Introduction

Radio pulsars – rapidly rotating highly magnetised neutron stars – are fascinating objects to study. Weighing more than our Sun, yet only 20 km in diameter, these incredibly dense objects produce radio beams that sweep the sky like a lighthouse. Since their discovery by Jocelyn Bell-Burnell and Antony Hewish at Cambridge in 1967 (Hewish *et al.* 1968), over 1600 have been found. Pulsars provide a wealth of information about neutron star physics, general relativity, the Galactic gravitational potential and magnetic field, the interstellar medium, celestial mechanics, planetary physics and even cosmology.

Milestones of radio pulsar astronomy

Pulsar research has been driven by numerous surveys with large radio telescopes over the years. As well as improving the overall census of neutron stars, these searches have discovered exciting new objects, e.g. pulsars in binary systems. Often, the new discoveries have driven designs for further surveys and detection techniques to maximise the use of available resources. The landmark discoveries so far are:

- The Cambridge discovery of pulsars (Hewish *et al.* 1968). Hewish's contributions to radio astronomy, including this discovery, were recognised later with his co-receipt of the 1974 Nobel Prize for Physics with Martin Ryle.
- The first binary pulsar B1913+16[1] by Russell Hulse and Joseph Taylor at Arecibo in 1974 (Hulse & Taylor 1975). This pair of neutron stars

1 Pulsars are named with a PSR prefix followed by a 'B' or a 'J' and their celestial coordinates. Pulsars discovered before 1990 usually are referred to by their 'B' names (Besselian system, epoch 1950). Later discoveries are only referred to by their 'J' names (Julian system, epoch 2000).

orbit each other every 7.75 h and, in about 200 Myr, will coalesce due to the emission of gravitational radiation at the expense of orbital energy. The measurement of orbital shrinkage (1 cm day^{-1}) due to this effect was the first experimental demonstration of the existence of gravitational waves. Hulse and Taylor received the 1993 Nobel Prize for Physics in recognition of their achievement.

- The first millisecond pulsar B1937+21 by Shrinivas Kulkarni, Donald Backer and collaborators at Arecibo (Backer *et al.* 1982). This remarkable neutron star spins at 642 Hz, very close to the theoretical rotation limit (see Chapter 3), and turns out to be a highly stable clock on short timescales; PSR B1937+21 remains the most rapidly spinning neutron star known, despite the subsequent discovery of over a hundred millisecond pulsars in sensitive searches. High-precision timing of millisecond pulsars has provided a wealth of applications in astronomy and physics (see Chapter 2).
- The first pulsar in a globular cluster M21 by Andrew Lyne and collaborators at Jodrell Bank (Lyne *et al.* 1987). Since this discovery, eighty pulsars have been found in twenty-four globular clusters and are being used as powerful probes of the physical properties of clusters and the pulsars therein. One recent application is the first detection of ionised gas in the cluster 47 Tucanae (Freire *et al.* 2001; see also Chapter 2).
- The first pulsar planetary system B1257+12 by Alexander Wolszczan and Dale Frail at Arecibo in 1990 (Wolszczan & Frail 1992). This remarkable system contains two Earth-mass planets and one of lunar mass (Wolszczan 1994) and was the first extra-solar planetary system to be discovered (see Chapter 2).
- The first triple system B1620–26: a pulsar, a white dwarf and a Jupiter-mass planet by Stephen Thorsett and collaborators in the globular cluster M4 (Backer *et al.* 1993a; Thorsett *et al.* 1993). This system highlights the rich variety of evolutionary scenarios possible in globular clusters (Sigurdsson *et al.* 2003; see also Chapter 2).
- The discovery of J0737–3039, the first 'double pulsar' system by Marta Burgay and collaborators in 2003 (Burgay *et al.* 2003, Lyne *et al.* 2004). This fascinating system, that consists of a 22.7 ms pulsar in orbit around a 2.77 s pulsar, is the first double neutron star binary in which both components have been observed as radio pulsars. As described in Chapter 2, it promises to place even more stringent constraints on strong-field gravitational theories than PSR B1913+16.

Present-day progress

Many of the most exciting pulsar discoveries in the past five years, including J0737–3039, are being made using the Parkes telescope. The scientific output of this relatively modest 64-m telescope currently dominates the flood of exciting pulsars being found, using a state-of-the-art 'multibeam' receiver system to collect data from thirteen independent points in the sky simultaneously. Indeed, over half of all known pulsars have been discovered by this system. Current highlights include three double-neutron-star binaries, a number of pulsars with ultra-high (10^{14} G) magnetic fields and over two dozen millisecond pulsars.

Progress elsewhere makes use of new and/or recently refurbished instruments, in particular the Green Bank Telescope, the Giant Metre Wave Radio Telescope and the upgraded Arecibo telescope. These sensitive instruments are being used to perform deep targeted searches for pulsars in supernova remnants and globular clusters. One exciting recent find is PSR J0514–4002, a 4.99 ms pulsar in a highly eccentric ($e = 0.89$) binary system in the globular cluster NGC 1851 (Freire *et al.* 2004).

Pulsar astronomy is a truly multi-wavelength field. Not only are neutron stars the only astronomical sources that are observed across the electromagnetic spectrum, they are one of the prime sources for gravitational wave observatories now coming online. Although this book deals mainly with radio observations, new high-energy instruments, e.g. *Chandra* and *XMM*, provide complementary windows in the electromagnetic spectrum to study pulsars and their environments (see Chapter 9).

Open questions

Some of the many open questions[2] in pulsar astronomy are:

- How many pulsars are in the Galaxy and what is their birth rate?
- How are isolated millisecond pulsars produced?
- How many pulsars are in Globular clusters?
- How many pulsar planetary systems exist?
- Do the magnetic fields of isolated neutron stars decay?
- What are the minimum and maximum spin periods for radio pulsars?
- What is the relationship between core collapse in supernovae and neutron star birth properties?

2 This list reflects our personal bias somewhat. Our apologies to those who have answered these questions to their satisfaction already, or have other unanswered questions which we have not included here!

- How many pulsar–black hole binaries exist?
- Are all magnetised neutron stars radio pulsars?
- How and where is the radio and high-energy emission produced?
- What is shape and structure of the radio beam?
- What is the role of propagation effects in pulsar magnetospheres?
- What is the composition of neutron star atmospheres, and how do they interact with the strong magnetic fields?

While we do not provide the answers in this book, it is hoped that the techniques described and the ever-increasing advances in observational sensitivity will go some way to expanding our knowledge in the future.

The future

Pulsar astronomy currently is enjoying one of the most productive stages in its relatively short (35 year) existence. The future of the field looks even brighter. As pulsar surveys continue to become more and more sensitive, the true character of the Galactic neutron star population is being revealed. The 305 m Arecibo radio telescope is being fitted with a multibeam receiver that will permit extremely sensitive large-scale surveys over the next 5–10 years that are expected to yield up to 1000 pulsars. Looking further ahead, the next-generation radio telescope – the Square Kilometre Array (SKA) – should be close to operational by 2015. This telescope, with a sensitivity of more than 100 times that of Parkes, is expected to detect essentially all of the $\sim 20,000$ active radio pulsars in the Galaxy, the emission beams of which intersect our line of sight. A full Galactic census should reveal a number of exciting systems for future study, including one of the 'holy grails' of pulsar astronomy: a pulsar orbiting a stellar-mass black hole (see Chapter 2).

Aims and layout of this book

There is now a growing need for astronomers to become proficient with a variety of techniques and instruments across the electromagnetic spectrum. Building on the excellent existing monographs describing the theory and observations of pulsars (Manchester & Taylor 1977; Michel 1992; Beskin, Gurevich & Istomin 1993; Lyne & Smith 2005) we describe the techniques of radio pulsar astronomy. Our aim is to make this field more accessible to a wider audience of astronomers.

In addition to describing the latest results and observational techniques and summarising relevant mathematical formulae, the book web site (see below and Appendix 3) with links to software packages and sample data sets. We aim to provide the reader with the necessary techniques to analyse radio pulsar observations. It is our hope that this combination will appeal as an introduction to graduate students and astronomers from other fields, as well as being a handy reference for seasoned pulsar observers. Although we strive to use the SI system of units wherever possible, we adopt other units (e.g. Gauss, parsec, Jansky) where in standard use by pulsar astronomers. In our compendium of useful formulae (see Appendix 2) we list the appropriate conversion factors for those who wish to convert these quantities into SI.

The first three chapters of the book discuss basic pulsar properties (see Chapter 1), uses of pulsars as physical tools (see Chapter 2) and some relevant theoretical background for interpreting observations (see Chapter 3). In Chapter 4, we discuss the effects of the interstellar medium on pulsar observations in some detail with particular attention to observable quantities. The most commonly used devices and techniques for pulsar data acquisition are then covered in Chapter 5. Our discussion of the fundamental observing techniques for single-dish pulsar astronomy is divided into pulsar searching (see Chapter 6), routine observations of known pulsars (see Chapter 7) and timing observations (see Chapter 8). Many of the techniques described in these chapters are brought into a single reference for the first time. Observations with multiple radio telescopes and instruments outside of the radio spectrum are reviewed briefly in Chapter 9. Appendices cover basic radio astronomy concepts (see Appendix 1), a collection of the most useful equations mentioned throughout the book (see Appendix 2) and a list of web-based resources which are available on the book web site (see Appendix 3). The index is designed to provide speedy access to key parts of the book and also serves as a glossary for some of the more commonly used abbreviations.

While this book can be read from cover to cover, it is perhaps best 'dipped into' for specific information as required. Each chapter contains a reading list for further references and details of relevant software freely available via the book web site

`http://www.jb.man.ac.uk/~pulsar/handbook`

We welcome all comments and feedback on this site and all contents of the book via email at the following address: `handbook@jb.man.ac.uk`.

Acknowledgements

We are deeply indebted to our colleagues for providing material used in some of the figures, making their data and software available or for invaluable feedback on earlier drafts of the chapters. In particular, our thanks go to Dimitris Athanasiadis, Don Backer, Ramesh Bhat, Dipankar Bhattacharya, Walter Brisken, Adam Chandler, Jim Cordes, Ali Esamdin, Andy Faulkner, Paulo Freire, Tim Hankins, Jon Hagen, George Hobbs, Aidan Hotan, Bryan Jacoby, Axel Jessner, Simon Johnston, Aris Karastergiou, Bernd Klein, Oliver Löhmer, Andrew Lyne, Olaf Maron, Maura McLaughlin, Peter Müller, Dipanjan Mitra, Dave Moffett, Steve Ord, Scott Ransom, Graham Smith, Ingrid Stairs, Steve Thorsett, Willem van Straten, and Norbert Wex. Our thanks also go to Jacqueline Garget at Cambridge University Press for her patience as we blatantly missed several 'deadlines' during the completion of this work. Frequent use was made of NASA's Astrophysical Data Service and the Los Alamos preprint server in the literature searches.

DRL would like to express his thanks to the Royal Society for financial support and for providing the intellectual freedom to pursue lengthy and, at times, seemingly never-ending projects such as this book. His wife Maura and their parrot Noel gave essential support and encouragement during the long months of late nights and early mornings of the winter of 2003/4 spent preparing the manuscript and in helping to edit in all the corrections from the proof reading stage. Without their love and patience, his contribution to this book would not have been possible.

MK would like to thank his colleagues and students for being patient at times when the work on the book seemed to drag on forever. Norbert Wex is thanked in particular for offering a seemingly endless stream of information about literature, profound background knowledge and countless enjoyable discussions. None of MK's contributions would have been remotely possible without the constant support from his wife Busaba and family. Without Busaba's love, reassurance and comfort but also her wake-up calls, many more nights of work would have been necessary.

1
The pulsar phenomenon

Observations of radio pulsars carried out over the past four decades have provided a wealth of information about the properties of neutron stars. In this chapter, we review briefly the current state of our knowledge based on the roughly 1600 pulsars now known. For the purposes of this discussion, we consider three main areas: (a) pulsar emission properties used to help understand and constrain mechanisms for the radio emission; (b) interstellar propagation effects on the pulsar signal; (c) pulsar population properties and their implications for the Galactic population of neutron stars.

1.1 Emission properties

The various properties of the observed emission from pulsars are explained most naturally by a simple picture in which the observed radiation is produced by the acceleration of charged particles along the field lines of highly magnetised rotating neutron stars (Gold 1968; Pacini 1968). In the following, we concentrate on the main results in support of this idea. The model will be explored further in Chapter 3.

1.1.1 The lighthouse effect

Figure 1.1 demonstrates the basic pulsar signal in the form of a recording of intensity received by a radio telescope as a function of time. This 22 s time series from PSR B0301+19 shows regularly spaced pulses with a repetition period $P = 1.38$ s. The now standard interpretation is that the pulses are produced by the *lighthouse effect* of an emission beam of a neutron star as it sweeps past our line of sight once per rotation. In this case, the rotation frequency $\nu = 1/P = 0.725$ Hz.

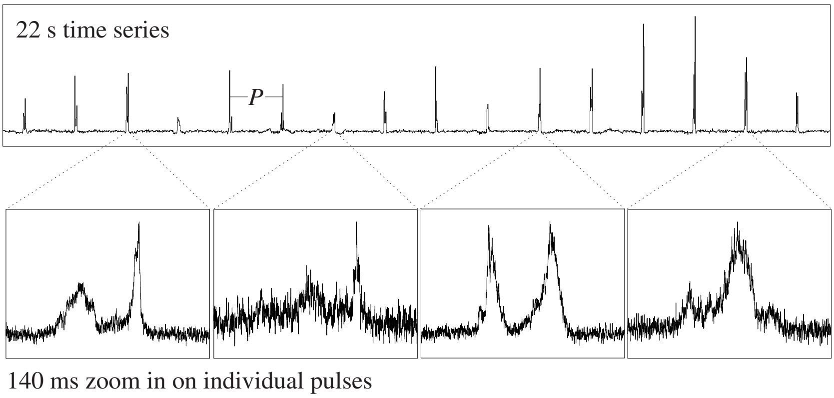

Fig. 1.1. A 22 s time series from the Arecibo radio telescope showing single pulses from PSR B0301+19. Insets show expanded views of selected pulses.

When placed in context of the range of spin periods observed, PSR B0301+19 is a fairly 'common-or-garden' pulsar. The most rapidly rotating neutron star currently known is PSR B1937+21 (Backer *et al.* 1982) with a period of only 1.56 ms. The corresponding rotation frequency of 642 Hz for this star rules out some models of the equation of state for neutron stars (see Chapter 3). In contrast, the longest period observed for any radio pulsar so far is 8.5 s (or a sedate 0.12 Hz) for PSR J2144–3933 (Young, Manchester & Johnston 1999). The distribution in spin period is distinctly bimodal. As we discuss further in Section 1.3, the short-period 'millisecond pulsars' form a separate (older) population with different evolutionary histories from the long-period 'normal pulsars'. Throughout our tour of the emission properties, we shall compare and contrast the millisecond and normal pulsars where appropriate.

1.1.2 Integrated profiles

Pulsars are very weak radio sources. Even with the sensitivity of current radio telescopes, individual pulses such as those shown in Figure 1.1 are observable from only the strongest sources. Most pulsars require the coherent addition of many hundreds or even thousands of pulses together, a process known as *folding*, in order to produce an *integrated pulse profile* that is discernible above the background noise of the receiver.

Remarkably, for a given pulsar, even though the individual pulses have different shapes (see Figure 1.1), the integrated pulse profile is usually very stable for any observation at the same radio frequency. As such it can be thought of as a 'fingerprint' showing a cross-sectional cut through each neutron star's emission beam[1]. A selection of integrated pulse profiles is shown in Figure 1.2. The time scale required to achieve a stable integrated profile varies between a few hundred to a few thousand pulse periods (Helfand; Manchester & Taylor 1975; Rankin & Rathnasree 1995). This turns out to be a key property for timing observations which we discuss further in Chapter 8.

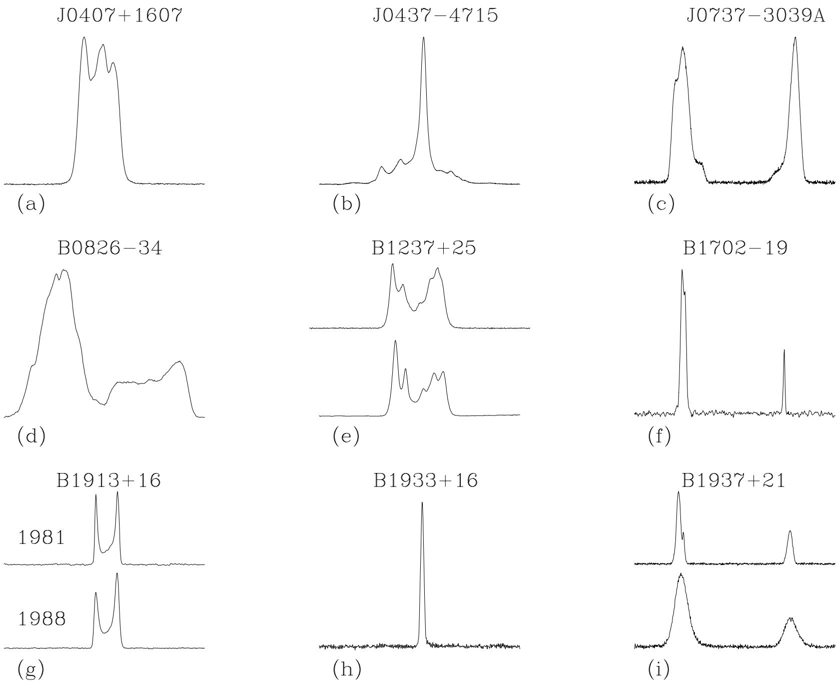

Fig. 1.2. Integrated pulse profiles for a sample of nine pulsars. With the exception of PSR B1237+25, each profile shows 360° of rotational phase. An expanded view of the profile of this pulsar is shown for two different modes. For PSR B1913+16 we show two 430 MHz profiles taken at separate epochs to highlight the profile evolution due to geodetic precession. These profiles are freely available on-line as part of the EPN database (see Appendix 3). For PSR B1937+21, we show two profiles observed with the Effelsberg radio telescope at 1.4 GHz. The upper profile was coherently de-dispersed and shows the true pulse shape. The lower profile was obtained with an incoherent filterbank system which results in much poorer time resolution (see Chapter 5).

1 As we explain in Chapter 3, the observed pulse shape depends critically on the size and structure of the emission beam, as well as the angle between our line of sight and the beam centre.

1.1.2.1 Pulse shapes

From the examples shown in Figure 1.2, it can be seen that the pulse shapes vary considerably in complexity. This sample has been chosen for illustrative purposes, often showing extreme cases. In the simplest case, as shown for PSR B1933+16, the pulse consists of a single component that is essentially Gaussian in form. A number of pulsars exhibit a characteristic double-peaked structure (e.g. PSR B1913+16) and even more complicated shapes with multiple components, e.g. PSR B1237+25.

While information about the structure of the emission beam can be inferred from an analysis of these pulse shapes (see Chapter 3), we note here simply that the pulse shapes fall into a number of different morphological categories depending on the number and placement of pulse components (Backer 1976; Rankin 1983a,b). Although it was thought initially that millisecond pulsar profiles were more complex than normal pulsars, studies identifying the number of components in profiles show these to be comparable for the two classes. On average, we observe 3 ± 1 components for normal pulsars and 4 ± 1 components for millisecond pulsars (Kramer *et al.* 1998).

In some cases, as shown dramatically for PSR B0826–34, pulsars show emission over the whole pulse period. This suggests strongly that the magnetic and rotation axes of such pulsars are aligned essentially and our line of sight remains inside the emission beam at all times.

1.1.2.2 Interpulses

The astute reader will notice three examples of *interpulses* in Figure 1.2. These are secondary pulses separated by about 180° from the main pulse. The simplest interpretation for this phenomenon is that the main pulse and interpulse originate from opposite magnetic poles of the neutron star. We see both poles if the magnetic and spin axes are almost orthogonally aligned. As shown in Chapter 3, polarisation measurements can be used to identify such cases. An alternative hypothesis, first presented by Manchester & Lyne (1977), is that interpulses represent the emission from extreme edges of a single wide beam. One example of this is the 22 ms relativistic binary pulsar J0737–3039A shown in Figure 1.2 that has two symmetric pulses (Burgay *et al.* 2003).

1.1.2.3 Profile evolution with time

Although almost all profiles are stable from epoch to epoch, there are a number of important exceptions. Temporal changes in pulse profiles have