td>0.1057 $\pm$ 0.0014</td>
<td>0.0358 $\pm$ 0.0006</td>
<td>0.0699 $\pm$ 0.0012</td>
</tr>
<tr>
<td></td>
<td>GMRT</td>
<td>596</td>
<td>0.0556 $\pm$ 0.0009</td>
<td>0.0280 $\pm$ 0.0004</td>
<td>0.0276 $\pm$ 0.0008</td>
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<td>0.0529 $\pm$ 0.0009</td>
<td>0.0273 $\pm$ 0.0005</td>
<td>0.0256 $\pm$ 0.0008</td>
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</table>
### Appendix E. Eclipse Versus Observation Frequency Data

**Table E.3:** Measured eclipse durations for PSR B1957+20 in Chapter 6, for full eclipse, $\Delta \phi_{\text{eclipse}}$, ingress, $\Delta \phi_{\text{in}}$, and egress, $\Delta \phi_{\text{eg}}$, along with formal 1\(\sigma\) uncertainties from the least squares fits.

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<tr>
<th>PSR</th>
<th>Telescope</th>
<th>$\nu$ (MHz)</th>
<th>$\Delta \phi_{\text{eclipse}}$</th>
<th>$\Delta \phi_{\text{in}}$</th>
<th>$\Delta \phi_{\text{eg}}$</th>
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</thead>
<tbody>
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<td>B1957+20</td>
<td>LOFAR</td>
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<td>0.0400 ± 0.0010</td>
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<tr>
<td></td>
<td></td>
<td>140</td>
<td>0.0873 ± 0.0009</td>
<td>0.0367 ± 0.0005</td>
<td>0.0506 ± 0.0007</td>
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<tr>
<td></td>
<td></td>
<td>163</td>
<td>0.0872 ± 0.0012</td>
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<td>0.0510 ± 0.0011</td>
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<td></td>
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<td>0.0846 ± 0.0012</td>
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<tr>
<td></td>
<td>GMRT</td>
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<td>0.0876 ± 0.0012</td>
<td>0.0385 ± 0.0007</td>
<td>0.0491 ± 0.0009</td>
</tr>
<tr>
<td></td>
<td></td>
<td>163</td>
<td>0.0872 ± 0.0012</td>
<td>0.0382 ± 0.0004</td>
<td>0.0510 ± 0.0011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>171</td>
<td>0.0846 ± 0.0012</td>
<td>0.0376 ± 0.0007</td>
<td>0.0470 ± 0.0010</td>
</tr>
<tr>
<td></td>
<td>328</td>
<td></td>
<td>0.0393 ± 0.0005</td>
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</tr>
<tr>
<td></td>
<td>389</td>
<td></td>
<td>0.0397 ± 0.0009</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>461</td>
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<td>0.0393 ± 0.0011</td>
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<tr>
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<td>Parkes</td>
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</tr>
<tr>
<td></td>
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<td>0.0397 ± 0.0009</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.0393 ± 0.0011</td>
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</tbody>
</table>

**Table E.4:** Measured eclipse durations for PSR J2051−0827 in Chapter 6, for full eclipse, $\Delta \phi_{\text{eclipse}}$, ingress, $\Delta \phi_{\text{in}}$, and egress, $\Delta \phi_{\text{eg}}$, along with formal 1\(\sigma\) uncertainties from the least squares fits. $^a$Inner-eclipse (see Chapter 6).

<table>
<thead>
<tr>
<th>PSR</th>
<th>Telescope</th>
<th>$\nu$ (MHz)</th>
<th>$\Delta \phi_{\text{eclipse}}$</th>
<th>$\Delta \phi_{\text{in}}$</th>
<th>$\Delta \phi_{\text{eg}}$</th>
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</thead>
<tbody>
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<td>0.0572 ± 0.0053</td>
<td>0.0804 ± 0.0033</td>
</tr>
<tr>
<td>J2051</td>
<td>GMRT</td>
<td>149</td>
<td>0.0953 ± 0.0015</td>
<td>0.0465 ± 0.0009</td>
<td>0.0488 ± 0.0012</td>
</tr>
<tr>
<td>J2051</td>
<td>GMRT</td>
<td>389</td>
<td>0.0920 ± 0.0015</td>
<td>0.0441 ± 0.0010</td>
<td>0.0478 ± 0.0011</td>
</tr>
<tr>
<td>J2051</td>
<td>GMRT</td>
<td>389</td>
<td>0.0848 ± 0.0018</td>
<td>0.0395 ± 0.0012</td>
<td>0.0453 ± 0.0013</td>
</tr>
<tr>
<td>J2051</td>
<td>Parkes</td>
<td>933</td>
<td>0.0563 ± 0.0107</td>
<td>0.0279 ± 0.0101</td>
<td>0.0284 ± 0.0037</td>
</tr>
<tr>
<td>J2051</td>
<td></td>
<td></td>
<td>0.0324 ± 0.0064 $^a$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table E.5:** Measured eclipse durations for PSR J2215+5135 in Chapter 6, for full eclipse, $\Delta \phi_{\text{eclipse}}$, ingress, $\Delta \phi_{\text{in}}$, and egress, $\Delta \phi_{\text{eg}}$. Note that quoted uncertainties are nominal due to the formal uncertainties not satisfactorily accounting for significant gaps in the data at ingress and egress.

<table>
<thead>
<tr>
<th>PSR</th>
<th>Telescope</th>
<th>$\nu$ (MHz)</th>
<th>$\Delta \phi_{\text{eclipse}}$</th>
<th>$\Delta \phi_{\text{in}}$</th>
<th>$\Delta \phi_{\text{eg}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>J2215</td>
<td>GMRT</td>
<td>650</td>
<td>0.392 ± 0.020</td>
<td>0.182 ± 0.020</td>
<td>0.210 ± 0.020</td>
</tr>
<tr>
<td>J2215</td>
<td>GMRT</td>
<td>1360</td>
<td>0.334 ± 0.050</td>
<td>0.158 ± 0.050</td>
<td>0.176 ± 0.050</td>
</tr>
</tbody>
</table>
Table E.6: Best-fit power law parameters for eclipse durations in Chapter 6, when fit to full eclipse durations, ingress durations and egress durations as a function of frequency, $\nu$, i.e. $\Delta \phi = A(\nu/150)^{-\alpha}$. $^a$ Chapter 3; $^b$ Fit to $\nu < 200$ MHz data only.

<table>
<thead>
<tr>
<th>PSR</th>
<th>Full eclipse</th>
<th>Ingress</th>
<th>Egress</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A$</td>
<td>$\alpha$</td>
<td>$A$</td>
</tr>
<tr>
<td>J1810+1744</td>
<td>0.129 ± 0.001</td>
<td>0.22 ± 0.02</td>
<td>0.050 ± 0.001</td>
</tr>
<tr>
<td>$^a$</td>
<td>0.127 ± 0.001</td>
<td>0.41 ± 0.02</td>
<td>0.049 ± 0.001</td>
</tr>
<tr>
<td>J1816+4510</td>
<td>0.114 ± 0.003</td>
<td>0.49 ± 0.06</td>
<td>0.035 ± 0.001</td>
</tr>
<tr>
<td></td>
<td>0.103 ± 0.002</td>
<td>0.42 ± 0.04</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.089 ± 0.001</td>
<td>0.34 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>$^b$</td>
<td>0.117 ± 0.001</td>
<td>0.11 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>J2051−0827</td>
<td>0.107 ± 0.001</td>
<td>0.11 ± 0.05</td>
<td></td>
</tr>
<tr>
<td>$^b$</td>
<td>0.091 ± 0.001</td>
<td>0.16 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>B1957+20</td>
<td>0.087 ± 0.001</td>
<td>0.18 ± 0.04</td>
<td>0.038 ± 0.001</td>
</tr>
<tr>
<td>J2215+5135</td>
<td>0.507 ± 0.019</td>
<td>0.21 ± 0.04</td>
<td>0.250 ± 0.008</td>
</tr>
</tbody>
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