Neutron Stars and Pulsars

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by

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Preface

When the existence of neutron stars was confirmed by the discovery of radio pulsars in August 1967, there was general optimism that it should not be too difficult to explore and understand the physical properties of a rotating magnetised compact star with $\sim$10 km radius. Forty years and more than 13 PhD student-generations later, everybody involved in the $\gg$neutron star business$\ll$ has lost this illusion, meanwhile learning how complex neutron stars are and how difficult it is to understand their physical properties.

Neutron stars form in supernova explosions and/or by an accretion induced collapse of a white dwarf. At the time of their discovery – and for many years later – it was generally accepted that neutron stars can only be observed as pulsars. According to the source of energy they were split into two classes, i.e. being powered by either rotation or accretion. Today, the neutron star world is much more intrincate than it was fourty decades ago. In addition to the accretion powered pulsars, which are predominantly bright X-ray sources, and the rotation-powered pulsars which are observed throughout the electromagnetic spectrum, there are now X-ray Dim Isolated Neutron Stars (XDINs), "radio-quiet neutron stars", Compact Central Objects (CCOs) in supernova remnants, Soft Gamma-ray Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs).

Accordingly, neutron stars manifest themselves in many different ways. They become visible by high-energy processes occurring on their surface or surrounding region. In most of these objects, ultra-strong magnetic fields are a crucial element in the radio, optical, X-ray and gamma-ray emission processes which dominate the observed spectrum.

Observationally, neutron star research is advancing steadily. A great array of space instruments (the Hubble Space Telescope, ROSAT, ASCA, BeppoSAX, RXTE and the Compton Gamma-Ray Observatory), launched in the last decade of the twentieth century have opened new windows on neutron star research with high quality data in energy bands from the optical to gamma-rays. With the more recently launched satellite X-ray observatories Chandra and XMM-Newton, the H.E.S.S. Array of Imaging Atmospheric Cherenkov Telescopes, upgraded radio observatories and ground based optical telescopes a number of questions which remained unanswered for many years could be addressed and have led to new and exciting findings which have changed the earlier picture of neutron star evolution substantially.

However, even in view of these great observational capabilities and the intense research over a period of more than 40 years, there are fundamental questions which still have not been answered. How are the different manifestations of neutron stars related to each other? What are the physical parameters which differentiate AXPs/SGRs/CCOs/XDINs and rotation-powered pulsars? What is the maximal upper bound for the neutron star mass and what is the range of possible neutron star radii? Is there any exotic matter in neutron stars? Do strange stars exist? And what are the physical processes responsible for the pulsars' broad band emission observed from the infrared to the gamma-ray band? These are just a few of the long standing open questions.

To adequately address these questions, it requires a wide range of scientific disciplines, including nuclear and condensed matter physics of very dense matter in neutron star interiors, plasma physics and quantum electrodynamics of the magnetospheres, relativistic magnetohydrodynamics of electron-positron pulsar winds interacting with some ambient medium. Not to forget the role of a test bed neutron stars provide for general relativity theories as well as being sources of gravitational waves. It is this variety of disciplines which, among others, makes the neutron star research so fascinating and attractive, not only for those who have been working in the field for many years but also for students and young scientists.

Especially students and young scientists often have the problem of finding a comprehensive reference with up-to-date information on multi-wavelength studies from neutron stars and pulsars and the various theoretical models. We have created this book to give them a reference at hand, which not only reviews the progress made since the early days of pulsar astronomy but focuses especially on questions such as (1) what have we learned about the subject and how did we learn it? (2) what are the most important open questions in this area? And (3) what new tools, telescopes, observations, calculations are needed to answer these questions?

Many of the authors who have contributed to this book have devoted a significant part of their scientific career on exploring the nature of neutron stars and understanding pulsars. Every one of us has paid special attention to write an educational comprehensive review article keeping beginners, students and young scientists as potential readers in mind. I am confident that this book will be a valuable source of information for them.

I am very thankful to all the authors for their contributions and to the referees for the time they have spent in getting the quality of the book to its final level.

Garching, *Werner Becker*
July 2008

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Chapter 1
Radio Pulsar Statistics

Duncan R. Lorimer

1.1 Introduction

Forty years after the discovery of radio pulsars by Jocelyn Bell and Antony Hewish at Cambridge in 1967 [22], the observed population presently exceeds 1,700 objects with spin periods in the range 1.4 ms to 8.5 s. Pulsar astronomy is currently enjoying a golden era, with over half of these discoveries in the past 7 years due largely to the phenomenal success of the Parkes multi beam survey [46]. From the sky distribution in Galactic coordinates shown in Fig. 1.1, it is immediately apparent that pulsars are concentrated strongly along the Galactic plane. This is particularly striking for the youngest pulsars known to be associated with supernova remnants. Also shown in Fig. 1.1 are the millisecond pulsars which have spin periods in the range 1.5–30 ms. The more isotropic sky distribution of the millisecond pulsars does not necessarily imply that they have a different spatial distribution; the difference simply reflects the observational bias against detecting short-period pulsars with increasing distance from the Sun. This is one of many selection effects that pervades the observed sample.

From such a violent birth in supernovae, it is perhaps not surprising to learn that pulsars are high-velocity objects. The right-hand panel of Fig. 1.1 shows pulsar proper motions on the plane of the sky taken from a recent study by [23]. The mean transverse speed of the current sample of 233 pulsars is $246 \pm 22\,\mathrm{km\,s^{-1}}$. From a sample of proper motions for pulsars younger than 3 Myr, Hobbs et al. find the mean 3-D velocity of pulsars to be $400 \pm 40\,\mathrm{km\,s^{-1}}$. The origin of these high velocities most likely lies in a combination of pre-supernova binary orbital motion (e.g. [24]) and/or impulsive kicks due to small asymmetries in the supernova explosions (e.g. [25]). Millisecond pulsars have significantly lower space velocities; their mean transverse speed is only $87 \pm 13\,\mathrm{km\,s^{-1}}$, while a study by Lyne et al. [44] showed the mean 3-D speed to be $130 \pm 30\,\mathrm{km\,s^{-1}}$. Despite these differences,

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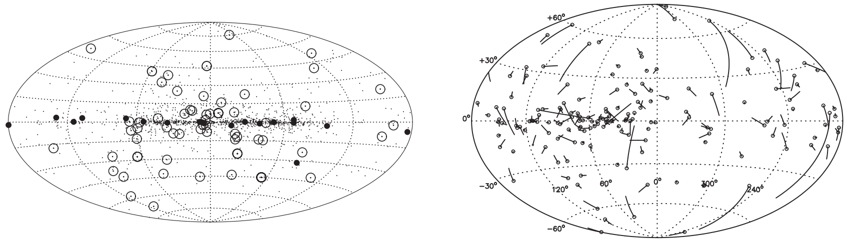

Fig. 1.1 *Left*: the distribution of pulsars in Galactic coordinates. Pulsar–supernova remnant associations and millisecond pulsars are shown by the *filled and open circles* respectively. *Right*: pulsar proper motions in Galactic coordinates (after [23]). The *solid lines* show the proper motion (neglecting the unknown radial velocity) over the last million years

population syntheses indicate that the two populations are consistent with the idea that all neutron stars share the same velocity distribution. The millisecond pulsars represent those binary systems which have survived and have necessarily smaller space velocities as a result [62].

The observed emission from radio pulsars takes place at the expense of the rotational kinetic energy of the neutron star. As a result, in addition to observing the pulsar's spin period, P, we also observe the corresponding rate of spin-down, $\dot{P}$. Such measurements give us unique insights into the spin evolution of neutron stars and are summarized on the P–$\dot{P}$ diagram shown in Fig. 1.2. The diagram contrasts the normal pulsars ($P \sim 0.5$ s and $\dot{P} \sim 10^{-15}$ s s^{-1} which populate the "island" of points) and the millisecond pulsars ($P \sim 3$ ms and $\dot{P} \sim 10^{-20}$ s s^{-1} which occupy the lower left part of the diagram).

The differences in P and $\dot{P}$ imply fundamentally different ages and magnetic field strengths for the two populations. Assuming the spin evolution of the neutron star to be a due to magnetic dipole radiation, we can make rough estimates of the inferred age $\tau \propto P/\dot{P}$ and magnetic field strength $B \propto (P\dot{P})^{1/2}$. Lines of constant B and τ are drawn on Fig. 1.2 from which we infer typical magnetic fields and ages of 10^{12} G and 10^7 yr for the normal pulsars, and 10^8 G and 10^9 yr for the millisecond pulsars. The rate of loss of rotational kinetic energy $\dot{E} \propto \dot{P}/P^3$ (also known as the "spin-down luminosity") is also indicated. As expected, these are highest for the young and millisecond pulsars.

In addition to spin behaviour, a very important additional difference between normal and millisecond pulsars is binarity. Orbiting companions are observed around about 80% of all millisecond pulsars but less than 1% of all normal pulsars. The companions are either white dwarfs, main sequence stars, or other neutron stars. Pulsars with low-mass companions (<0.5 $M_\odot$ – predominantly white dwarfs) usually have millisecond spin periods and essentially circular orbits with orbital eccentricities in the range $10^{-5} < e < 10^{-1}$. Measurements of white-dwarf "cooling ages" (see [65]) agree generally with millisecond pulsar characteristic ages and support the idea that these binary systems have typical ages of a few Gyr. Binary pulsars with high-mass companions (>1 $M_\odot$ – neutron stars or main sequence stars) have larger spin periods (>20 ms) and are in more eccentric orbits: $0.1 < e < 0.9$.

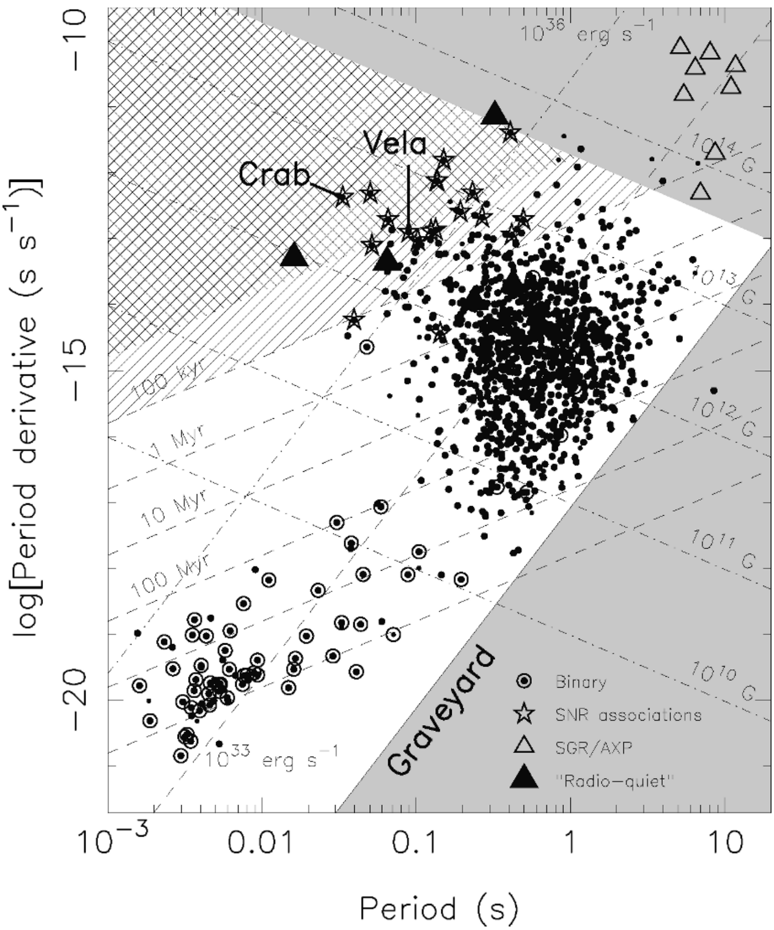

Fig. 1.2 The ubiquitous P–$\dot{P}$ diagram showing isolated and binary radio pulsars, "radio-quiet" pulsars, soft-gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs). Figure kindly provided by Michael Kramer

The existence of binary pulsars can be understood by a simple evolutionary scenario which starts with two main-sequence stars (see [8]). The initially more massive (primary) star evolves first and eventually explodes in a supernova to form a neutron star. The high velocity imparted to the neutron star at birth and dramatic mass loss during the supernova usually is sufficient to disrupt most (90% or more) binary systems [54]. Those neutron stars remaining bound to their companions spin down as normal pulsars for the next 10^{6-7} yr. Later on, the remaining (secondary) star comes to the end of its main sequence lifetime and begins a red giant phase. For favourable orbital parameters, the strong gravitational field of the neutron star attracts matter from the red giant and forms an accretion disk. As a result, the system becomes visible as an X-ray binary.

The accretion of matter transfers orbital angular momentum to the neutron star, spinning it up to short periods and dramatically reducing its magnetic field [10]. A limiting spin period is reached due to equilibrium between the magnetic pressure of the accreting neutron star and the ram pressure of the in-falling matter [1, 19, 32]. Such "spun-up" neutron stars are often referred to in the literature as *recycled pulsars*. Unlike the young pulsars with high spin-down rates, the now weakly-magnetized recycled pulsars appear in the lower-left hand part of the P–$\dot{P}$ diagram and spin down much more gradually and over a longer timescale.

The ultimate fate of the binary system depends on the mass of the secondary star. The two main outcomes are double neutron star binaries, for secondaries massive enough to explode as a supernova, and neutron star-white dwarf binaries for less massive secondaries. Very recently, the first double neutron star system has been found, PSR J0737–3039, in which both stars are observed as pulsars: a 22.7-ms pulsar "A" [11] and a 2.7-s pulsar "B" [45]. In the framework of the above model, we identify A as the first-born neutron star with a short spin period and low inferred magnetic field, while B is the younger, second-born, neutron star with a higher magnetic field.

1.2 The Observed Pulsar Spatial Distribution

Pulsar astronomers are extremely fortunate in that they have a reasonably accurate means of estimating distances to their objects from measurements of pulse dispersion caused by free electrons in the interstellar medium (see [70]). In Fig. 1.3, the most recent Galactic electron density model [15] is used to project the current sample of pulsars in the ATNF catalog (`www.atnf.csiro.au/research/pulsar/psrcat`) onto the Galactic plane. Two main features can be seen in this

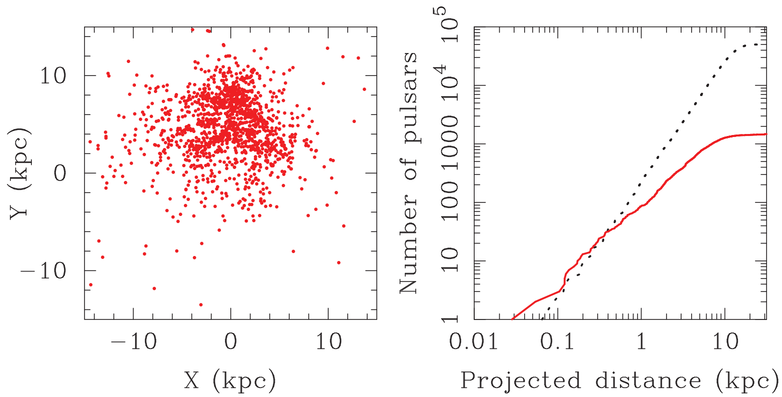

Fig. 1.3 *Left*: the currently known pulsar population projected onto the Galactic plane. The Galactic center is at the origin and the Sun is at (0.0,8.5) kpc. *Right*: cumulative distribution as a function of projected distance from the Sun. The *solid line* is the observed sample while the *dashed line* is the expected distribution of a simulated population free from selection effects

diagram: (a) pulsar positions trace the spiral-arm structure of our Galaxy (though this is somewhat incestuous, since spiral arms are now incorporated into the electron density model); (b) rather than being distributed about the Galactic center, the majority of pulsars are clearly biased towards the bright/nearby objects.

To get an idea of how biased the sample is, the right panel of Fig. 1.3 shows the cumulative distribution of pulsars as a function of distance from the Sun projected onto the Galactic plane. Also shown is the expected distribution for a simulated population in which there are no selection effects. As can be seen, the two samples are closely matched only out to a kpc or so before the selection effects become significant. From these curves, we deduce that *less than 10% of the potentially observable population in the Galaxy is currently detectable.*

The number of potentially observable pulsars in the Galaxy can be estimated very crudely by the source counting method (see, e.g. [31]) where one uses the cumulative distribution and counts sources out to a distance where the sample is thought to be more or less complete. By assuming some underlying spatial distribution function, this number can be extrapolated to get the total number of pulsars in the Galaxy. Based on Fig. 1.3, we count 100 objects out to 1 kpc, i.e. a mean surface density of $100/(\pi \times 1\mathrm{kpc}^2) \simeq 30\,\mathrm{kpc}^{-2}$. If pulsars have a radial distribution similar to that of other stellar populations, the corresponding local-to-Galactic scale factor is $1{,}000 \pm 250\,\mathrm{kpc}^2$ [55]. With this factor, we estimate there to be of order 30,000 potentially observable pulsars in the Galaxy.

1.3 Selection Effects in Radio Pulsar Surveys

The inverse square law. Like all astronomical sources, observed pulsars of a given luminosity L are strongly selected by their apparent flux density, S. For a pulsar at a distance d from the Earth which beams to a certain fraction f of 4π sr, $S = L/(4\pi d^2 f)$. Since all pulsar surveys have some limiting flux density, only those objects bright or close enough will be detectable. Note that in the absence of prior knowledge about beaming, geometrical factors are usually ignored and the resulting "pseudo-luminosity" is quoted at some standard observing frequency; e.g., at 1,400 MHz, $L_{1400} \equiv S_{1400} d^2$.

The radio sky background. A fundamental sensitivity limit is the system noise temperature, T_{sys}. While every effort is made to minimize this at the telescope, synchrotron radiating electrons in the Galactic magnetic field contribute significantly with a "sky background" component, T_{sky}. At observing frequencies $\nu \sim 0.4\,\mathrm{GHz}$, T_{sky} dominates T_{sys} along the Galactic plane. Fortunately, $T_{\mathrm{sky}} \propto \nu^{-2.8}$ so this effect is significantly reduced when $\nu > 0.4\,\mathrm{GHz}$.

Propagation effects in the interstellar medium. Dispersion and scatter-broadening of the pulses in the interstellar medium hamper detection of short period and/or distant objects. The effects of scattering are shown in Fig. 1.4. Fortunately, like T_{sky}, the scatter-broadening time τ_{scatt} has a strong frequency dependence, scaling roughly

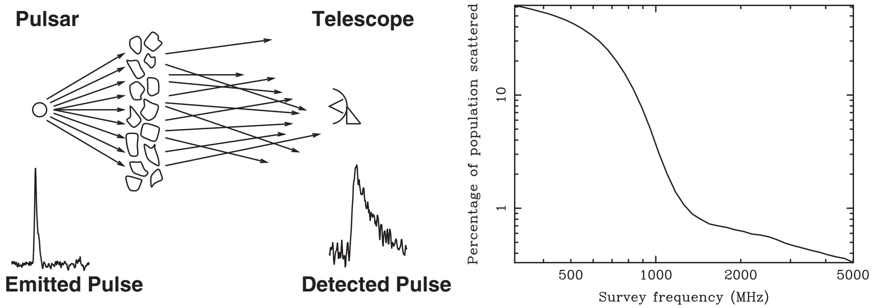

Fig. 1.4 *Left*: pulse scattering by irregularities in the interstellar medium shown here as an idealized "thin screen" of material lying midway between the pulsar and the observer. *Right*: a simulation showing the fraction of pulsars undetectable due to scattering as a function of observing frequency

as ν^{-4}. Figure 1.4 shows that for survey frequencies below 1 GHz, scattering "hides" a large fraction of the population. Additionally, scintillation, the diffractive and refractive modulation of apparent flux densities by turbulences in the interstellar medium [56] affects pulsar detection. For example, two northern sky surveys carried out 20 years apart with comparable sensitivity [17, 59] detected a number of pulsars above and below the nominal search thresholds of one experiment but not the other. Surveying the sky multiple times minimizes the effects of scintillation and enhances the detection of faint pulsars through favourable scintillation.

Finite size of the emission beam. The fact that pulsars do not beam to 4π sr means that we see only a fraction f of the total active population. For a circular beam, Gunn and Ostriker [21] estimated $f \sim 1/6$. A consensus on the precise shape of the emission beam has yet to be reached. Narayan and Vivekanand [50] argued that the beams are elongated in the meridional direction. Lyne and Manchester [41], on the other hand, favour a circular beam. Using the same database, Biggs [9] presented evidence in favour of meridional compression! All these studies do agree that the beam size is period dependent, with shorter period pulsars having larger beaming fractions. Tauris and Manchester [64] found that $f = 0.09\,[\log(P/\mathrm{s}) - 1]^2 + 0.03$, where P is the period. A complete model for f needs to account for other factors, such as evolution of the inclination angle between the spin and magnetic axes.

Pulse nulling. The abrupt cessation of the pulsed emission for many pulse periods, was first identified by [3]. Ritchings [57] presented evidence that the incidence of nulling became more frequent in older long-period pulsars, suggesting that it signified the onset of the final stages of the neutron star's life as an active radio pulsar. Since most pulsar surveys have short ($<$few minutes) integration times, there is an obvious selection effect against nulling objects. Means of overcoming this effect are to look for individual pulses in search data [51], survey the sky many times, or use longer integrations. Indeed, 35-min pointings in the Parkes multi-beam survey have been particularly successful in this regard, discovering a number of nulling pulsars [69].

Radio intermittency. Recently, a new class of "sometimes pulsars" has been found. These provide unique and new insights into neutron star physics and populations [28]. The prototype, PSR B1931+24, shows a quasi-periodic on/off cycle in which the spin-down rate increases by $\sim$50% when the pulsar is in its on state compared to the off state! While the behaviour of this pulsar appears to be linked to the increase in magnetospheric currents when it is on, there is no satisfactory explanation for this effect. Since PSR B1931+24 is only visible for 20% of the time, we can readily estimate that there should be at least five times as many similar objects. We believe this number may be severely underestimated. It is important to establish how many similar objects exist, and what the related timescales of their non-emitting state are. An even more extreme class of intermittent neutron stars are the so-called rotating radio transients (RRATs; [47]) which are reviewed by Mclaughlin in this volume.

1.4 Techniques to Account for Observational Selection

Although the source-counting trick mentioned in Sect. 1.2 gives us an idea of the size of the underlying population, to make further inroads, we really need to make full use of all available data. From an observationally-biased sample, we seek to characterize the underlying population accounting for the aforementioned selection effects. For a given survey of integration time, τ, and bandwidth, $\Delta\nu$, the quantity

$$S_{\rm min} \sim \frac{T_{\rm sys}}{G}\sqrt{\frac{W/P}{\Delta\nu\tau}} \tag{1.1}$$

is the limiting sensitivity to pulsars of a certain period, P, and post-detection pulse width, W, given an antenna with gain, G, and system temperature, $T_{\rm sys}$. In practice, survey thresholds vary as a function of sky position and pulsar parameters. The problem is best tackled using a Monte Carlo approach which attempts to model these subtleties. Below we outline two contrasting techniques to make inferences about the underlying population.

1.4.1 Population Inversion Techniques

The first method, originally developed by Large [33], is of particular interest to determine the spatial distribution of the parent population. Given the observed distribution $N(P,z,R,L)$ in terms of period, P, distance from the Galactic plane, z, Galactocentric radius, R, and luminosity, L, we may write

$$\mathrm{d}N(P,z,R,L) = V(P,z,R,L)\,\rho(P,z,R,L)\;\mathrm{d}P\,\mathrm{d}z\,\mathrm{d}R\,\mathrm{d}L, \tag{1.2}$$

where V is the volume of the Galaxy effectively searched and ρ is the underlying (true) distribution of the population. Since we know N and can estimate V on the

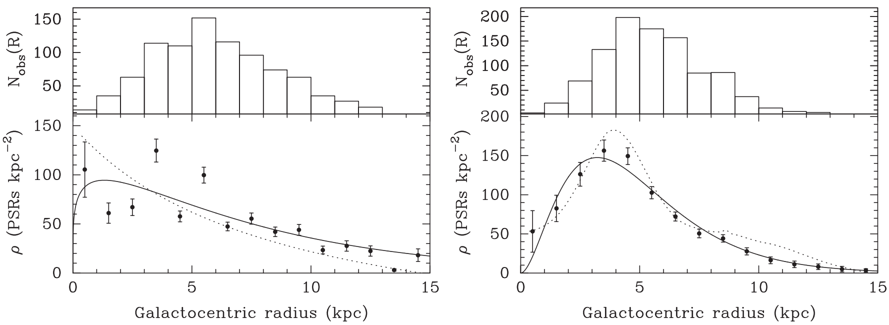

Fig. 1.5 *Left*: the observed radial distribution (*top panel*) and corrected Galactic radial density function $\rho(R)$ (*lower panel*) derived using the electron density model derived by Lyne, Manchester and Taylor [42]. *Right*: the observed and corrected density functions derived using the [15] model. In both cases, the *dotted curves* show the assumed form of the radial distribution used, while the *solid lines* shows a fit to the corrected distribution (after [38])

basis of pulsar survey sensitivities,[1] we can invert (1.2) to solve for ρ. The only simplification required to do this is to assume that P, z, R and L are independent quantities. Fortunately, apart from a very weak coupling between P and z, there are no significant relationships between any of these parameters. The problem then reduces to four equations which can be solved for the underlying distributions: $\rho_P(P)$, $\rho_z(z)$, $\rho_R(R)$ and $\rho_L(L)$.

Of particular interest is ρ_R, the underlying radial pulsar density. For many years, the standard reference for ρ_R was Lyne, Manchester and Taylor [42]. Their results were approximated in most subsequent work using a Gaussian distribution for ρ_R (e.g. [49]). However, as can bee seen from Fig. 4 of their paper, the form of ρ_R at small R is poorly constrained [6] and there is no reason to prefer a Gaussian over a function which tends to zero at small R. Using the results of the Parkes multi-beam survey, which has discovered many more pulsars in the inner Galaxy, [38] revisited this question and their results are shown in Fig. 1.5. They found that the underlying form of any radial distribution derived from the current sample is closely coupled to the assumed distribution free electrons assumed to calculate pulsar distances. Further progress on the radial density distribution of pulsars requires independent distance estimates for more pulsars in the inner Galactic quadrants. Another possibility worth exploring would be to treat the electron density distribution as a free parameter in future studies.

1.4.2 Monte Carlo Population Synthesis

The above technique can be regarded as a "snap-shot" approach to the problem. It makes no attempt to incorporate time-dependent effects such as period and

[1] For any given pulsar with luminosity L and survey with sensitivity $S_{\min}$ defined in equation (1), $V = (L/S_{\min})^{3/2}$. This needs to be computed over the whole sky for various survey thresholds using a Monte Carlo simulation.

luminosity evolution, which may be significant. By far the most common means to investigate the pulsar population has been via full-blown population syntheses which attempt to follow the birth, life and death of pulsars and the survey detection thresholds. The main problem with this approach is in reconciling the many assumptions necessary in such a simulation. Indeed, many of the details of the model (e.g. magnetic field evolution) are virtually a matter of personal taste and different authors have different preferences on what principles to adopt. In one of the most recent approaches of this type, [18] have detailed a comprehensive approach to this problem and describe a model which appears to mimic many of the observed population characteristics.

Following an earlier review of pulsar statistics [48], we can summarize the essential ingredients of a population synthesis by the following pseudocode. For each model pulsar, we need to:

1. Generate an initial position in the model galaxy based on some assumed R and z distributions and assuming either axisymmetry or spiral arm structure
2. Generate an initial 3-D velocity with respect to the local standard of rest
3. Generate an age from a flat distribution out to some maximum time, $T_{\rm max}$
4. Generate a birth spin period and magnetic field from some preferred distribution functions
5. Solve the equation of motion in a model for the galactic gravitational potential to compute the current position and velocity
6. Solve a model for the pulsar spin evolution to compute the current period and period derivative
7. Generate a pulse width from some radiation beam model and determine whether the pulsar is observable from the Earth
8. If the pulsar is observable, generate a luminosity using some simple model $\left(\text{e.g. } L \propto f(P,\dot{P})\right)$ and hence compute the flux observed from the Earth
9. Decide, based on models for major pulsar surveys, whether this pulsar is detectable

This sequence would then be carried out for $N_{\rm model}$ model pulsars, where the resulting model birth rate is $N_{\rm model}/T_{\rm max}$. By comparing the resulting model detectable pulsars with the observed sample, it is possible to optimize the model parameters and investigate the results of different assumptions. For further discussion on the philosophy of this approach, the interested reader is referred to [18].

1.5 Outstanding Problems

In view of the difficulties in correcting for these selection effects, and the inherent problem of small-number statistics, many controversies have pervaded pulsar statistics over the years. I review here a personal selection of some of the many unsolved topics. My apologies to those who have, to their satisfaction, already solved these problems!

1.5.1 Population Size and Birth Rate

How many radio-active pulsars are in our Galaxy and its globular cluster systems? What is the birth rate of normal and millisecond pulsars? How do they compare to their proposed progenitor populations? What fraction of neutron stars are born as radio pulsars? These are perhaps the most fundamental of all questions in this field, yet a satisfactory answer to them is still not known. A combination of small-number statistics, uncertain assumptions about the beaming fraction and errors in the pulsar distance scale (which carry over to the luminosity function) have conspired to produce a wide range of estimates ranging by four orders of magnitude from 10 pulsars per century (e.g. [63]) to 0.001 pulsars per century [2] for the normal population.[2]

A recent birth rate calculation was carried out by [68] using a sample of 815 normal pulsars from the Parkes multi-beam survey. By analysing the flow or "current" of pulsars across the P–$\dot{P}$ diagram [52, 67], the total birthrate of the population was found to lie between 1–2 pulsars per century for 1,400-MHz luminosities above 1 mJy kpc^2. Dividing the population into groups according to magnetic field strength, Vranesevic et al. found that over half of the total birthrate is contributed by pulsars with fields $>2.5 \times 10^{12}$ G. This is in spite of the fact that such pulsars make up less than 30% of the observed sample and, based on their scale factors, only about 5–10% of the total population.

The main problem with birth rates determined from pulsar current analyses is that they are inherently lower limits, since they do not account for pulsars with luminosities below the sample limit (1 mJy kpc^2 in the above case). The all-encompassing nature of the Monte Carlo approach is not subject to such limits and provides an estimate of the true birth rate of the population. The most recent analysis of this kind [18] finds the birth rate in their optimal model to be 2.8 ± 0.1 pulsars per century. However, as noted by these authors, the true uncertainty in this number is likely to be larger by a factor of 5 when accounting for the various model assumptions and plausible input parameter ranges.

While the birth rate of millisecond pulsars is significantly smaller than for normal pulsars (e.g. [44]), it is not clear whether their proposed progenitors, the low-mass X-ray binaries, can account for the whole population. This latter issue is the well publicized "millisecond pulsar birth rate problem" [29]. More recent studies, using a larger sample of objects, have shown that the discrepancy was most likely due to small-number statistics. The current consensus, for the Galactic disk population, is that the millisecond pulsar population is consistent with the low-mass X-ray binaries [44].

[2] I have taken extreme values from the literature to make the point here. See the caveats made in both the cited papers before taking these numbers too literally!

1.5.2 The Birth Spin Periods of Pulsars

The initial spin period distribution of pulsars has been the topic of much debate. Although earlier studies found the data to be consistent with all pulsars being born with short periods ($\sim$20 ms; e.g. [42]), other authors find evidence for a broader distribution (e.g. [67]). The latter authors used a pulsar current analysis and found evidence for a step function at $P = 0.5$ s in their distribution of pulsar current. This was claimed as evidence for an "injection" of pulsars into the population with $P \sim 0.5$ s. Subsequent studies have either confirmed (e.g. [49]) or refuted these claims (e.g. [35]). In the recent pulsar current analysis of [68], the observed distribution of pulsar current is consistent with up to 40% of all pulsars being born with periods in the range 0.1–0.5 s. Similar results were found by [38] using a slightly larger sample.

1.5.3 Period Evolution and Field Decay of Isolated Pulsars

The classic model for spin-down of an isolated pulsar is to write the braking torque as a generalized power law. For an angular velocity $\Omega = 2\pi/P$, the equation of motion is given by $\dot{\Omega} = K\Omega^n$, where K is proportional to the braking torque and n is the so-called braking index. For a constant value of K and pure magnetic dipole braking $n = 3$, the equation of motion on the P–$\dot{P}$ diagram is such that pulsars follow a slope of -1 in a log–log plot like Fig. 1.2, i.e. along the lines of constant dipole magnetic field.

The dipolar braking hypothesis can be tested for a handful of young pulsars, where timing measurements provide n. So far, all six measured values of n are consistent with a flat distribution in the range 1.4–2.9. In other words, all of the pulsars with measured values of n are moving along lines with slopes greater than -1 on the P–$\dot{P}$ diagram. When these vectors are plotted (see, for example [40]) one sees that the directions these young pulsars are moving would place them above the pulsar island! So the conundrum is, either the pulsars in the island have a different set of progenitors than the young objects, or there is some evolution in the braking index as a function of time.

The evolution in braking index can either be provided by integrating the equation of motion assuming that n is genuinely a function of time, or that K decays with time. In all simulations of the P–$\dot{P}$ plane that I am aware of to date, the shape of the diagram is reproduced by modeling the evolution of K with time. Excellent fits to the observed diagrams (see, for example, Fig. 8 in [20] can be obtained by decay laws of the form $K(t) \propto \exp(-t/t_D)$ for decay times t_D of a few million years. This is usually interpreted as exponential decay of the magnetic moment of the neutron star on a timescale of a few million years. While earlier versions of these simulations were criticized [66] as not taking into account period dependent beaming, the work of [20] does, I believe, account for this effect and still prefers a short magnetic field decay time. Recently, [14] have proposed a new model for pulsar spin-down where the inclination angle between the spin and magnetic axes of the neutron star are taken into account. This model seems to explain the P–$\dot{P}$ distribution and the observed braking indices and appears to be very promising. Further investigation of this model are required.

Despite the good agreement on the P–$\dot{P}$ plane, there are a number of vexing issues: (a) spontaneous decay of the magnetic field on such short timescales is inconsistent with the observations of millisecond pulsars which have Gyr ages and yet field strengths at the level of 10^8 G; (b) the exponential model is inconsistent with all braking index measurements, since it always predicts an effective $n \geq 3$; (c) in principle, the same behaviour could be reproduced by modeling the evolution of n rather than field decay; (d) what is the ultimate fate of low-braking-index pulsars? For example, the Vela pulsar has $n = 1.4$ [43] and is moving towards the magnetars on the P–$\dot{P}$ diagram, rather than the pulsar island. Lyne [40] proposed that such objects might be the progenitors of the magnetars. This idea requires further investigation.

1.5.4 Statistical Puzzles in the Millisecond Pulsar Population

Twenty-five years after the discovery of the first millisecond pulsar [4], the sample of these objects currently known is now close to 200, with the majority being found in searches of globular clusters (for a review, see [12]). While searches in clusters are far from straightforward, finding millisecond pulsars in the Galactic disk is a difficult endeavor due to the dispersive and scattering effects of the interstellar medium which hamper their detection. Indeed, only 55 out of roughly 1,500 pulsars (4%) currently known in the Galactic disk are millisecond pulsars. Despite this low fraction, the numbers are now at the level where statistically significant trends can be identified in the sample and inferences made about the underlying population.

One such example is the apparent difference in luminosities between isolated and binary millisecond pulsars, first noted by Bailes et al. [7] from 430-MHz observations, in which isolated millisecond pulsars were on average fainter than their binary counterparts; this trend was also seen by [27] in 1,400-MHz data. More recently [34] revisited this issue from a different perspective. They found that, while the velocity distribution of the isolated millisecond pulsars is compatible with that of binary systems, there appears to be a difference in the distribution of heights above the Galactic plane for the two populations, with solitary millisecond pulsars being more tightly clustered than the binary systems. As discussed by Lommen et al., given identical velocity dispersions, the only way to explain the different scale heights would be if the isolated millisecond pulsars are truly fainter on average and therefore easier to detect closer to the Earth and hence closer to the Galactic plane. If the luminosity difference is a real effect, then it represents an important clue to the origin of millisecond pulsars.

Lorimer et al. [39] have recently revisited this issue using an updated sample of millisecond pulsars. While they confirm the effect seen by Bailes et al. [7] from samples of pulsars selected by 430-MHz surveys, the same trend is not apparent in surveys carried out at 1,400 MHz. There are two possible explanations as to why the luminosity difference is not seen in both the 430-MHz and 1,400-MHz samples. The first possibility is that the high-frequency sample does not probe the luminosity function as deeply as the low-frequency sample. From the current data, it remains a tantalizing possibility that the effect is only seen in the 430-MHz sample which is more sensitive to the low end of the luminosity function than at 1,400 MHz.

A second possibility is that the difference is due to a selection effect. It is well established [44] that 430-MHz surveys probe only the local population of millisecond pulsars out to a distance of 2–3 kpc at most due to propagation effects in the interstellar medium. As a result, samples of pulsars from these surveys tend to be stacked in favour of nearby low-luminosity objects. For any reasonable luminosity function, the high-luminosity pulsars are rarer objects. If isolated millisecond pulsars are simply less numerous than their binary counterparts, small-number statistics will therefore bias the sample in favour of low luminosity objects as there is a greater chance of having a low-luminosity pulsar in the sample compared to a higher luminosity one.

Through simulations, Lorimer et al. [39] confirm that this effect could play a significant role in the observed sample. When averaged over many simulations, the median 430-MHz luminosity of the sample with 10 pulsars was 20% lower than the larger sample. Based on the currently available data, they conclude that there is no requirement for the isolated pulsars to have different spatial, kinematic or luminosity distributions than binary millisecond pulsars. It remains a mystery, however, as to whether isolated millisecond pulsars formed through a different underlying process.

A related issue concerns the origin of the 6.2-ms pulsar B1257+12, the only pulsar planetary system known in the Galactic disk [71] and is something of an anomaly among the millisecond pulsar population. The three planets (A, B and C) in the system known so far have orbital periods of 25, 67 and 98 days with masses of 0.02, 4.3 and 3.9 Earth masses respectively [26]. The one other planetary system known, PSR B1620–26, in the globular cluster M4 could have formed through exchange interactions in the cluster [60]. However, such interactions are not expected in the Galactic disk. Did the planets in the form from a debris disk of circum-pulsar material? Why are planets not seen around other Galactic millisecond pulsars? Although small planets such as A in the 1257 system could be undetectable in some millisecond pulsar timing (e.g. [39]), the signals from higher mass planets such as B and C would be unmistakable in timing residuals. Based on the current sample, the fraction of millisecond pulsars with planets appears to be less than $1/55 \sim 2\%$.

1.5.5 Where Are All the Isolated "Recycled" Pulsars?

The discovery of new pulsars often sheds light on previously unseen areas of the neutron star "zoo" which likely represent quite rare evolutionary processes. One example is the discovery of two isolated pulsars J2235+1506 [13] and J0609+2130

[36] with spin properties similar to the double neutron star binaries. Camilo et al. suggested that J2235+1506 might be the remains of a high-mass binary system that disrupted during the second supernova explosion.

Is this hypothesis consistent with the observations? One way to test this is to consider the fraction, η, of binary systems that remain bound after the second supernova explosion. Numerous authors have followed the orbital evolution of a wide variety of binary systems containing neutron stars using detailed Monte Carlo simulations. For example, [53] find $\eta \sim 4\%$. We therefore expect for each double neutron star system we observe to find of order 20 systems which disrupted. Currently we know of eight double neutron star binaries. Why, then, do we not see of order 160 pulsars like J0609+2130 or J2235+1506? [5] suggests that this could be reconciled if the kick velocities to the neutron stars in these systems are not as high as the bulk of the population. This currently outstanding problem may indicate a different evolutionary scenario for these objects and warrants further study.

1.5.6 How Much Do We Understand About Globular Cluster Pulsars?

Following the early globular cluster discoveries, a detailed analysis by [30] characterized the population properties of globular cluster pulsars and found their total active population to be $\sim 10^4$. Such a large population appeared to be far higher than could be explained by low-mass X-ray binaries alone and suggested that there is an even greater birthrate problem in cluster millisecond pulsars than in the Galactic disk. Unlike the disk population, the problem has so far not been resolved; this may be a selection effect – to my knowledge, the work of Kulkarni et al. has not been superceded.

With the recent renaissance in globular cluster discoveries reviewed [12], the population of pulsars known in clusters has undergone a four-fold increase. Although some care will be necessary to model the effects of interstellar scintillation and Doppler smearing due to rapid orbital motion, two selection effects which are very important in globular cluster surveys, there is clearly now much to be learned from a systematic study of the latest results. Some key questions are: what is the number and birth rate of cluster pulsars? what conditions (if any) are necessary for pulsar production in clusters? how many relativistic binaries are there in clusters, and what impact do these systems have on the cosmic rate of binary inspiral?

1.6 Concluding Remarks

Pulsar astronomy is currently enjoying the most productive phase of its history, with applications providing a wealth of new information about compact-object astrophysics, general relativity, the Galactic magnetic field, the interstellar medium, binary evolution, planetary physics and even cosmology. Our understanding of the Galactic pulsar population has improved dramatically thanks largely to the success of the Parkes multi-beam survey [46]. Astronomers are currently active in a number of new surveys which will bring significant advances in sensitivity.

At Parkes, a multi-beam survey at 6 GHz is currently underway covering the inner Galaxy for highly dispersed and scattered pulsars. A 1.4-GHz multi-beam survey now underway at Arecibo should discover over 300 normal pulsars [38]. To date, around 40 pulsars have been found [16] with the most exciting object so far being the highly relativistic binary PSR J1906+0746 [37]. The superior period sensitivity of ALFA over other surveys at Parkes suggest that a substantial number of millisecond pulsars will also be found. Searches with the 100-m Green Bank telescope (GBT) are currently focusing on globular clusters, where 56 pulsars have so far been found – about half of all currently known cluster pulsars! Plans are also afoot, however, to survey the sky at 350 MHz with the GBT. Following earlier pilot studies (Hessels, Ransom et al., private communication) which discovered several new pulsars, drift-scan surveys will commence in summer 2007 with the aim of covering much of the sky in the coming 5 yr. Simulations we have carried out suggest that of order 100 millisecond pulsars could be discovered by the GBT.

In the Netherlands, a 328-MHz pulsar survey is being carried out in a "grating array" mode using the Westerborg synthesis radio telescope [58] in which multiple sub-beams are formed within the large primary beam of the array. So far a number of pulsars have been found and under investigation. The multi-beaming concept is likely to be technology used here is likely to be exploited further with the planned Low Frequency Array (LOFAR; `lofar.org`) which is expected to find of order 1,500 pulsars in surveys carried out at frequencies at or below 200 MHz [61]. LOFAR would be a fantastic probe of the local pulsar population and provide vital new constraints on the low end of the shape of the luminosity function.

These and other up and coming surveys are only a precursor for what might be possible with the Square Kilometer Array (SKA), an ambitious world-wide collaboration currently planned for the year 2020 (see `skatelescope.org`). Simulations for pulsar surveys with this instrument demonstrate that the increase in sensitivity of the SKA (around two orders of magnitude over current radio telescopes!) would mean that essentially every Galactic pulsar beaming towards us (of order 30,000 objects!) could be detectable. Perhaps by the year 2030, the sample of radio pulsars will be finally free of selection effects.

An Open Approach to Pulsar Population Syntheses

The Monte Carlo techniques used in Sect. 1.4 have been implemented by a number of authors over the years. As mentioned in Sect. 1.5, there are examples of similar modeling treatments reaching different conclusions. Indeed, Andy Fruchter once applied Benjamin Disrali's famous quote to this field, saying that "there are lies, damned lies and pulsar statistics". Although perhaps a little facetious,