

Chapter 1

Introduction

Since the serendipitous discovery of the first radio pulsar by Jocelyn Bell in 1967 (Hewish et al., 1968), the number of known radio pulsars increased to more than 1500 by 2005, and at the time of writing stands at 2213 according to the *ATNF Pulsar Catalogue*¹ (Manchester et al., 2005).

Prior to the launch of the current generation of γ -ray space telescopes, the vast majority of pulsars were discovered in the radio band. Fewer than ten of these radio pulsars were visible in the γ -ray band (Thompson, 2001). This comparative lack of γ -ray pulsars, as well as the comparatively small datasets associated with those pulsars, made it very difficult to learn much about the mechanisms behind the observed γ -ray pulsations, and even more difficult to determine how these mechanisms arise in the context of emission models. Thus the study of γ -ray pulsars had hit a wall due to a shortage in detected γ -ray pulsars and a lack of good statistics. This would be the state of affairs until the launch of the Large Area Telescope (LAT) aboard the *Fermi* mission in 2008 (Atwood et al., 2009).

The *Fermi* LAT represented a major advance in sensitivity, energy range, and sky coverage over its predecessors (e.g., the Energetic Gamma Ray Experiment Telescope, or EGRET, aboard the *Compton Gamma Ray Observatory*, or CGRO; see, e.g., Thompson, 2001).

Since the launch of *Fermi* LAT, the number of known γ -ray pulsars has increased² to over 120. This number continues to increase. These discoveries have sparked renewed interest in the study of γ -ray pulsars, and have enabled the study of not only individual γ -ray pulsars, but of an entire population of them. It has also made various multiwavelength studies that include the γ -ray band possible.

The multiwavelength study that is most relevant to the work reported in this dissertation is by Weltevrede et al. (2010). They studied the radio and γ -ray properties of six *Fermi* LAT pulsars exhibiting single-peak profiles in the γ -ray band. The study presented in this dissertation is also concerned with those six γ -ray pulsars, but approaches the data using a geometric modelling framework to obtain independent predictions for their geometric parameters (see Section 1.5).

Before the results obtained by Weltevrede et al. (2010) can be discussed, it is necessary to first describe the different ways in which pulsars are observed. It is also necessary to introduce the basic parameters these studies attempt to determine. In this regard the following two sections,

¹ Accessible online at <http://www.atnf.csiro.au/people/pulsar/psrcat/> [date of access: 22 April 2013]

² <https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars> [date of access: 22 April 2013]

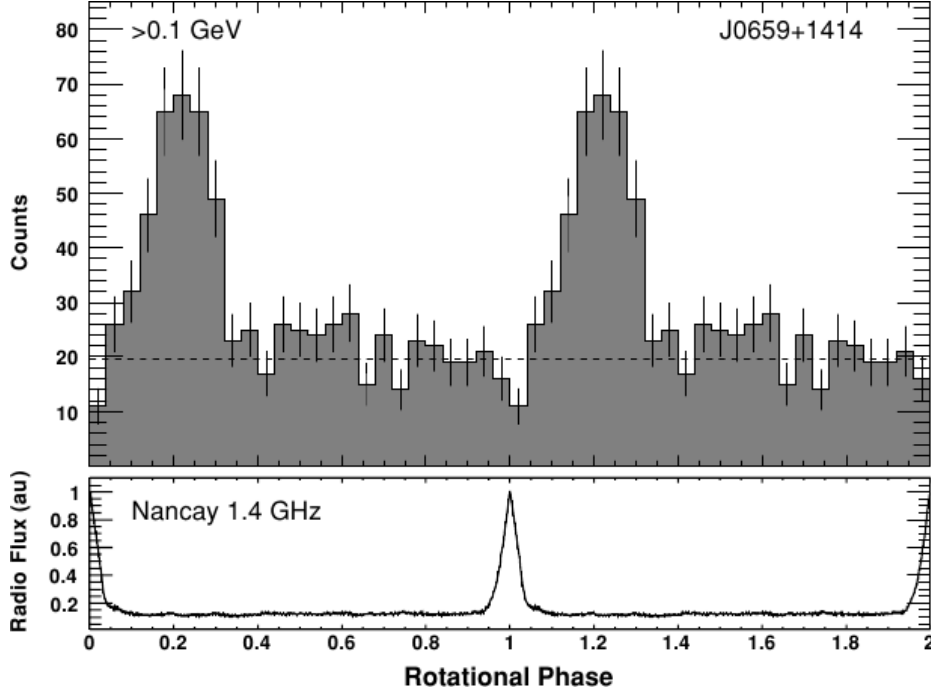


Figure 1.1: Example γ -ray (top panel) and radio (bottom panel) LCs for PSR J0659+1414 generated from *Fermi* LAT and Nançay Radio Telescope data respectively. In both cases two rotations are shown, with the start of both profiles aligned according to the position of the centre of the radio peak. This means that the actual lag in phase between the radio and γ -ray peaks is also accurately depicted. The γ -ray profile consists of twenty-five bins with the estimated background emission level indicated by the dashed line. The errors on the γ -ray counts are also shown. Adapted from Weltevrede et al. (2010).

Section 1.1 and Section 1.2, will introduce the pulsar observables and the basic picture of a pulsar. These sections are followed by a brief overview of the work done by Weltevrede et al. (2010) and the work presented in this dissertation. Section 1.5 lastly gives an overview of the structure of this dissertation, along with some information on what to expect in the chapters contained therein.

1.1 Pulsar observables

Pulsars are observed as sources of pulsed radiation displaying distinct periodicity covering a wide range of energy bands. These observations are usually organised in the form of so-called emission profiles, or light curves (LCs), which relate how the intensity of the emission changes with time during a single rotation of the pulsar. These profiles are produced by the stacking of observed emission from numerous rotations of the pulsar. Figure 1.1 shows the radio and γ -ray emission profiles for one of the pulsars relevant to this study, PSR J0659+1414. The top panel is the γ -ray LC and the bottom panel is the radio LC. In both panels two rotations of the pulsar are shown for the sake of clarity. The plane containing both the rotation axis and magnetic axis of the pulsar is usually chosen as the fiducial plane. The point in phase where the fiducial plane passes the observer defines $\phi = 0$. The centre of the radio peak is usually taken to correspond with the passing of the fiducial plane. The actual radio-to- γ phase lag of the observed peaks is preserved in Figure 1.1. The radio and γ -ray profile shapes, along with this radio-to- γ phase lag, make up the properties of the observed LCs that the fits in this study will try to reproduce (see Section 3.5).

Along with these LCs, both phase-averaged and phase-resolved spectra of the observed emission

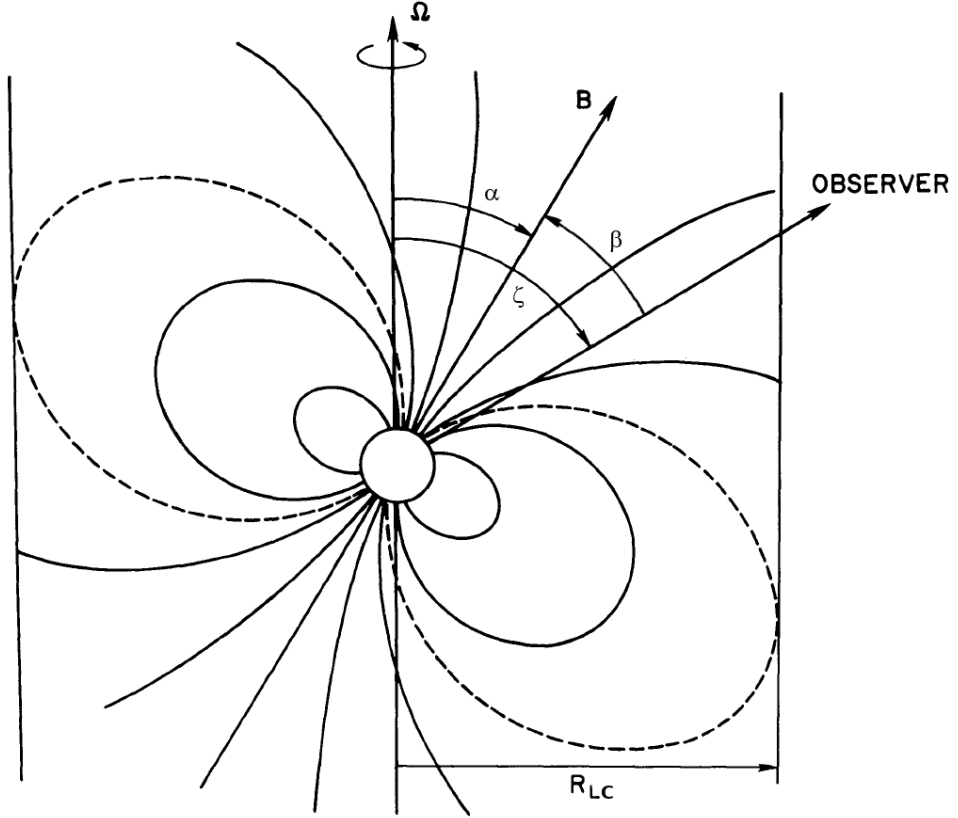


Figure 1.2: A diagram showing the geometric parameters associated with an individual pulsar: The inclination angle, observer angle, and impact angle. The rotation and magnetic axes, as well as the light cylinder are shown.

can also be obtained in several energy bands. These spectra are useful in the study of the magnetospheric environment of the pulsar, as well as providing insight into the radiation mechanisms which are responsible for the observed emission.

Polarisation observations are also made in some energy bands, with the most relevant example being the observations used by Weltevrede et al. (2010) to obtain constraints on the geometric parameters of five of the six *Fermi* LAT pulsars considered in this study. They obtained their results by applying a polarisation model corrected for special relativistic effects (Blaskiewicz et al., 1991) to polarisation data available for the 5 pulsars using a χ^2 statistical goodness-of-fit test. For more detail see the paper by Weltevrede et al. (2010).

1.2 The basic pulsar picture: the geometric parameters

A pulsar is a rapidly spinning neutron star (NS) with a dipole magnetic field inclined relative to the rotation axis. In Figure 1.2 a basic representation of a pulsar system is shown. Corotation with the NS is only possible up to a distance R_{LC} from the rotation axis. The boundary between the region where corotation is possible and the region where it is not, is called the light cylinder and is indicated by the two vertical lines in Figure 1.2. The most important consequence of this limit on corotation is that magnetic field lines can only close inside the light cylinder. The dashed line in Figure 1.2 shows the shape of the last closed field line.

The two most important parameters associated with a pulsar, in the context of this study, are

the inclination and observer angles. The inclination angle α is the angle at which the magnetic axis of a pulsar is inclined with respect to its rotation axis. The observer angle ζ is the angle between the observer’s line of sight and the rotation axis of the pulsar. These two quantities are called the geometric parameters. A third quantity can be derived from these two angles: the so-called impact angle $\beta = \zeta - \alpha$. It is also commonly referred to when discussing the geometric parameters of pulsar systems, especially in the context of radio observations (e.g., Weltevrede et al., 2010).

1.3 The work done by Weltevrede et al. (2010)

Weltevrede et al. (2010) generated best-fit χ^2 contours in (α, β) -space using a rotating vector model (RVM) for radio polarisation (Radhakrishnan & Cooke, 1969) to fit the position angle (PA) swing seen in the radio polarisation data available for five of the six pulsars they investigated (PSR J0631+1036, PSR J0659+1414, PSR J0742–2822, PSR J1420–6048, and PSR J1718–3825). Additionally, they generated a second set of contours in (α, β) -space corresponding to the beam half-opening angle $\rho(\alpha, \beta)$ implied by the observed width W of the radio profile. They further derived a value for ρ for each pulsar from the offset of the inflection point of the PA-swing profile with respect to the centre of the total intensity profile (as first described by Blaskiewicz et al., 1991) and located these values on the derived $\rho(\alpha, \beta)$ contours. Weltevrede et al. (2010) indicated that, due to the poorly understood systematics involved in deriving this ρ value from the PA-swing, it is not possible to specify errors for these derived values. The uncertainty in ρ stems from the assumption that the radio emission originates from a symmetric conal ring of uniform emissivity, centred on the magnetic axis. This assumption is made when deriving an emission height using the observed PA-swing, and is likely to dominate the total uncertainty in the radio analysis performed by Weltevrede et al. (2010).

Another point to take into account concerning the study conducted by Weltevrede et al. (2010) is that they assumed a static dipole magnetic field structure, neglecting rotational sweepback (Weltevrede et al., 2010). They also assumed that the radio emission originates from a constant-emissivity annulus located on the last open field line and symmetric about the magnetic axis. Some models for the radio emission (e.g., Lyne & Manchester, 1988) also consider patchy emission regions. Weltevrede et al. (2010) also state that there is uncertainty in the choice of fiducial plane, especially when the radio profile is complex, as in the case of PSR J1420–6048 and PSR J1718–3825. This uncertainty may have a large effect on the quality of the fits obtained for PSR J1420–6048 and PSR J1718–3825 in this study due to the requirement to reproduce the radio-to- γ phase lag as reported by Weltevrede et al. (2010).

1.4 The work reported in this dissertation

Weltevrede et al. (2010) reported the discovery of six single-peak γ -ray pulsars using *Fermi* LAT data. They obtained constraints on the geometric parameters of five of these pulsars by applying the RVM to high-quality polarisation data, as well as considering the geometry implied by the widths of the radio profiles. In addition, the outer gap (OG) and two-pole caustic (TPC) geometric models for γ -ray emission (see Section 3.2) predict single-peak profiles over a comparatively small portion

of their solution space, which means that independently obtaining best-fit emission profiles for these six pulsars in the context of these geometric models would potentially improve the constraints on the geometric parameters of these pulsars. Furthermore, since high-quality radio emission profiles are available for these six pulsars, it should be possible to further improve the constraining power of the geometric modelling approach by additionally requiring the reproduction of the shape of the radio profiles as well as the lag between the peaks of the radio and γ -ray profiles.

The work presented in this dissertation aims to accomplish these improved constraints. The following results are obtained:

- Independent constraints on the values of the geometric parameters (see Section 1.2) of the six single-peak *Fermi* LAT pulsars studied by Weltevrede et al. (2010), namely PSR J0631+1036, PSR J0659+1414, PSR J0742–2822, PSR J1420–6048, PSR J1509–5850, and PSR J1718–3825. (Section 6.2)
- Best-fit radio and γ -ray LCs for these pulsars based on the derived constraints. (Section 6.2)
- A comparison of the derived constraints on (α, ζ) obtained in this work with those obtained on (α, β) by Weltevrede et al. (2010). (Section 7.1)
- Estimates, with errors, for the values of the flux correction factor f_Ω (see Section 3.5.2) for each pulsar, based on the constraints obtained for their respective geometric parameters. (Section 5.2)
- Improved qualitative understanding of the geometric models employed in this study, including an understanding of the magnetic field assumed by these models (Chapter 4).

1.5 Overview of Dissertation

Chapter 2 is an introduction to the basic pulsar astrophysics relevant to this study, and provides the tools with which, and context within which, the work presented in this dissertation can be understood.

Chapter 3 introduces the geometric models (OG and TPC) that are going to be employed here, as well as the magnetic field structure assumed by these models. This chapter also describes how these models can be used to obtain predicted emission profiles and introduces the visual tools used to accomplish the aims of this study.

Chapter 4 investigates the effects on the predicted LCs of the various parameters relevant to the geometric models used in this study. This investigation is crucial in the development of a good qualitative understanding of the LCs produced by the various geometric models. This qualitative understanding is useful when evaluating the obtained results, and lies at the basis of their interpretation.

Chapter 5 is a step-by-step account, using PSR J1509–5850 as an example, of the method used to obtain the best-fit LCs and the subsequently inferred parameter constraints.

Chapter 6 describes the obtained results for all six pulsars in this study. These results are then compared to the results of an independent study conducted by Weltevrede et al. (2010).

Chapter 7 discusses the results obtained and the conclusions that can be drawn from them.