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# Millisecond Pulsars

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# Millisecond Pulsars

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Cover illustration: Artistic impression of a millisecond pulsar in a binary system including the magnetic field structure and the surrounding accretion disk. Reproduced from https://svs.gsfc.nasa.gov/10144. Credits: Dana Berry (Skyworks Digital; Lead Animator), Michael McClare (HTSI; writer); NASA.

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# Preface

Observing pulsars provides a unique view of the physics of matter at densities exceeding those of atomic nuclei and magnetic fields not reproducible on Earth. The unparalleled stability and frequency of the pulsations make them very accurate clocks. The discovery of a radio pulsar in the late sixties itself proved the very existence of neutron stars. The quickest spinning pulsars allow attaining the highest accuracy. It is no surprise that pulsars spinning with a period of a few milliseconds had a substantial impact on many fields in astronomy and physics. Modelling the pulse arrival times of the 59 ms Hulse & Taylor binary pulsar unveiled how the orbit was shrinking at the exact rate due to gravitational waves, more than 30 years before the actual detection by the *LIGO/VIRGO* interferometers. Later, a double pulsar system provided the most stringent tests of the predictions of General Relativity to date. The outstanding stability of the spin of millisecond pulsars allowed the masses of two dozen neutron stars to be precisely measured and even discovered the first planets ever detected outside the Solar System. Regularly monitoring arrays of radio millisecond pulsars may unveil the stochastic background of gravitational waves due to the interaction of supermassive black holes at the centre of galaxies. Millisecond X-ray pulsars can even be used as a navigation tool for interplanetary probes, as the recently launched NICER/Sextant mission aims at demonstrating.

*What is the behaviour of the strong nuclear interaction? What are the constituents at ultrahigh densities in neutron star cores? How do old neutron stars in binaries evolve? How does their magnetosphere interact with the surrounding plasma to accelerate particles and emit radiation observed at all wavelengths?* These are just a few of the questions that millisecond pulsars are helping us answer and will settle shortly with the next generation of instruments. Although almost 40 years have passed since the discovery of the first radio millisecond pulsar, their number keeps growing. The progress in high timing resolution detectors and the opening of new observing windows are the key drivers. The late 1990s greeted the discovery of a millisecond pulsar shining at X-ray energies. The GeV gamma-ray band followed in the late 2010s, more recently joined by the visible and the ultraviolet wavebands.

Millisecond pulsars are a very diverse class of sources, as their emission owes to different mechanisms at the various stages of their complex evolutionary history. The *recycling* scenario established an evolutionary link between neutron stars in X-ray binaries being spun-up by mass accretion and radio millisecond pulsars whose emission is due to particles accelerated in their rotating magnetosphere. Incidentally, the discovery of millisecond pulsars in 1982 bridged the community of radio (and later gamma-ray) astronomers who looked for faint coherent signals from pulsars in binaries with X-ray astronomers who dealt with the much brighter accretion-powered binaries. The need for a genuine multi-wavelength approach in the study of these systems has only become more evident with the discovery of millisecond pulsars switching back and forth accretion and rotation-powered regimes over a few days, or perhaps even less.

Currently, we know more than 500 rotation-powered radio millisecond pulsars and two dozen accretion-powered X-ray progenitors. Although the bias in detecting very quickly spinning radio pulsars has considerably diminished, the shortest spin period ever observed (1.4 ms) lies well above the Keplerian break-up limit predicted by most of the equations of state proposed for neutron star matter. Some mechanisms must limit the acceleration imparted by mass accretion. The steady emission of gravitational waves seems a crucial ingredient. Theoretical works are ever more timely, as the sensitivity of gravitational wave detectors starts to graze the expected flux of millisecond pulsars.

The speed and compactness of millisecond pulsars make them truly relativistic objects. They spin so quickly that particles at their equator travel at more than ten per cent the speed of light. Also, the long accretion phase which spun them up made them more massive than younger neutron stars. Special and general relativistic effects significantly modify the trajectory and energy of photons emitted from spots on their surface, such as those observed at X-ray energies from spin-powered millisecond pulsars or during outbursts and thermonuclear bursts in accreting millisecond pulsars. The corresponding oscillation pattern encodes information on the mass and the size of the neutron star. Modelling the X-ray pulse profiles of millisecond pulsars stands out as one of the most accurate and effective ways to constrain the equation of state models of neutron stars from observations. Recently, modelling of data collected by the *NICER* mission provided the first long-awaited simultaneous measurements of the mass and radius of a spin-powered millisecond pulsar, unveiling an unexpectedly complex magnetic field configuration. Soon the X-ray polarimetry window is going to reopen, thanks to the forthcoming launch of the Imaging X-ray Polarimetry Explorer (*IXPE*) and X-ray Polarimeter Satellite (*XPoSat*), and the planned enhanced X-ray Timing and Polarimetry (*eXTP*) mission. These missions may help hold the long-standing promise of the high energy astrophysics of supplying theoretical nuclear physics the pressure-density relation required to understand how the strong interaction behaves at sub-nuclear distances.

Our knowledge and understanding of the properties of millisecond pulsars have rapidly progressed during the last decades. A book that could sum up the recent progress in observations and theory seemed timely. The idea of actually writing it originated from a session on millisecond pulsars that we convened as part of the

42nd Scientific Assembly of the Committee on Space Research (COSPAR) that took place in Pasadena, USA, in July 2018.

This book covers in nine chapters the many multi-faceted aspects of millisecond pulsars. Radio millisecond pulsars are the vast majority. The rotation of the magnetic field of these pulsars powers such emission and causes the neutron star to spin down steadily. In Chap. 1, the authors (B. Bhattacharyya & J. Roy) provide an introduction to rotation-powered pulsars and a general description of the properties of the $\sim$500 radio millisecond pulsars discovered so far.

The last decade also saw the somehow unexpected discovery that rotation-powered millisecond pulsars are also bright gamma-ray sources, summing up to roughly half of the whole population of gamma-ray pulsars. Nowadays, targeting unidentified Fermi sources has become an efficient way to discover both the magnetospheric pulsed emission of millisecond pulsars and the continuous emission from intra-binary shocks that characterize pulsars in compact binaries. D. F. Torres and J. Li summarize the current results on the gamma-ray emission from millisecond pulsars in Chap. 2.

The high energy emission of millisecond pulsars somehow resembles slower gamma-ray pulsars and suggests a similar emission mechanism taking place in the outer magnetosphere of the pulsar. However, the exact location and physics of these objects are still not fully known. A. K. Harding discusses in Chap. 3 the current understanding of the emission physics of millisecond pulsars, as well as the outstanding problems.

Soon after the discovery of a radio pulsar in a binary in 1975, Bisnovatyi-Kogan and Komberg argued that accretion of the mass lost by the companion star could have spun up the neutron star. When radio astronomers eventually saw a 1.6 ms millisecond pulsar in 1982, scientists swiftly argued that a previous X-ray bright evolutionary phase had to have occurred. The weakly magnetized neutron star had to be spun up by the accretion of the mass transferred by a sub-solar companion star through a disk. In 1998, the detection of millisecond X-ray pulsations from an X-ray transient observed by the *Rossi X-ray Timing Explorer* eventually crowned with success the significant efforts to find the accreting progenitors of millisecond pulsars. Accreting millisecond X-ray pulsars are the evolutionary link between neutron star low mass X-ray binaries and spin-powered millisecond pulsars, or, at least, a sub-sample of them (the so-called black widows and redbacks). In Chap. 4, T. Di Salvo and A. Sanna review the observed spectral and timing properties, putting particular attention to peculiar systems and the latest discoveries. They address the long-term spin and orbital evolution of some specific sources, as well as some of the unsolved problems.

A few accreting neutron stars in low mass X-ray binaries show coherent brightness oscillations during some of the thermonuclear X-ray bursts originating from their surface. This phenomenon has a high potential to understand the extreme physics of the stellar surface, including modes of oscillations and thermonuclear flame spreading as the accreted matter burns, and to measure neutron star parameters. In Chap. 5, S. Bhattacharyya presents the current observational and theoretical understanding of burst oscillations, as well as the main problems of the field yet to be solved.

A few *transitional* millisecond pulsars that switch back and forth radio and X-ray pulsar regimes in response to variations of the mass accretion rate are one of the most recent add-ons to the zoo of millisecond pulsars. These pulsars eventually demonstrated how close the evolutionary link between accretion and rotation-powered millisecond pulsar is. Transitional millisecond pulsars showcase over a few days (or perhaps less) all the possible outcomes of the interaction between the pulsar wind of particles and radiation and matter in an accretion disc. A. Papitto and D. de Martino review in Chap. 6 the main observational results obtained in the last decade, highlighting the numerous enigmas yet to be solved and the vast discovery potential yet to be explored.

The observed orbital and stellar properties of each binary system hosting a millisecond pulsar represent a present-day snapshot of how the binary reached that configuration and provide clues and constraints to the secular evolution. In Chap. 7, F. D'Antona and M. Tailo review how much the current understanding of the binary evolution can account for these fossil records and their group properties. They focus on the fundamental role of the close-by neutron star in altering the structure of the donor star, compared to an ordinary stellar companion.

Whereas the old millisecond pulsars we observe are relatively weakly magnetized neutron stars, about ten per cent of neutron stars are assumed to be born as magnetars. Millisecond rotation at birth is key to the generation of their tremendous magnetic fields. Formation mechanisms comprise the collapse of a quickly spinning stellar core or a white dwarf and the merging of two (light) neutron stars. A powerful rotation-driven emission of electromagnetic and/or gravitational waves should follow soon after a millisecond magnetar is born. This emission can contribute significantly to the radiative output of long and short Gamma-Ray Bursts, Hyper Luminous Supernovae and Fast Radio Bursts. S. Dall'Osso and L. Stella discuss in Chap. 8 the conditions to form a millisecond magnetar and how it can be observed, with an emphasis on the possibility of detecting the associated GW signal.

Neutron stars are unparalleled natural laboratories to investigate the fundamental constituents of matter and their interactions under extreme conditions not replicable in terrestrial laboratories. I. Bombaci discusses in Chap. 9 some of the present models for the equation of state (EoS) of dense matter, their application to neutron star physics, and the possibility of transitions to a quark deconfined phase in the star, with the resulting realization of two coexisting families of compact stars in nature.

This book includes substantial background introductory material and recent theoretical and multi-wavelength observational results. It aims at providing professional astronomers, graduate students and other beginners a timely summary of the enormous progress in the field of millisecond pulsars during the last decades. We warmly thank all the authors of the chapters for their dedication to keeping the information included in this book as comprehensive and up-to-date as possible, especially considering the additional challenges posed by the pandemic.

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# Chapter 1
# Radio Millisecond Pulsars

**Bhaswati Bhattacharyya and Jayanta Roy**

**Abstract** The extreme timing stability of radio millisecond pulsars (MSPs) combined with their exotic environment and evolutionary history makes them excellent laboratories to probe matter in extreme condition. Population studies indicate that we have discovered less than five per cent of the MSPs of our Galaxy, implying that a huge majority of radio MSPs are waiting to be discovered with improved search techniques and more sensitive surveys. In this chapter, we provide an overview of the present status of ongoing and upcoming surveys for MSPs. Observed spectra, profile and polarisation properties of known radio MSPs are also summarised. Finally, we describe how the timing studies of radio MSPs enable a huge science return including attempts to detect gravitational waves using an array of MSPs, gravity tests using individual interesting MSP systems, as well as probing the intra-binary material using eclipses observed in MSPs in compact binary systems.

## 1.1 Introduction to Parameters of Radio MSPs

Millisecond pulsars (MSPs) are rapidly rotating neutron stars (rotational period of few tens of milliseconds) with very small spin-down rates. Whereas the spin period of the radio pulsars span around four orders of magnitude (1.4 ms to 23 s), MSPs are defined here by a periodicity <30 ms. With extremely stable periods and very low period derivative values, MSPs are the most precise celestial clocks and occupy the bottom-left corner in the $P - \dot{P}$ diagram (see Fig. 1.1, where blue squares mark MSPs; see also Fig. 4.1). Since rotation-powered pulsars spin down at a rate which depends on the magnetic field strength and the spin period of the pulsar, it is inferred that the magnetic field of an MSP is a few orders of magnitude weaker than an *ordinary*, slower pulsar. MSPs are assumed to have acquired their high rotational rate by accretion of matter, and thereby transfer of angular momentum, from a

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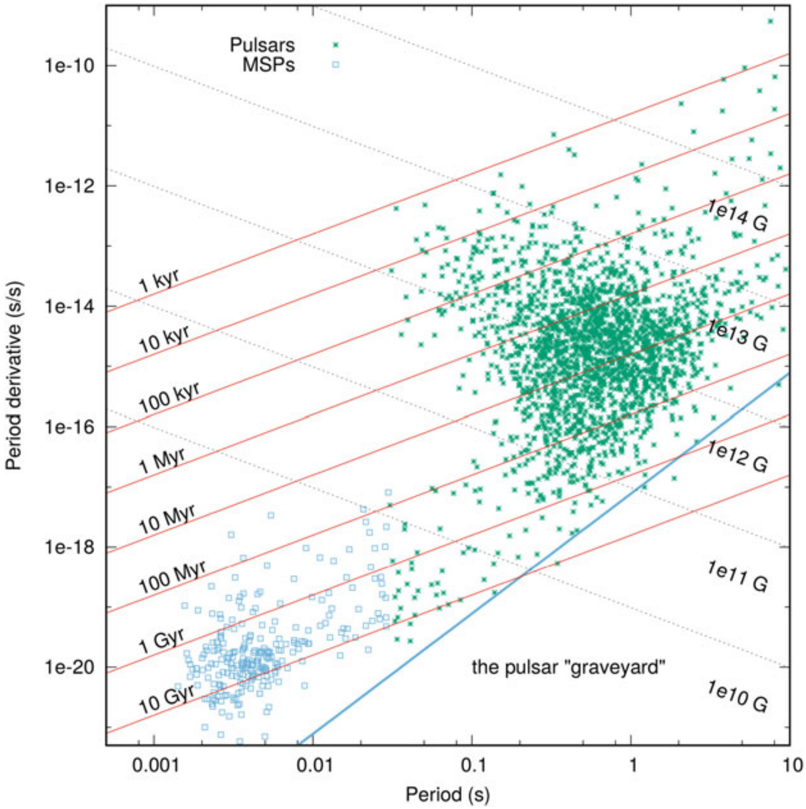

**Fig. 1.1** Period versus period derivative of the *ordinary* ($P > 30\,\mathrm{ms}$) pulsar and the millisecond pulsars. Data taken from the ATNF pulsar catalogue ([67], http://www.atnf.csiro.au/research/pulsar/psrcat)

low mass ($< M_\odot$) companion star in a binary system [1, 12]. Mass accretion is also possibly responsible for the decay of the magnetic field of the neutron star. Such a recycling scenario (discussed in Sect. 4.1) is now supported by observational evidences of accreting millisecond pulsars (see Chap. 4) and of a few transitional systems switching states between radio MSP and low-mass X-ray binaries (see Chap. 6).

MSPs are still a small population compared to the classical *ordinary* pulsars (spin period >30 ms). A total of 512 MSPs are reported in the lists maintained by E. Ferrara and D. Lorimer[1] and by P. Freire,[2] as of November 2020, whereas 2450 slower *ordinary* pulsars are listed in the Australia Telescope National Facility

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[1] Available at http://astro.phys.wvu.edu/GalacticMSPs/.

[2] Available at http://www.naic.edu/~pfreire/GCpsr.html.

**Table 1.1** Parameters of the known radio MSPs

| Parameters | Range of values (units) |
|---|---|
| Spin period ($P$) | 1.4–30 ms |
| Spin period derivative ($\dot{P}$) | $10^{-18}$–$10^{-22}$ |
| Magnetic field strength (B) | $10^7 - 10^9$ G |
| Age | $10^7 - 10^{11}$ years |
| Dispersion measure (DM) | 2.6–540 pc cm$^{-3}$ |
| DM distance (d) | 0.11–49 kpc |
| Flux density ($S_{1400}$) | 0.01–150 mJy |
| Companion mass ($M_{cmin}$) | 0.009–1.39 $M_\odot$ |
| Orbital period ($P_b$) | 0.065–669 days |
| Eccentricity (e) | 0–0.95 |
| Semi-major axis ($A_1$) | 0.0018–100 lt-sec |

(ATNF) database [67].[3] The parameters of the MSPs listed in the ATNF pulsar catalog are summarised in Table 1.1. The recycling scenario of MSPs suggests that most of them should be part of a binary system, and this actually occurs in $>80\%$ of the known systems.

MSPs in binary systems have an orbital period ranging from 75 min to 669 days, and a mass of the companion star between 0.009 and 1.39 $M_\odot$ (see also Fig. 6.1). More than 60% of the binaries hosting an MSP have an orbital period $P_b > 1$ day. These large-period binary MSPs essentially fall into three groups, depending on the mass of the companion star. The majority ($\sim$85%) have a low-mass ($<0.4\,M_\odot$) Helium white dwarf companion, but higher-mass (seemingly Carbon–Oxygen) white dwarfs, as well as neutron star companions are also found. The mass of the companion increases as a function of orbital period, following theoretical expectations [76]. Most of the MSPs are in nearly circular orbit with only $\sim$8% of known binaries having known eccentricity value $>0.1$. Tauris and Savonije [96] and Hui et al. [43] analysed the observed orbital properties of a binary MSPs with a white dwarf companion and reported a positive correlation between the orbital period and the eccentricity. However, different trends were obtained for MSPs with a Helium white dwarf companion, and MSPs with a Carbon–Oxygen white dwarf. They also reported two gaps in the distribution of orbital period (between 35–50 days and between 2.5–4.5 days). On the other hand, MSPs in binaries with a short ($P_b < 1$ day) orbital period also include eclipsing pulsars (see Sect. 1.4.3) either with a non degenerate main-sequence companion with a mass in the range 0.1–0.8 $M_\odot$ (dubbed *redbacks*) or with a $<0.06\,M_\odot$ brown dwarf (termed *black widows*). The reader is referred to the Chap. 7 for a detailed discussion of the origin and evolutionary channels of MSPs.

D. Lorimer [61] estimated the presence of around 40,000 MSPs in the Galaxy, indicating that a large number of MSPs are waiting to be discovered. Presently, only $\sim$15% of the $\sim$3000 known pulsars are MSPs, either in the Galactic disk or in

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[3] Available at https://www.atnf.csiro.au/research/pulsar/psrcat/.

globular clusters. Thus, it is possible that the known parameter range of the MSPs does not represent the true distribution.

This chapter presents a overview of radio millisecond pulsars. Sect. 1.2 details spectra and polarisation properties of the MSPs. Searches for radio MSPs are detailed in Sect. 1.3. Some aspects of the timing studies of radio MSPs are presented in Sect. 1.4.

## 1.2 Properties of Radio MSPs

### *1.2.1 Spectra and Luminosity*

Kramer et al. [49] compared the spectral dependence of the flux density $S_\nu$ on the frequency $\nu$ observed from *ordinary* ($P > 30\,\text{ms}$) pulsars and MSPs in the 0.7–3.1 GHz band. They concluded that the average spectra of MSPs are steeper than *ordinary* pulsars. They derived a mean spectral index of the power-law relationship $S_\nu \propto \nu^\alpha$ of $\alpha = (-1.8 \pm 0.1)$ for a set of 32 MSPs located in the Galactic disk and a mean index of $\alpha = (-1.60 \pm 0.04)$ for *ordinary* pulsars in the same frequency range. The median values for both samples were $-1.8$ and $-1.7$, respectively. However, they also pointed out that the steeper spectral index for MSPs could be due to the selection bias of having fainter (and farther) *ordinary* pulsars in the sample, with a relatively flatter spectral index. Indeed, restricting the data set to sources that are closer than 1.5 kpc, they found that mean spectral index of MSPs and *ordinary* pulsars are similar ($\alpha = -1.6 \pm 0.2$ for MSPs and $\alpha = -1.7 \pm 0.1$) for *ordinary* pulsars), with a median value of $-1.65$ and $-1.66$, respectively. Note that a more recent study by Bates et al. [11] based on larger sample of *ordinary* pulsars reported that the distribution of the spectral index has a mean of $-1.4$ and a standard deviation of 1.0. Although the number of MSPs has increased drastically in last two decades since the study by Kramer et al. [49], the flux at more than one observing frequency was reported only for a small fraction of the newly discovered MSPs. In a more recent study, Dai et al. [27] investigated 24 MSPs observed with the Parkes 64-m telescope in three bands, centred at 730, 1400 and 3100 MHz. Figure 1.2 plots the flux density spectra of these MSPs. They reported that the spectra of a few pulsars significantly deviated from a single power-law across the observing bands. Although a spectral steepening at high frequencies was observed for a few MSPs, for some other a spectral flattening was instead observed. Dai et al. [27] also studied the pulse phase-resolved spectral index of MSPs and found that different profile components have different spectral indices which overlap with one another. We conclude that considering the observed diversity of the spectral properties of MSPs, and in the absence of systematic flux measurements for a large sample of MSPs, it is not possible to draw a firm conclusion from the comparison of the steepness of the spectra of MSPs and *ordinary* pulsars.

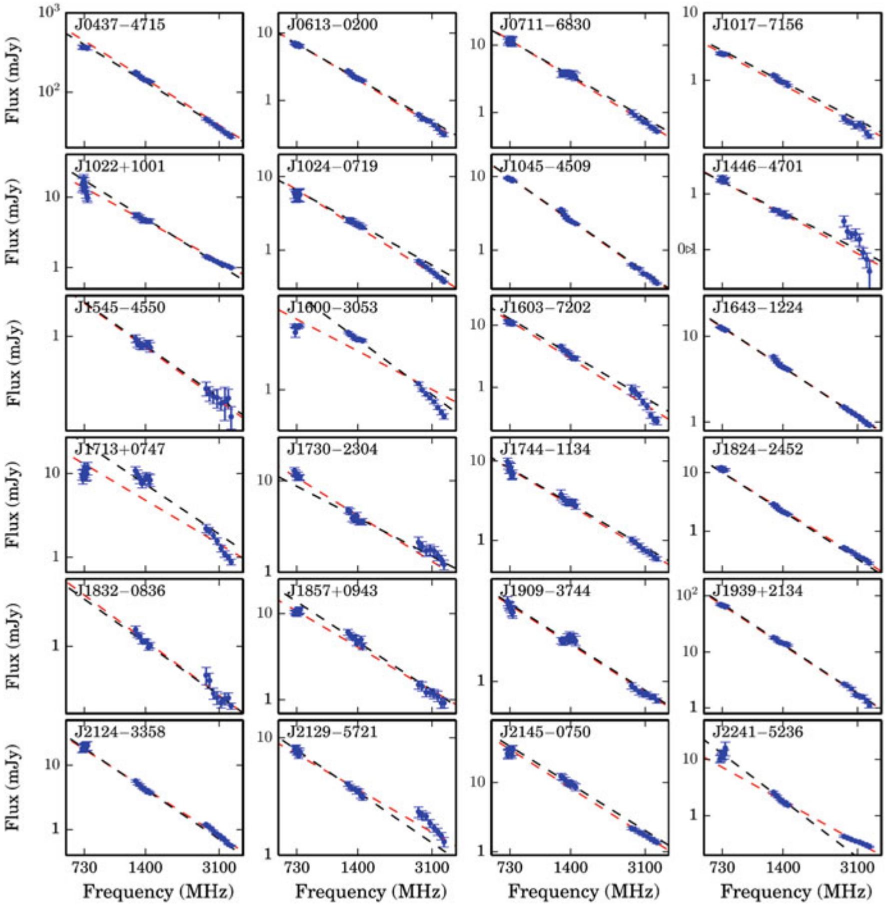

**Fig. 1.2** Flux density spectra for 24 MSPs. The red and black lines are for spectral index spectra fitted with power law $\alpha_1$ and $\alpha_2$, respectively. Credit: Dai et al., MNRAS, 449, 3223 (2015) [27]

*Ordinary* pulsars exhibit low-frequency turn overs in the spectra, while this is still debated for MSPs. Kuzmin et al. [54] analysed the spectra of 30 MSPs down to 100 MHz, and most of them did not exhibit any low frequency turn over. On the other hand, Kunyoshi et al. [53] found that one forth of the MSPs for which the spectrum was observed down to 100 MHz (i.e., 10 out of 39 MSPs) showed evidence of a turn over.

MSPs tend to be less luminous and less efficient radio emitters compared to *ordinary* pulsars. To obtain this result, Kramer et al. [49] used a luminosity estimator $S \times d^2$ equal to the product of the average flux density observed at 1.4 GHz times the square of the distance, and found that the luminosity of MSPs are an order of magnitude fainter than *ordinary* pulsars. They also restricted the comparison of the luminosity distribution to sources within a distance of 1.5 kpc, and concluded that the luminosity difference becomes less prominent. In addition, they noted that some high luminosity MSPs (which should be easy to detect) are missing and that that isolated MSPs are generally fainter than the ones in binaries, which could be attributed to different evolutionary history.

### *1.2.2 Pulse Profile and Polarisation Properties*

Xilouris et al. [100] reported that the pulse profiles of MSPs are slightly more complex than *ordinary* pulsars. They considered the number of Gaussian components required to represent the pulse profile as a measure of their complexity. They found that MSP profiles could be fitted with four Gaussian components on average, whereas three components were enough for *ordinary* pulsar.

*Ordinary* pulsars follow a systematic behaviour, where the observed pulse profile becomes narrower at higher frequencies, which is known as the 'radius to frequency mapping' [63, 81]. Xilouris et al. [100] reported a much less marked dependence on frequency for MSP profiles, instead. They identified three categories of MSPs: (i) almost no dependence, (ii) a very slow 'radius to frequency mapping', and (iii) contrary to 'radius to frequency mapping'. They suggested that the observed profile complexity, including the low-level emission and the unusual features identified in some of the MSPs, could result from emission from outer gaps [87]. The sample of MSPs studied by Dai et al. [27] also confirmed that most MSPs have very wide profiles with multiple components. The majority of the MSPs in their sample showed a duty cyle higher than 50%, with the profile components which did not show an appreciable dependence on the observing frequency.

Whereas the investigation by Dai et al. [27] covered the frequency range 730–3100 MHz in three bands, a more recent study by Kondratiev et al. [47] presented a census of MSPs using the LOw-Frequency ARray (*LOFAR*) in the frequency range 110–188 MHz. They found that the separation between the different components of the profiles seen at low-frequency by *LOFAR* was compatible with that seen at higher frequencies. Also the width of the profiles was similar at different frequencies. Thus low-frequency observations also supported that there was very little pulse profile dependence on frequency. This is different from the classical pulsars and indicates a more compact emission region in the MSP magnetosphere and possibly higher multipolar components. In addition, the observed pulse shapes indicated that the emission beam of MSPs are narrower than the classical pulsars. Ravi et al. [85] suggested that the features of MSPs radio profiles represent caustics in the emission beam. They proposed that the radio emission of MSPs could originate in wide beams higher up in the pulsar magnetosphere (up to or even beyond the null charge surface). The physics of the emission of MSPs is thoroughly discussed in Chap. 3.

Xilouris et al. [100] also studied for the first time the polarization profiles of MSPs and found that the the polarization degree is higher than in *ordinary* pulsars. In addition, the swings of the polarization position angle of MSPs are flatter. The polarization position angle curves of the MSPs exhibit smaller excursions and cannot be described by rotating vector model (RVM, [80]). This warrants different models to explain the MSP polarization properties. To address this, some models suggested emission from locations which extend over a substantial fraction of the light cylinder [8]. In addition, it is possible that special geometries of MSPs in binaries [21], or the existence of higher multipole moments in the magnetosphere of MSPs [66], can explain the observed polarization properties for individual MSPs.

Dai et al. [27] reported that the secondary pre- and post-cursors peaks in the profile generally have a higher fractional linear polarization than the main pulse. They also observed that the circular polarization showed complicated variations with both frequency and pulse phase, and different pulse components often had different signs of circular polarization. They studied the distributions of the fractional linear and circular polarization across the frequency bands, finding that although the fractional linear polarization was similar across three bands, both the fractional and net circular polarization decreased at lower frequencies. They further reported that the polarization angle sweep for all the MSPs of their sample were extremely complicated and could not be fitted using the RVM. As an example, Fig. 1.3 shows the polarization profile or MSP J0437–47. They also noted that the polarisation angle profile could significantly evolve across the observing frequency band.

## 1.3 Searches for Radio MSPs

The improvement in the technique of analysis made the rate of discovery of pulsars in ongoing surveys at major telescopes to increase dramatically over the last decade (see Fig. 1.4). However, the population of currently known MSPs ($\sim$500) is less than one per cent of the predicted number of potentially observable radio pulsars in the Galaxy ($1.2 \times 10^5$; [35]). The *PsrPopPy*[4] code is widely used to infer predictions on the underlying unseen population of MSPs [11]. Once the survey specifications are given as input, the *PsrPopPy* simulation can predict the number of MSPs that can be potentially discovered. For example, *PsrPopPy* simulations predicted that $\sim$3000 MSPs will be discovered by the Square Kilometre Array (*SKA*, [45]; see Fig. 1.5). Thus, population studies indicate that many MSPs are waiting to be discovered. A large fraction of the MSPs are faint sources requiring sensitive searches and improved analysis techniques to be discovered.

The sensitivity of the pulsar survey is calculated using the radiometer equation. A pulsar will be detectable (with a $5\sigma$ detection significance) in a survey made of an incoherent array of smaller telescopes, if it exceeds some minimum flux density

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[4] https://github.com/samb8s/PsrPopPy.

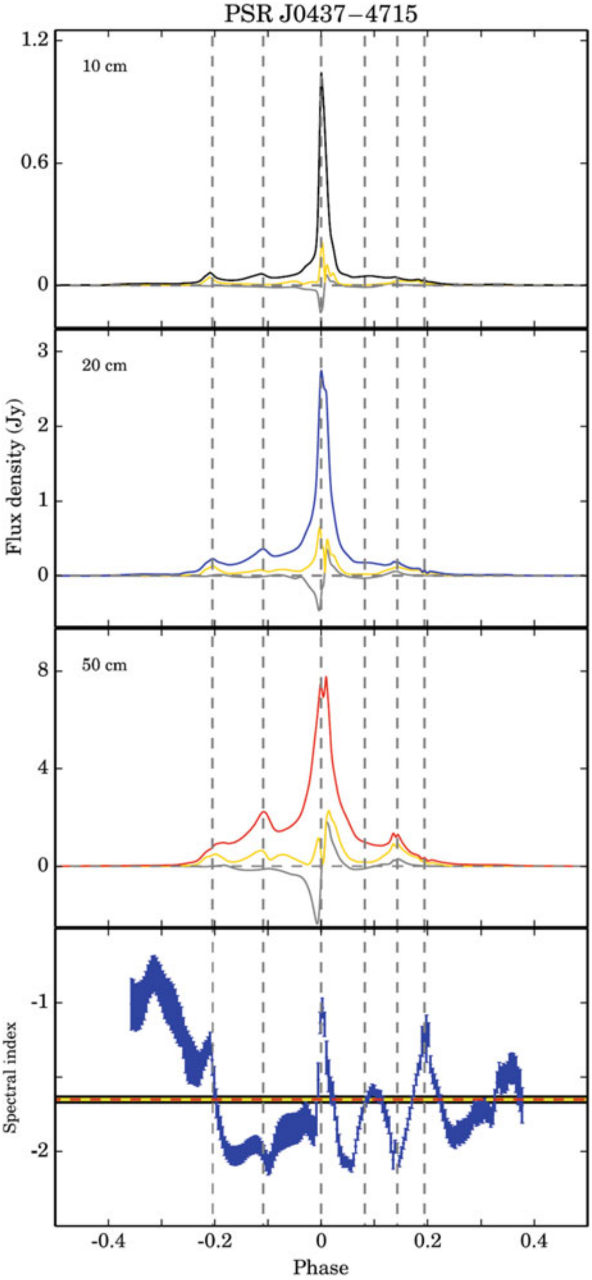

**Fig. 1.3** The polarization profile of PSR J0437–4715 and phase-resolved results. The spectral index observed at different pulse phases is reported in the bottom panel. The leading and trailing parts have steeper spectral indices, whereas the outer edges of the profile have flatter spectra. Credit: Dai et al., MNRAS, 449, 3223 (2015) [27]

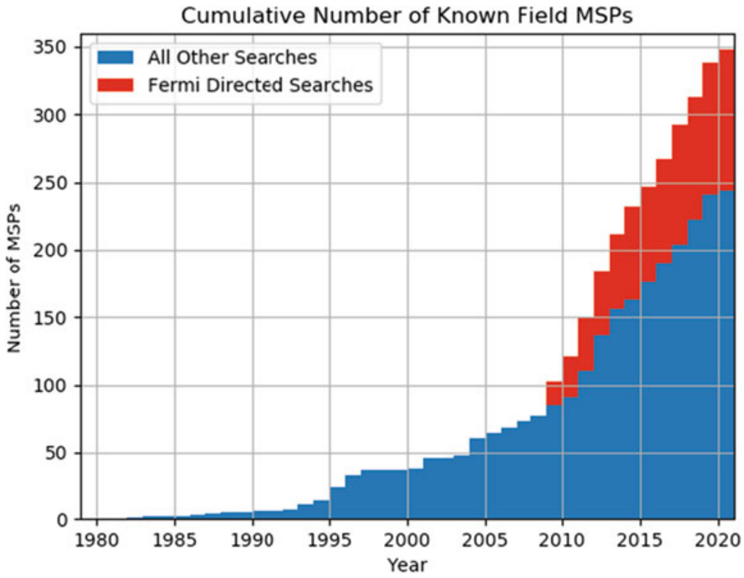

**Fig. 1.4** Cumulative number of known MSPs in the Galactic field. Fermi-directed searches have contributed to one-third of this number. Figure courtesy of Paul Ray

($S_{\rm pulsar}$) that can be calculated using the radiometer equation:

$$S_{\rm pulsar} \sim 5 \frac{T_{\rm rec} + T_{\rm sky}}{G\sqrt{B N_{\rm p} N_{\rm a} t}} \sqrt{\frac{w}{P - w}} \tag{1.1}$$

where $T_{\rm rec}$ and $T_{\rm sky}$ are the temperatures of the receiver and sky, respectively, $G$ the gain of individual antennas, $B$ the bandwidth, $N_{\rm p}$ the number of orthogonal polarizations needed to construct the total intensity, $N_{\rm a}$ the number of antennas, $t$ the integration time, $w$ the effective pulse width (including all instrumental smearing), and $P$ the pulse period. The limiting sensitivity of different surveys can be calculated using the survey parameters in this equation. The discovery of new MSPs is hampered by their radio faintness and requires deeper searches with larger telescopes. Ongoing searches with the Green Bank Telescope (*GBT*), the Parkes telescope, Effelsberg, Arecibo, the Giant Metrewave Radio Telescope (*GMRT*), and the Five hundred meter Aperture Spherical Telescope (*FAST*) have discovered a good number of MSPs, bringing the total number of MSP in the Galactic field to ~353,[5] and total number of MSPs in Globular cluster to 147. Some of the major radio telescopes that are actively discovering MSPs are large single dish telescopes (e.g. Arecibo, *GBT*, Parkes), and their limiting sensitivity has almost been

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[5] http://astro.phys.wvu.edu/GalacticMSPs/GalacticMSPs.txt.

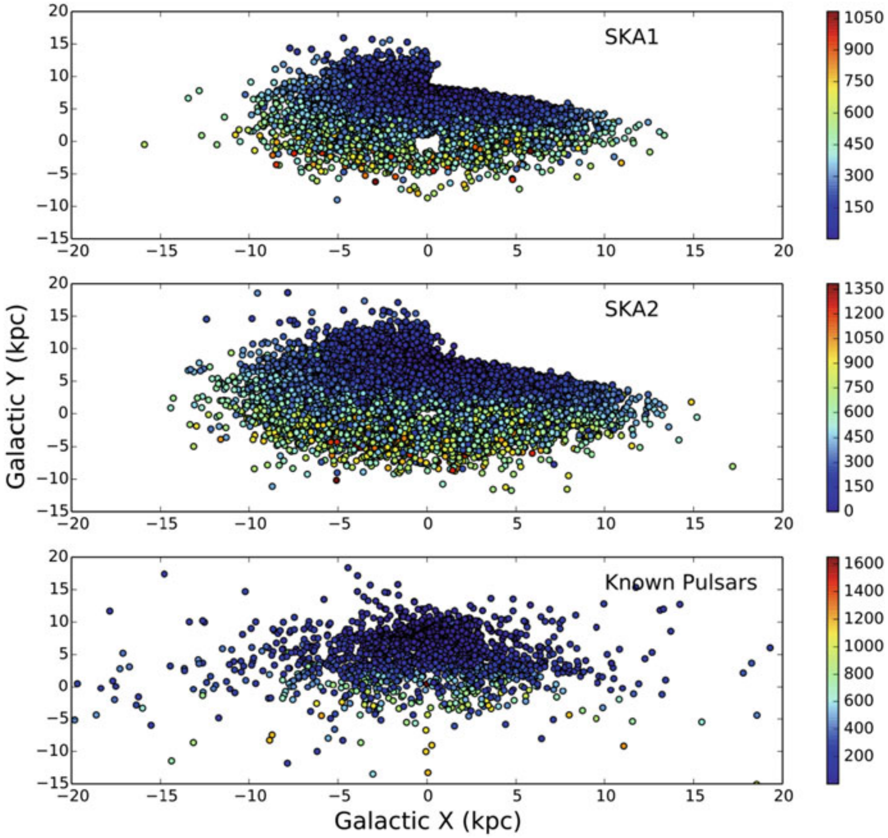


**Fig. 1.5** *PsrPopPy* simulation of the number of pulsars expected to be found with the *SKA* along with their distribution throughout the Galaxy, projected onto the Galactic plane, compared to the distribution of currently known pulsars. The color coding indicates the approximate range of dispersion measures of the simulated pulsars. Credit: Keane et al., in "Advancing Astrophysics with the Square Kilometre Array", Proceedings of Science, PoS(AASKA14), id. 040 (2015), [45]

reached. Thus, large arrays of many smaller telescopes are the future to increase the sensitivity, and this will ultimately lead to the world's largest telescope, the Square Kilometer Array (*SKA*).

In spite of the fact that the rate of discovery of pulsars in ongoing surveys at major telescopes has increased dramatically over the last decade, the presently known population is a very small fraction of the predicted number of MSPs. Since MSPs are intrinsically faint and most of the MSPs are part of binary systems, a binary acceleration search (and sometimes jerk search, i.e., searching up to period double derivatives) is also required, in addition to a search for dispersion measure and periodicity. The details of search techniques are described in Sect. 1.3.1. Targeted searches and wide-area blind surveys are two popular ways to look for the large

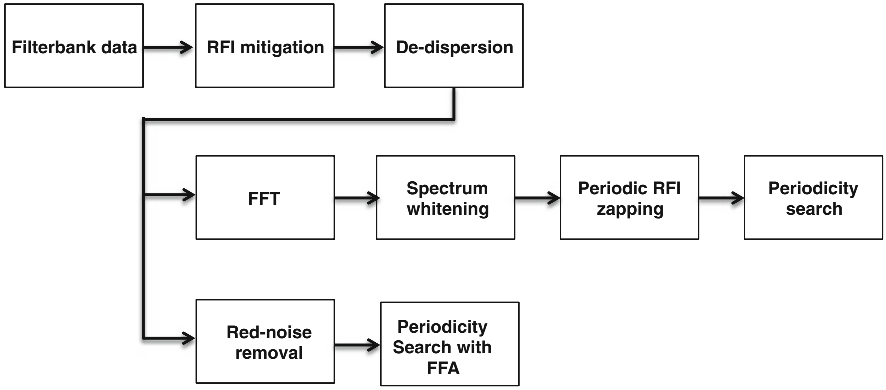
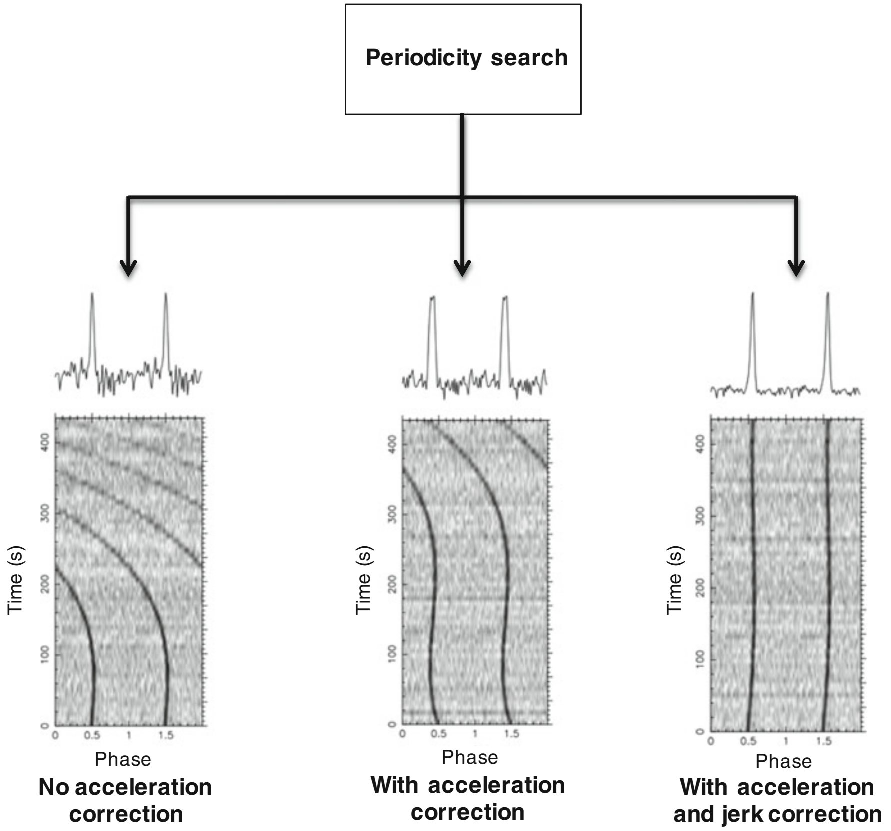


**Fig. 1.6** Functional blocks for pulsar search processing. The de-dispersed time samples are processed concurrently using frequency-domain search (with Fast Fourier Transforms) and time-domain periodicity search (with Fast Folding Algorithm, FFA)

number of the MSPs which are yet unseen. In Sects. 1.3.2 and 1.3.3 we describe these two MSP search techniques.

### 1.3.1 Search Techniques

Pulsar search processing is a computing-intensive task. Figure 1.6 shows a typical functional block diagram for a search analysis. The time-frequency filterbank data from the telescope are first processed to excise broad-band and narrow-band radio frequency interference (RFI). RFI mitigated filterbank data are then fed into a de-dispersion transform module, which corrects for the frequency dependent dispersive delays at various trial dispersion measure (DM) values. The pipeline performs a periodicity search for each of the de-dispersed time-series. The periodicity search in frequency-domain involves Fast Fourier Transforms (FFT), spectrum whitening to remove the instrumental red-noise, and masking periodic RFIs (e.g. impulsive signals from AC power-line). In parallel, the de-dispersed time-series can also be searched for periodic signals in the time-domain. The increase in computing power enhanced the sensitivity of on-going surveys with large single dishes or interferometric arrays, making them progress through a hitherto unexplored parameter space. Since the majority of MSPs are in binaries, a periodicity search requires the correction of the line-of-sight acceleration caused by the orbital motion of the pulsar. Thus, in addition to the constant acceleration search, for systems like double neutron star binaries with higher companion mass, the assumption of constant spin frequency-derivative over the span of the observation is no longer valid. The periodicity search employs a jerk search, i.e. searching over the period and the first two period-derivatives that corrects the binary acceleration effect on much shorter



**No acceleration correction**

**With acceleration correction**

**With acceleration and jerk correction**

**Fig. 1.7** The effect of line-of-sight acceleration for a simulated system containing a pulsar in 1.2 h circular orbit with companion mass of 1.4 $M_{\odot}$. The tracks indicate the pulse intensities as function of time and the averaged pulse profiles are shown on the top

time scales even for a fraction of the orbit. Figure 1.7 shows the improvement obtained in a periodicity search that involves no acceleration, a constant acceleration and acceleration+jerk, respectively. The comparison is done for a simulated system containing a 22 ms pulsar and a neutron star companion (1.4 $M_{\odot}$) in a 1.2 h circular orbit. Correcting for the binary acceleration significantly enhances the signal-to-noise (S/N) of the signal, making a detection much easier. However such an acceleration (and jerk) search increases the pulsar search processing cost by more than an order of magnitude. For example, Anderson et al. [2] reported an increase by a factor of ∼80 of the processing time while searching for highly accelerated pulsars in Terzan 5 globular cluster. A new 2.93 ms pulsar, J1748–2446 am, was discovered with the jerk search which had not been detected before with an acceleration-only search [2]. Discovering such systems is important as they provide unique laboratories to test the theories of gravity (see Sect. 1.4.2). The population of non-recycled slow pulsars (period > 100 ms) contains several interesting objects, such as pulsars showing pulse intermittence, drifting and nulling, all of which are important probes of the emission physics. We also know two ultra-slow pulsars with a period longer than 10 s; these pulsars graze the theoretical death-line and are interesting to probe the conditions at which the radio emission is expected to cease. The instrumental red-noise and radio frequency interference (RFI) reduce the search sensitivity at the low frequency end of the power spectrum of the detected time series, where the signal from these objects is strongest. In addition, due to the shorter duty cycle of long period pulsar, the number of harmonics used in the frequency-domain periodicity search limits the signal recovery from the power spectrum. For this reason, the ongoing surveys (e.g. [19] for HTRU survey, [72] for PALFA survey, [70] for SUPERB survey) also perform a time-domain search with a Fast Folding Algorithm (FFA; [92]), simultaneously to the frequency-domain periodicity search.

## *1.3.2 Targeted Searches*

Targeted searches are more sensitive to pulsars compared to wide-area surveys that cover the sky blindly. They allow deeper searches through longer observations (making the surveys more sensitive) as well as multiple visits per source. This is precious because in some cases a pulsar can be missed in a single observation due to scintillation, eclipses, or acceleration in a binary system. Such deep observations can characterise specific environments in unique ways. Targeted surveys also probe different types of MSPs, so probing the evolutionary links between different classes.

### 1.3.2.1 Follow–Up of High Energy Sources

The radio and the high-energy ends of electromagnetic spectrum are highly complementary in pulsar searches, since the highest sensitivity and resolution is attained in the radio domain but the largest observable energy output (though smaller in terms of photon counting statistics) is attained at higher energies (see Chap. 2).

Targeted searches of high-energy sources proved particularly efficient compared to blind surveys for pulsars, especially for the *Fermi* directed searches. Since August 4, 2008, the Giga-election-volt $\gamma$-ray sky has been surveyed by the *Fermi* Large Area Telescope (*LAT*, [6]), the primary instrument on-board the *Fermi* Gamma-ray Space Telescope. An increasing number of unassociated $\gamma$-ray point sources appear at each *Fermi* LAT catalog release. Targeted searches for radio pulsations at the position of such unassociated LAT point sources is coordinated by the *Fermi* Pulsar Search Consortium (PSC). Till now, 95 new MSPs are been discovered in this effort,[6] which amounts to about one third of the the total known Galactic MSP population. Figure 1.4 plots the cumulative number of known Galactic MSPs

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[6] https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars.