

# Radio pulsar populations

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**Abstract** The goal of this article is to summarize the current state of play in the field of radio pulsar statistics. Simply put, from the observed sample of objects from a variety of surveys with different telescopes, we wish to infer the properties of the underlying sample and to connect these with other astrophysical populations (for example supernova remnants or X-ray binaries). The main problem we need to tackle is the fact that, like many areas of science, the observed populations are often heavily biased by a variety of selection effects. After a review of the main effects relevant to radio pulsars, I discuss techniques to correct for them and summarize some of the most recent results. Perhaps the main point I would like to make in this article is that current models to describe the population are far from complete and often suffer from strong covariances between input parameters. That said, there are a number of very interesting conclusions that can be made concerning the evolution of neutron stars based on current data. While the focus of this review will be on the population of isolated Galactic pulsars, I will also briefly comment on millisecond and binary pulsars as well as the pulsar content of globular clusters and the Magellanic Clouds.

## 1 Selection effects in radio pulsar surveys

The current sample of radio pulsars is now close to 2000 and is continuously increasing thanks to a wide variety of large-scale and targeted searches being carried out at most of the major radio observatories. The approximate rate of discoveries at the current time is about 100 pulsars per calendar year, and we expect this trend to continue and accelerate over the next decade as more powerful facilities come online (both at radio and non-radio wavelengths). An excellent example of recent progress can be seen in the flurry of radio pulsar counterparts to Fermi gamma-ray sources as reported by Ray and Saz Parkinson elsewhere in these proceedings. It is

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important to note, however, that while this sample represents a great improvement over, say, the situation 20 years ago, it still likely only amounts to a few percent of the underlying population of pulsars whose properties we wish to constrain. The main observational selection effects that cause this are summarized below.

### ***1.1 Flux–distance relationship***

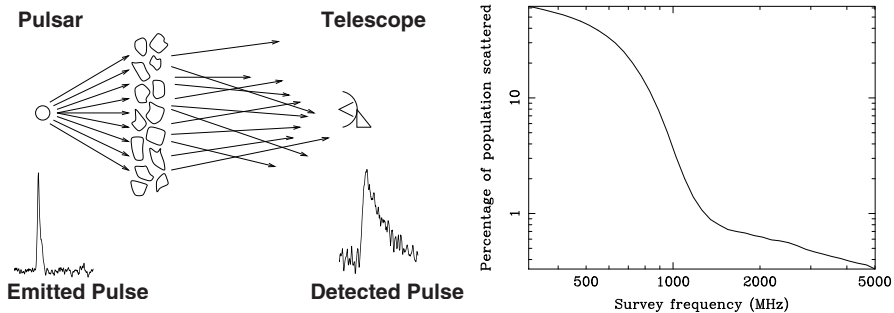
Like all astronomical sources, observed pulsars of a given luminosity  $L$  are strongly selected by their apparent flux density,  $S$ . In a classical Euclidean model, for a pulsar a distance  $d$  from Earth which beams to a certain fraction  $f$  of  $4\pi$  sr, the flux density  $S = L/(4\pi d^2 f)$ . This is known as the inverse square law and is commonly assumed for astrophysical sources. 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 ‘pseudoluminosity’ is quoted at some standard observing frequency; e.g., at 1400 MHz,  $L_{1400} \equiv S_{1400} d^2$ . Recently, the validity of the inverse square law has been called into question by Singleton et al. [1], and that perhaps the flux scales as  $1/d$  instead. It is important to fully investigate this claim. As Singleton et al. point out, if confirmed, it would have dramatic implications for many of the conclusions presented here. In a search for radio transients in M31 with Westerbork, Rubio-Herrera [2] has investigated the implications of non- $1/d^2$  scalings on his results and finds that many more transients should have been observable for a  $1/d$  law, and that a  $1/d^2$  law is consistent with the number of candidates seen. For now, we note that any flux–distance relationship will bias the sample towards bright and/or nearby objects.

### ***1.2 The radio sky background***

A fundamental sensitivity limit on any radio observation is the system noise temperature, normally expressed in Kelvins as  $T_{\text{sys}}$ . 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,  $T_{\text{sky}}$ . At observing frequencies  $\nu \sim 0.4$  GHz,  $T_{\text{sky}}$  dominates  $T_{\text{sys}}$  for observations along the Galactic plane. Fortunately,  $T_{\text{sky}} \propto \nu^{-2.8}$  so this effect is significantly reduced when  $\nu > 0.4$  GHz.

### ***1.3 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. Fortunately, like  $T_{\text{sky}}$ , the scatter-broadening time  $\tau_{\text{scatt}}$  has a strong fre-



**Fig. 1** 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.

quency dependence, scaling roughly as  $\nu^{-4}$ . **Fig. 1** 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 [3] affect pulsar detection. For example, two northern sky surveys carried out 20 years apart with comparable sensitivity [4, 5] 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 detectability of intrinsically faint pulsars.

#### 1.4 Finite size of the emission beam

The fact that pulsars do not beam to  $4\pi$  sr means that we see only a fraction  $f$  of the total active population. For a circular beam, Gunn & Ostriker [6] estimated  $f \sim 1/6$ . A consensus on the precise shape of the emission beam has yet to be reached. Narayan & Vivekanand [7] argued that the beams are elongated in the meridional direction. Lyne & Manchester [14], 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. A very popular model assumed by current studies derives from the work of Tauris & Manchester [10] who found that  $f \approx 0.09 [\log(P/\text{s}) - 1]^2 + 0.03$ , 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 and the beaming of millisecond pulsars.

## 1.5 Pulse nulling

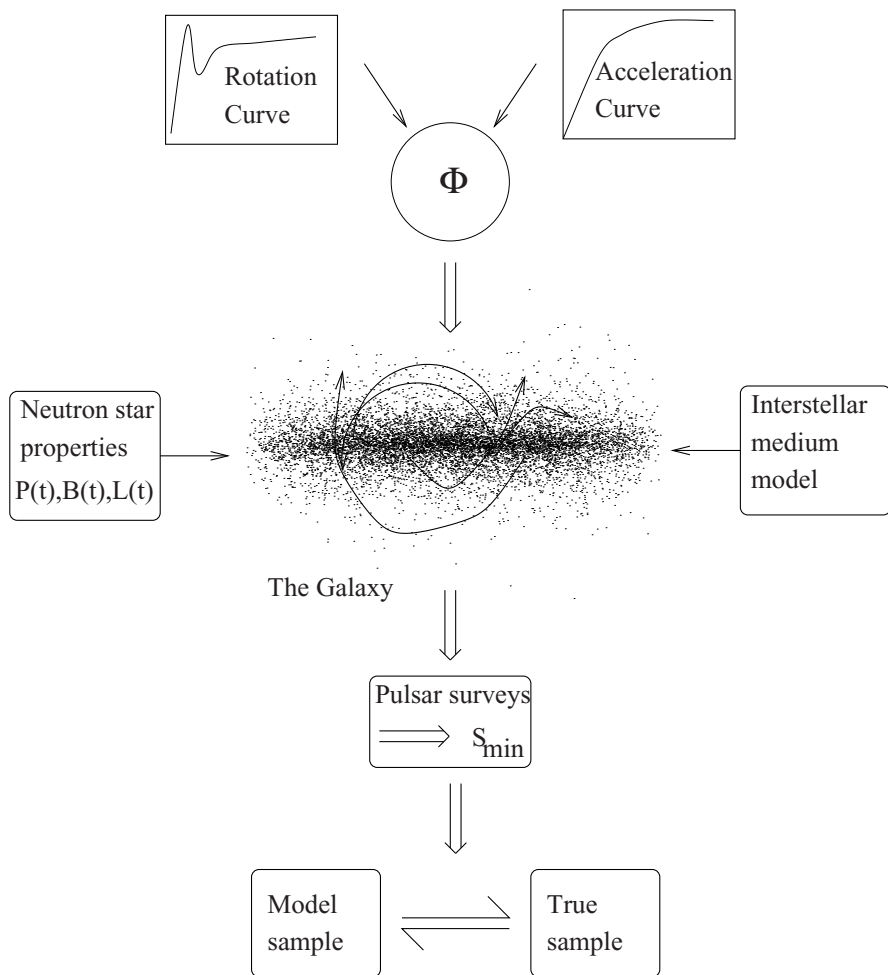
The abrupt cessation of the pulsed emission for many pulse periods, was first identified by Backer [11]. Ritchings [12] subsequently presented evidence that the incidence of nulling became more frequent in older long-period pulsars, suggesting that it signified the onset of the final stages of the neutron star's life as an active radio pulsar. Since most pulsar surveys have short ( $< \text{few min}$ ) integration times, there is an obvious selection effect against nulling objects. Means of reducing the impact of this effect are to look for individual pulses in search data [13], survey the sky many times, or use longer integrations. Indeed, the longer dwell times (35-minute pointings) used in the Parkes multibeam survey have been particularly successful in this regard, discovering a number of nulling pulsars [14].

## 1.6 Intermittency

Recently, a new class of “intermittent pulsars” has been found. These provide unique and new insights into neutron star physics and populations [2]. 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. These pulsars, and their cousins the rotating radio transients (discussed in Section 4.1), remain a very exciting area of current research.

## 2 Correcting the biases in the observed sample

How can we account for the effects discussed above and recover the properties of the underlying pulsar populations? While some progress can be made analytically (see, e.g. the early work of Gunn & Ostriker [6]), the non-uniform nature of all the above effects more readily lends itself to a Monte Carlo approach to modeling pulsar populations and their detection. The two main ways to implement such models can be thought of as either a fully dynamical approach or a static “snapshot” model. For the former case, a simulation is created in which a model galaxy of pulsars is seeded according to various prescriptions of birth locations and initial rotational parameters. Each of these synthetic pulsars is then “evolved” both kinematically in a model for the Galactic gravitational potential and rotationally using a model for neutron star spin-down. The properties of the resulting population are then saved.



**Fig. 2** Schematic summarizing a fully dynamical Monte Carlo simulation of the Galactic pulsar population. The main ingredients are the model gravitational potential ( $\Phi$ ), some prescription for the neutron star evolution with time and a model of the interstellar medium. Pulsars whose apparent flux densities exceed those of the main surveys ( $S_{\min}$ ) are saved and the resulting “model sample” is compared to the actual sample of pulsars detected by those surveys.

Using detailed models for the pulsar surveys, it is possible to compute whether each synthetic pulsar is actually detectable and the properties of these “observable” pulsars are saved. These samples may then be compared to the real observed sample to assess the validity of the Monte Carlo model. The process is summarized in Fig. 2. The snapshot approach differs from the fully dynamical approach in that the pulsars are seeded at their final positions in the model galaxy without assuming anything about spin-down or kinematic evolution and thus form a picture of the current-day population. To model pulsar detectability, both approaches are based around the well-known pulsar radiometer equation [16] which has been demonstrated to provide an adequate description of the sensitivity of pulsar surveys [17].

The advantage of the snapshot approach over the dynamical one is that it is simpler, requiring fewer assumptions about motion in the galaxy or spindown and can often be optimized to form a model with a unique best solution. Its major downfall, however, is that its simplicity means that it says very little if anything about the progenitor population. Fully dynamical models provide insights into these details, and can for example describe the distribution of pulsars in  $P$  and  $\dot{P}$  space about which the snapshot approach is blind to. However, as discussed below, a major point to keep in mind is that there is often no unique model that can describe the data and some care needs to be exercised when interpreting the conclusions.

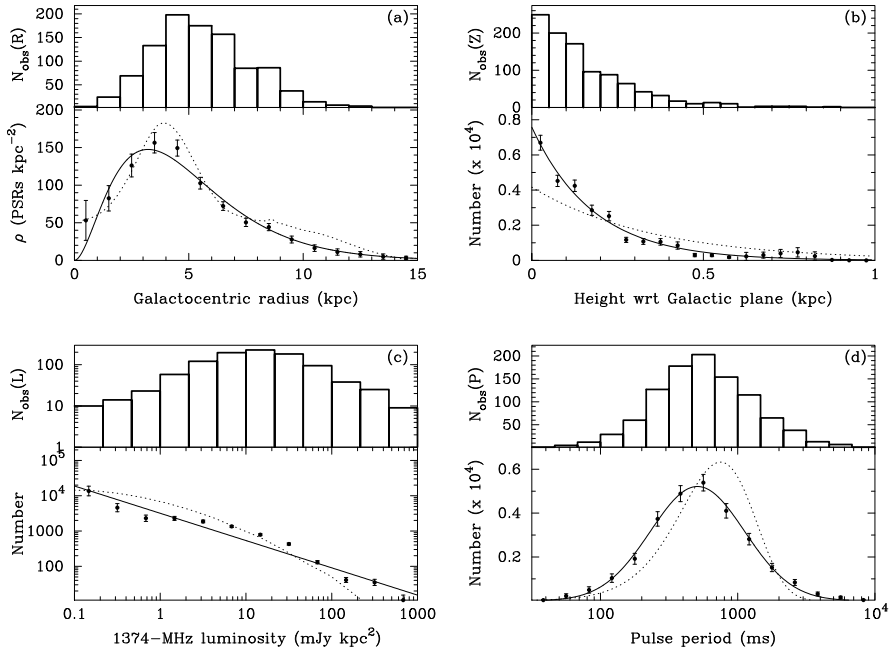
### 3 Recent results

With these caveats in mind, we now briefly review some of the latest findings of studies which adopt either the snapshot or full dynamical modeling approach.

#### 3.1 Pulsar space distribution

Models of the Galactic distribution of pulsars have been constructed from observationally biased samples for many years [18, 19, 20]. These studies typically follow the snapshot approach in which the population can be represented in terms of four independent distribution functions: Galactocentric radius  $R$ , vertical dispersion from the Galactic plane  $z$ , pulse period  $P$  and luminosity  $L$ . In a recent approach of this kind [21], we investigated models which accounted for the observed distribution of pulsars seen by the Parkes Multibeam Pulsar Survey [22] which provides the largest uniform sample (over 1000 Galactic pulsars) for such analyses. Using an iterative Monte Carlo approach, we found that it is possible to find a unique model which converges to the same functional form regardless of the initial shape of the distribution functions in  $R$ ,  $L$ ,  $z$  and  $P$ . An example of the model output is shown in Fig. 3 which contrasts the underlying and observed distribution functions for the final model. The  $L$ ,  $z$  and  $P$  distributions show the number of pulsars as a function

of each parameter. For  $R$ , the results are shown as the projected surface density of objects on the Galactic plane,  $\rho(R)$ .



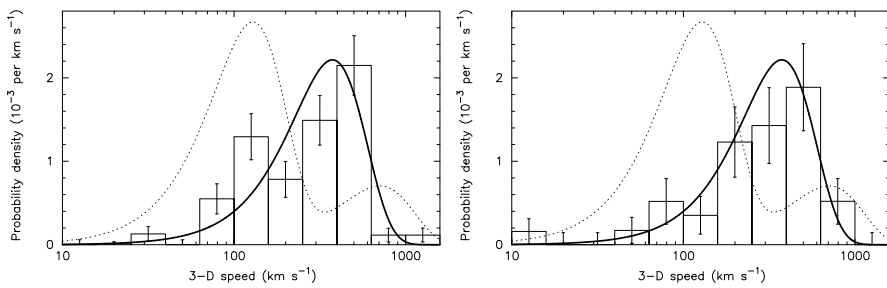
**Fig. 3** Observed number distribution from our input sample (upper panels) and derived distributions (lower panels) for the parameters: (a)  $\rho(R)$ ; (b)  $z$ ; (c)  $L$ ; (d)  $P$ . The solid curves are smooth analytic functions fitted to the data (see [21] for details). The dotted curves show: (a) the assumed radial density function of free electrons (from the NE2001 electron density model); (b) an exponential  $z$  distribution with a scale height of 350 pc; (c) a log-normal fit to the optimal pulsar population model derived by [23]; (d) a period distribution derived from studying pulse-width statistics [24].

One important limitation of this approach is that the form of the spatial distributions  $R$  and  $z$  depends heavily upon the assumed model for the Galactic distribution of free electrons. The model shown in Fig. 3a assumes the commonly used “NE2001” model [25]. An example of this dependence is the  $R$  distribution in which the pulsars naturally follow the  $R$  distribution of free electrons. While the NE2001 model achieves a high level of sophistication, including electron density enhancements in spiral arms, and can account for a wide variety of observations, it is known to have a number of shortcomings [26, 27] which are currently being addressed in a new model (Cordes, private communication). In Fig 3b, for example, it is seen that the optimal model  $z$  distribution is significantly larger than observed — this is a direct result of the NE2001 electron scale height [21]. It is conceivable that future population studies with larger samples of pulsars could be carried out where the distribution of free electrons is allowed to vary. At the current time, however, one

should be mindful of the fact that any conclusions about the spatial distribution of pulsars are strongly coupled to models of the free electron density.

### 3.2 Pulsar velocities

A number of studies of the birth velocities of pulsars have been carried out over the years and there has been much debate as to whether the distribution for nonrecycled pulsars is unimodal [28] or bimodal [29, 30]. Recent studies [31, 23] find no compelling evidence to model the distribution with multiple components and the individual 1-D components of the pulsar's birth velocity vector follow either a Gaussian [31] or exponential form [23] with a mean value in the range 400–500 km s<sup>-1</sup>.



**Fig. 4** Normalized 3-D velocity probability density functions obtained from the observed 1-D (left) 2-D (right) distributions using a deconvolution technique [31]. The uncertainties on each histogram bin are calculated as the square root of the number of pulsars in each bin. The dotted curve shows the 3-D distribution favoured by Arzoumanian et al. [30]. The solid curve is the best-fitting Maxwellian distribution to the histogram from the 2-D distribution with  $\sigma = 265$  km s<sup>-1</sup>.

Fig. 4 shows the results of a deconvolution process from Hobbs et al. [31] where the 3-D space velocity distribution may be derived self consistently by appropriately deprojecting either the 1-D or 2-D distributions of young pulsars (defined to be those with characteristic ages less than 1 Myr). As can be seen, a previously suggested two-component model is not implied by these data. While it is found for millisecond and binary pulsars that the velocity distribution is different to the normal pulsars shown here, the main conclusion to take away from current results is that the distribution of velocities for isolated radio pulsars is unimodal.

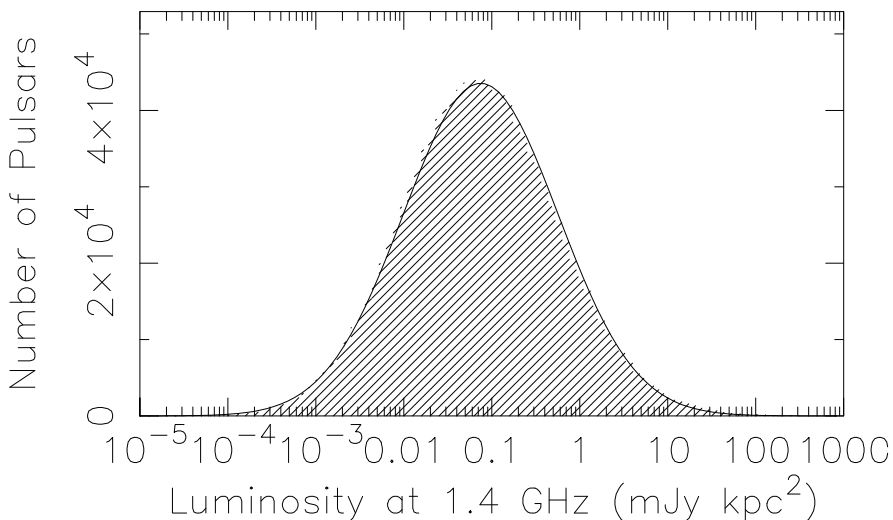
### 3.3 Pulsar luminosities

Because of the strong connection between distance and luminosity, any uncertainty in the pulsar distance scale propagates through to an uncertainty in the luminosity function [32]. Two critical questions concerning pulsar luminosities we wish to an-



swer are: (1) what, if any, evolution in luminosity is there with pulsar age? (2) what is the shape of the luminosity function? The idea of a decay in luminosity has been in the literature for some time. Taylor & Manchester [19] have pointed out that the simple fact that the distribution of pulse periods tails off at long periods demands that the luminosity decays with time. If the luminosity were constant, many more pulsars would be observed. This can be readily shown via simulations in which assigning the luminosity to a pulsar at random results in a pile up of pulsars at high  $P$  and low  $\dot{P}$  which is not observed in the real sample [23].

The exact form of the luminosity decay remains contentious, however. While the best dynamical models can account for the observed data with a simple power law model in which  $L \propto P^\alpha \dot{P}^\beta$ , the values of the exponents  $\alpha$  and  $\beta$  are neither readily found from fits to the observed population [33] nor are uniquely constrained from the dynamical modeling [34].

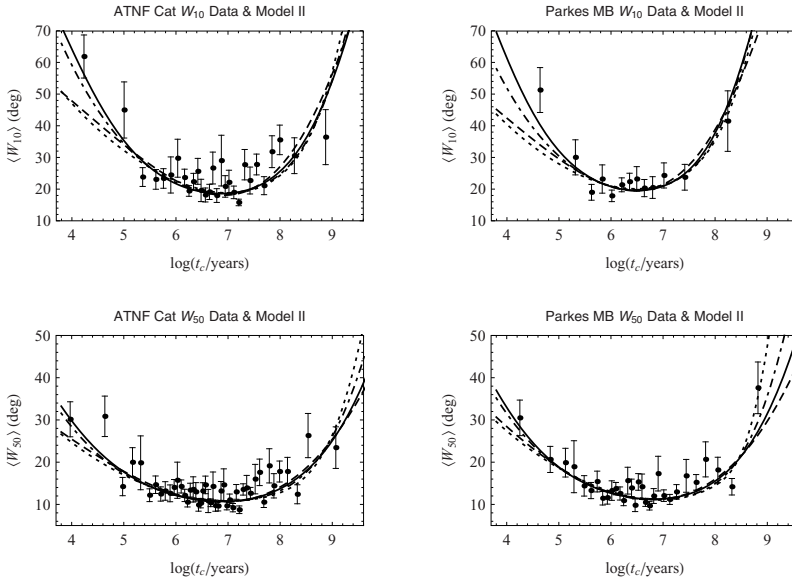


**Fig. 5** Results from Faucher-Giguère & Kaspi [23] which show the underlying luminosity function (defined to be at a frequency of 1.4 GHz) for their optimal model of the isolated pulsar population. The solid line shows a Gaussian fit to the data where the mean of the distribution in  $\log L$  is  $-1.1$  and the standard deviation is  $0.9$ .

One result that does appear to be robust is the form of the luminosity distribution. While the snapshot models typically favour some sort of power-law distribution for the number of pulsars  $N(L)$  in which  $d \log N / d \log L \sim -1$ , they remain agnostic about the distribution of luminosities *below* the minimum value in the observed sample,  $L_{\min}$ . The dynamical approach suggests that the underlying shape of the luminosity function is log-normal in form [23]. The parent luminosity distribution from this simulation is shown in Fig. 5. Simulations with different spin-down models all appear to show the same basic shape [34, 35] Whether this distribution applies to millisecond pulsars is currently unclear.

### 3.4 Magnetic alignment

Recently, two groups have provided strong evidence that the angles between the magnetic and spin axes of neutron stars are not random and, in fact, appear to decay on a timescale of  $10^7$  yr or less. Weltevrede & Johnston [36] provide strong empirical evidence for such magnetic alignment based on the statistics of pulsars which exhibit interpulses. They point out that the fraction of pulsars whose profiles can be described by viewing an orthogonal rotator is strongly linked to the stars' rotational period, with a much higher interpulse fraction observed at longer periods than would be expected from randomly inclined lighthouse beams. Unless the observational sample is in some way biased, their conclusions appear to be irrefutable. In an independent approach, Young et al. [37] also find evidence for magnetic alignment from an analysis of the pulse width statistics of pulsars. They argue, from graphs of pulse width versus characteristic age (see examples in Fig. 6) which show a turn-up at long periods, that only alignment on a timescale of a few million years can explain the increase in pulse width. The two competing effects which shape these curves are the narrowing of pulse widths with period, and the alignment of the magnetic axis which means that older pulsars are more likely to be seen as aligned objects where the emission occupies a larger fraction of the rotational period.

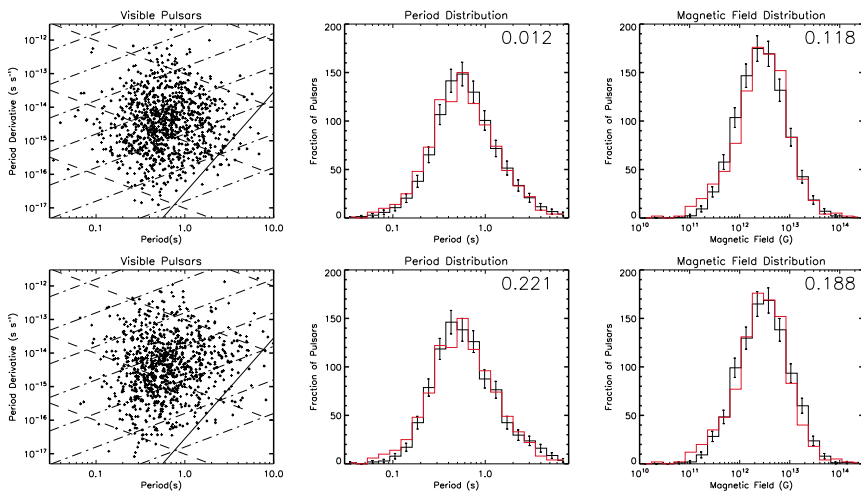


**Fig. 6** Results of model fits by Young et al. [37] to various pulse-width characteristic age relations for Parkes multibeam data. All the models shown include the effects of magnetic alignment on a timescale of a few million years. The increase of pulse widths at large characteristic ages appears only to be explained by the alignment process.

Both the above studies suggest that some sort of alignment is taking place in isolated radio pulsars. As pointed out by Ridley & Lorimer [34] however, this observation throws up a conundrum when one attempts to construct a self-consistent model of spin-down evolution. The standard magnetic dipole model, in which the braking torque is proportional to the square of the sine of the inclination angle, does not do a good job of reproducing the  $P - \dot{P}$  diagram if this angle evolves with time in the manner expected above. Furthermore, the hybrid spin-down model of Contopoulos & Spitkovsky [38] which can account for alignment, appears to provide a very poor description of the observed distribution in  $P - \dot{P}$  space. A more sophisticated model for pulsar spindown is needed which can reconcile these differences.

### 3.5 Magnetic field decay

No discussion of pulsar statistics would be complete without a mention of magnetic field decay — a contentious issue that has raged for the past 30 yr. For many years, it was believed that the magnetic fields of isolated pulsars decayed exponentially on a  $1/e$  timescale of 10 Myr or less [20]. Popular opinion switched toward favouring models with essentially no field decay in the 1990s [39, 40].



**Fig. 7** Results of simulations by Popov et al. [35] which show how comparable results can be found by modeling the population without field decay (upper panels, following the prescription given by Faucher-Giguère & Kaspi [23]) and with field decay (lower panels, following a magneto-thermal model of Popov et al. [35]). Both models give statistically equivalent results. The observed distributions in period and magnetic field strength are shown by the red histograms. Kolmogorov-Smirnov probabilities that the model and observed data are drawn from the same parent population are shown on the top right hand corner of each histogram. The model distributions are shown with statistical error bars. Both models appear to provide equally viable descriptions of the data.

Nowadays, the community is split between no significant magnetic field decay [23, 34] and a decaying field [41, 35]. The simulations shown in Fig. 7 present models of the radio pulsar population with and without the effects of magnetic field decay. Is this another example of covariance between model parameters, or fundamental differences in modeling techniques? For me, the answer remains to be found.

## 4 Final thoughts and future prospects

In this review, I have focused on a number of recent results concerning the population of isolated pulsars. While we have come a long way in understanding the distribution of these object in the Galaxy, their initial velocity dispersion and luminosity function, much remains to be understood in terms of their spin-down behaviour. A model which can account for the observed magnetic alignment, nulling, beaming and spin-down evolution is a major goal for any future study. Some further areas that are ripe for research are summarized briefly below.

### 4.1 *Rotating radio transients*

An even more extreme class of intermittent neutron stars are the so-called rotating radio transients [3]. Their detection was made possible by searching for dispersed radio bursts [43] which often do not show up in conventional Fourier-transform based searches [44]. Since the initial discovery, a significant effort has gone in to searching for and characterizing more RRATs. Over 30 are currently known [45, 46, 47, 48, 49] but only seven have timing solutions, with four of these only recently achieved [49]. Recently, Lyne et al. [50] reported the detection of two glitches in RRAT J1819–1458. While these events are similar in magnitude to the glitches seen in young pulsars and magnetars, they are accompanied by a long-term *decrease* in the spin-down rate, suggesting that it previously occupied the phase space populated by the magnetars. Further observations are needed to confirm this “exhausted magnetar” hypothesis. The Galactic population of such objects is potentially significant and it remains to be determined whether alternative evolutionary scenarios need to be invoked other than core-collapse supernova [51]. Further work will certainly clarify this issue as known sources are better characterized.

### 4.2 *Millisecond pulsars*

For many years, studies of the Galactic population of millisecond pulsars have been plagued by small-number statistics [52]. More meaningful results were obtained during the 1990s with the advent of all-sky surveys of the local population [53]

where it was found that the velocity distribution of millisecond and binary pulsars is significantly lower than that of the normal isolated population discussed above. Presently, with an exponentially growing sample of millisecond pulsars we are in an era where it is possible for the first time to carry out full population syntheses of the Galactic population. Story et al. [54] have carried out much work in this area and have paved the way for future studies, though many questions remain to be answered including: (i) what is the overall Galactic distribution of millisecond pulsars?; (ii) is the millisecond pulsar luminosity function comparable to normal pulsars?; (iii) are all millisecond pulsars produced in low-mass X-ray binary systems?; and (iv) what is the origin of isolated millisecond pulsars?

### ***4.3 Pulsars in the Magellanic Clouds***

Currently 19 radio pulsars are known in the Large and Small Magellanic Clouds [55]. Ridley & Lorimer [56] recently carried out a snapshot analysis of this population assuming the log-normal luminosity function for Galactic pulsars described above. We found that there are roughly 18,000 and 11,000 normal pulsars in the large and small clouds respectively. After accounting for beaming effects, and the fraction of high-velocity pulsars which escape the clouds, the estimated birth rates in both clouds appear to be comparable and in the range 0.5–1 pulsar per century. Although higher than estimates for the rate of core-collapse supernovae in the clouds, these pulsar birth rates are consistent with historical supernova observations in the past 300 yr. A fully dynamical model incorporating the kinematics and spindown of the pulsars in the Magellanic Clouds would be a logical extension of this work.

A substantial population of active radio pulsars (of order a few hundred thousand) have escaped the clouds and populate the local intergalactic medium. For the millisecond pulsar population, the lack of any detections from current surveys leads only upper limits of up to 40,000 sources in the two clouds. A new survey with greatly improved time and frequency resolution currently underway at Parkes could detect a few of these sources (if they exist) and place valuable constraints on the total population. Giant-pulse emitting neutron stars could also be seen by this survey.

### ***4.4 Globular cluster pulsars***

The first pulsar in a GC was found over 20 years ago [57]. Currently, there are 140 radio pulsars in 26 GCs [58]. Progress towards the current sample has proceeded in two phases. In the late 1980s and early 1990s, searches uncovered about two dozen of the brightest objects [59]. Further progress was only made later, around the year 2000, when a combination of advances in high-frequency broadband receivers, software algorithms, computing power and data storage capabilities led to a resurgence of discoveries [60, 61, 62, 63, 64] and interest from observers and theorists [15].

While much of the recent focus on the observational results mentioned above has been on revealing unique systems and their applications for fundamental physics, relatively little attention has been paid on understanding the population of GC pulsars as a whole. In fact, the last major study into GC pulsar statistics were carried out in the late 1980s [80]. A major finding of this work was that the birth rate required to sustain the population of  $\sim 10^4$  MSPs estimated in all GCs was 100 times higher than the birth rate of their proposed progenitors [68], the LMXBs. Since then, the discovery of large numbers of quiescent LMXBs [81] has decreased this disparity, but another potential problem has emerged. If NSs are formed as in the Galaxy, i.e. in the core collapse supernovae of massive stars, then the large resultant velocities observed among the young pulsars [31] would eject the vast majority of all NSs from GCs. This would result in a very small number of primordial NSs in clusters. How do GCs retain enough NSs to form all the quiescent LMXBs and MSPs we observe? Are there other NS formation mechanisms at work? We anticipate significant progress in many of these areas in the near future.

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