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Searching for millisecond pulsars: surveys, techniques and prospects

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Abstract
Searches for millisecond pulsars (which we here loosely define as those with periods < 20 ms) in the galactic field have undergone a renaissance in the past five years. New or recently refurbished radio telescopes utilizing cooled receivers and state-of-the art digital data acquisition systems are carrying out surveys of the entire sky at a variety of radio frequencies. Targeted searches for millisecond pulsars in point sources identified by the *Fermi* Gamma-ray Space Telescope have proved phenomenally successful, with over 50 discoveries in the past five years. The current sample of millisecond pulsars now numbers almost 200 and, for the first time in 25 years, now outnumbers their counterparts in galactic globular clusters. While many of these searches are motivated to find pulsars which form part of pulsar timing arrays, a wide variety of interesting systems are now being found. Following a brief overview of the millisecond pulsar phenomenon, we describe these searches and present some of the highlights of the new discoveries in the past decade. We conclude with predictions and prospects for ongoing and future surveys.

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(Some figures may appear in colour only in the online journal)

1. Introduction

Since their discovery 45 years ago (Hewish *et al* 1968), just over 2000 pulsars have been found, enabling some of the most fascinating astronomical discoveries over that same time span. The majority of these are radio pulsars that have been found in large-area surveys, though a significant fraction, especially of millisecond pulsars (MSPs), were found in targeted searches. Large-area surveys entail a methodic search of large, generally contiguous, regions of the sky for pulsars; while targeted searches involve the search of a known object, such as a gamma-ray source or a supernova remnant, for the detection of a pulsar. Because we are still only sampling a small fraction of the underlying population, almost all surveys result in some new and often unexpected discovery, many of which have an impact beyond the astrophysical study of neutron stars. Some highlights from the past few years are: the double pulsar J0737–3039 (Lyne *et al* 2004), which has provided some of the best tests of strong-field general relativity (Kramer *et al* 2006), as well pulsar-white dwarf systems that place stringent limits on tensor–vector–scalar theories of gravity (Bhat *et al* 2008, Lazaridis *et al* 2009, Freire *et al* 2012, Antoniadis *et al* 2013); PSR J1614−2230, a 2 solar mass neutron star that has provided the best constraints yet on the equation of state of ultra-dense matter (Demorest *et al* 2010); and the unexpected discovery of a population of gamma-ray pulsars and MSPs (Abdo *et al* 2009). As discussed by several other authors in this focus issue, e.g. the article by Manchester, one of the most exciting prospects is the direct detection of gravitational waves using a pulsar timing array (PTA) of precision MSPs, which will help to usher in a new era of gravitational wave astronomy.

Searching for MSPs is fraught with unique challenges that do not affect searches for long-period pulsars to the same degree. The sampling rate necessary to detect MSPs is high, as is the required spectral resolution. The latter is needed to overcome the deleterious effects of dispersive smearing by free electrons in the interstellar medium. While long-period pulsars can be detected with of order 100 channels sampled every few milliseconds, a typical survey optimized for MSPs employs several thousand frequency channels and samples data every 100 μs or less. This pushes MSP searches to very high data rates and well into the realm of the National Science Foundation's new buzzword: 'big data'. Furthermore, about three quarters of all MSPs are found in binary systems, whereas most long-period pulsars are isolated (see figure 1(*a*)). Acceleration in a binary system induces a Doppler shift in the observed pulse period that would render many systems undetectable without specialized (and computationally intensive) search techniques. Systems in which the companion eclipses the pulsar for large fractions of time may require multiple observations to detect. All of these factors make high-performance computing a must for modern pulsar surveys. The scientific payoff is well worth the effort, however, and indeed is absolutely necessary in the era of PTAs. A successful detection of gravitational waves will require many ultra-high precision MSPs, ideally distributed isotropically across the sky. The optimal MSP for a PTA will be bright and have narrow pulse profile features, allowing for precise pulse time of arrival measurements. It will furthermore be free from difficult to model binary effects (such as eclipses and interactions with intra-binary gas) and will suffer from a minimum of ISM effects (see the article in this focus issue by Stinebring for an in-depth discussion of ISM effects), both of which can lead to large residuals in pulsar timing models. Additionally, the optimal MSP will have minimum noise that is intrinsic to the pulsar, such as variability in emission from its magnetosphere, an effect known as phase jitter (Cordes and Shannon 2010, Osłowski *et al* 2011). For an overview of the noise processes intrinsic to pulsars, see the article in this focus issue by Cordes. Finding such pulsars is now a primary motivation for large-area and/or targeted pulsar surveys at nearly all major radio observatories.

The evolutionary pathways that lead to the variety of observed MSPs are not fully understood. An excellent starting point is the cartoon showing the formation of the various systems in figure 1(*b*). Starting with a binary system, a neutron star is formed during the supernova explosion of the usually initially more massive star. Most binaries do not survive

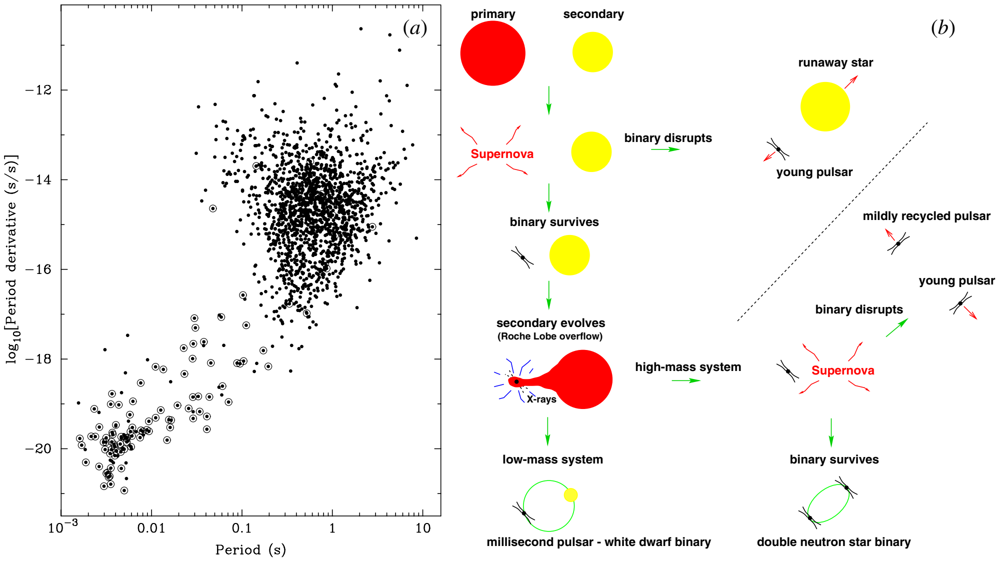

Figure 1. (*a*): $P - \dot{P}$ diagram showing the current sample of radio pulsars. Binary pulsars are highlighted by open circles. (*b*): Binary evolution scenarios involving pulsars (see text) (Lorimer 2008).

this event, and over 90% (Portegies Zwart and Yungelson 1998) are disrupted due to either catastrophic mass loss (Hills 1983) and/or natal kicks imparted to the neutron star (Bailes 1989). For binaries which survive, and where the companion evolves into a red giant, the old spun-down neutron star can be revived as a pulsar by accreting matter from its companion, spinning it up to shorter periods (Alpar *et al* 1982). The term ‘recycled pulsar’ is used to describe such objects. During accretion, x-rays produced by the frictional heating of in-falling matter onto the neutron star make such systems visible as x-ray binaries. For an overview of x-ray binaries, see e.g. Bhattacharya and van den Heuvel (1991).

Two classes of x-ray binaries exist that are relevant to recycled pulsars: neutron stars with high-mass or low-mass companions. In a high-mass x-ray binary, the companion is massive enough that it evolves on a 10^{6-7} yr timescale before exploding as a supernova, producing a second neutron star. For binaries which survive the explosion, the result is a double neutron star binary. At least nine such systems are currently known (Lorimer 2008). Most relevant to the formation of MSPs are low-mass x-ray binary systems (LMXBs) where the companion evolves and transfers matter onto the neutron star on a much longer timescale (of order 10^8 yr or more), spinning it up to periods as short as a few ms (Alpar *et al* 1982). Tidal forces during the accretion process serve to circularize the orbit. During this spin-up phase, the secondary sheds its outer layers to become a white dwarf in a circular orbit around a rapidly spinning MSP. This theoretical description connecting LMXBs to the formation of new MSPs has been confirmed observationally in recent years in the detection of an accretion disk around PSR J1023+0038 (Archibald *et al* 2009) and even more recently the connection of the LMXB IGR J18245-2452 and PSR J1824-2452 (Papitto *et al* 2013).

2. Searching the sky for new MSPs

Figure 2 summarizes the progress in searching for MSPs since their discovery in 1982 (Backer *et al* 1982). As can be seen, thanks to a large number of different surveys being carried out

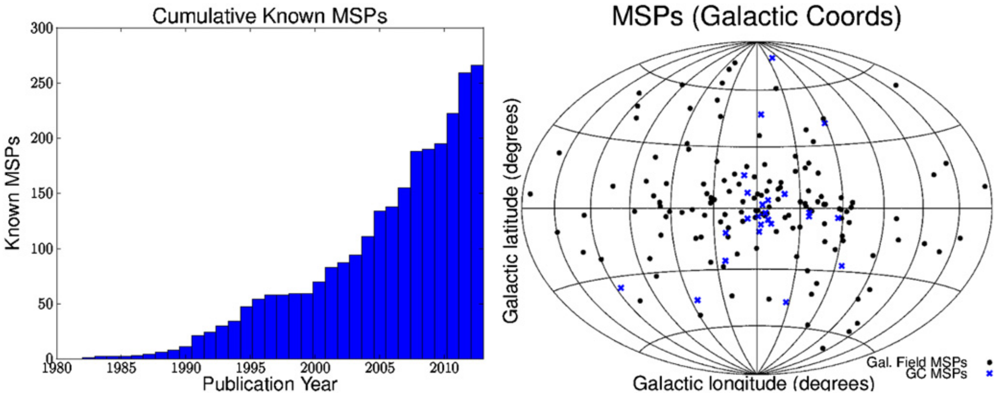

Figure 2. Left: the number of MSPs from the ATNF pulsar catalog (see the appendix) in the galactic field and globular clusters as a function of publication date. Right: MSPs in the galactic field (black dots) and in globular clusters (blue X's) shown in galactic coordinates. The center of the image corresponds to the location of the galactic center and the x-axis represents the galactic plane.

with different telescopes (see subsections 2.1 and 2.2 below), we are currently enjoying a burst in the number of systems being found.

There are two general methods for searching for new pulsars. One is to do targeted searches of known objects such as globular clusters. In recent years, searches of sources identified, using the Fermi Gamma-Ray Space Telescope, as point sources with pulsar characteristics have lead to the discovery of many new MSPs. The second method for finding new pulsars is to systematically search large regions of the sky. We will describe each of these approaches in more detail below.

2.1. Targeted searches

Globular clusters are excellent targets for finding new MSPs. Due to their increased stellar density in comparison to the galactic field, globular clusters are environments in which interactions between stars, such as those required to produce MSPs, are more likely to occur. In addition, the high probability of exchange interactions (Sigurdsson and Phinney 1990, Phinney and Sigurdsson 1991) means that the observed population of MSPs in clusters has a significant fraction of 'exotic systems' with high orbital eccentricities (D'Amico *et al* 1993), short orbital periods (Camilo *et al* 2000) and large inferred masses Freire *et al* (2008). To date, a total of 144 pulsars have been found in 28 cluster[7]. All but four of these pulsars show characteristics akin to recycled pulsars and 129 of the currently known pulsars have $P < 20$ ms. Searches of globular clusters have long been fruitful for finding new MSPs (Manchester *et al* 1991, Biggs *et al* 1994, D'Amico *et al* 2001, Ransom *et al* 2005), but from a PTA standpoint they are of limited use. Acceleration in the globular cluster potential, as well as acceleration and jerk from nearby stars, leads to large timing residuals on long timescales. Globular clusters are also typically a factor of a few more distant than typical PTA MSPs, and hence typically an order-of-magnitude fainter.

Targeted searches of bright *Fermi* point sources have been amazingly successful at identifying new MSPs. To date, more than 50 MSPs have been discovered that are coincident with *Fermi* point sources. Many of these are 'black widow' or 'redback' systems that often

[7] See www.naic.edu/~pfreire/GCpsr.html for more information.

eclipse due to excessive material surrounding the companion and show significant and, from the point of view of PTAs, undesirable intra-binary effects. For further information on such systems, see Freire (2005), Roberts (2011), and references therein. Despite the number of 'black widow' and 'redback' systems in the *Fermi*-discovered set of MSPs, at least ten are now being timed regularly by the various PTA projects. A recent review of the *Fermi* searches can be found in Ray *et al* (2012).

2.2. Large area surveys

Although targeted searches have been successful in finding new MSPs, large-area surveys are required in order to find the MSPs in the galactic field which are not necessarily strong gamma-ray emitters. Following initial searches in the 1980s with relatively poor sensitivity, large-area surveys have undergone two major renaissance periods. The first of these took place during the 1990s following Wolszczan's discovery of two recycled pulsars at high galactic latitudes in an Arecibo drift-scan survey (Wolszczan 1991). Subsequently, a prescient paper by Johnston and Bailes (1991) demonstrated that the local population of MSPs revealed by all-sky surveys at ~0.4 GHz should be largely isotropic. This work inspired a number of 400 MHz pulsar surveys during the 1990s which led to a sample of about 30 MSPs by the end of the decade. The main contributions made were at Parkes where a 436 MHz Survey of the southern sky resulted in the discovery of 17 new MSPs (Manchester *et al* 1996), and at Arecibo where a number of groups surveyed significant portions of the Arecibo visible sky and found a similar number of MSPs. For an excellent review of these searches, see Camilo (1995, 1999).

The second renaissance period began during the late 1990s with the emergence of the most prolific pulsar survey so far, the Parkes Multibeam Pulsar Survey (PMPS). The PMPS made use of the 20-cm (L-band) multibeam system on the Parkes telescope to survey the galactic plane for new pulsars using 13 independent beams at a time (Manchester *et al* 2001). So far, well over 1000 pulsars have been discovered by this system and the original PMPS survey of the galactic plane ($|b| < 5^\circ$) carried out in the early 2000s (Manchester *et al* 2001, Morris *et al* 2002, Kramer *et al* 2003, Hobbs *et al* 2004a, Faulkner *et al* 2004, Lorimer *et al* 2006) has discovered around 800 new pulsars including 30 new MSPs. Additional discoveries are still being made by groups reprocessing the data (Eatough *et al* 2013, Knispel *et al* 2013, Mickaliger *et al* 2012). Following the success of the PMPS, surveys extending the surveyed area to intermediate and high latitudes were also performed using the Parkes multibeam L-band feed. These surveys are the Swinburne Intermediate Latitude Survey (Edwards *et al* 2001) and the Swinburne High Latitude Survey (Jacoby *et al* 2009). These two surveys discovered eight and five new MSPs, respectively.

Inspired by the success of the PMPS surveys, a 7-beam L-band system was commissioned at Arecibo in 2004 and has been used for pulsar and neutral hydrogen surveys ever since. The Pulsar Arecibo L-band Feed Array (PALFA) survey covers the region of the Galaxy with galactic latitude less than $\pm 5^\circ$ in the galactic longitude ranges $32^\circ < \ell < 77^\circ$ and $168^\circ < \ell < 214^\circ$. Initial data were taken using a data acquisition system with 100 MHz bandwidth which has subsequently been upgraded to sample the full 322 MHz band from the receiver. To date, the PALFA survey has discovered 116 pulsars, with 17 of these being new MSPs.

With most of the pulsar searching efforts at Arecibo and Parkes being devoted to L-band multibeam systems, at Green Bank, an opportunity to return to drift-scan searching arose when the GBT was closed to allow repair of its azimuth track during summer 2007. Drift-scan observations at 350 MHz carried out during this period covered over 10000 deg^2 in the declination ranges $-7.7^\circ \leqslant \delta \leqslant 38.4^\circ$ and $-20.7^\circ \leqslant \delta \leqslant 38.4^\circ$. Further details of the survey coverage, data processing, and sensitivity can be found in Boyles *et al* (2013) and Lynch *et al* (2013). Data processing for the drift-scan survey is now complete, and 35 pulsars have been discovered, including seven MSPs and recycled pulsars. Twenty-four pulsars from early data processing are presented in Boyles *et al* (2013) and Lynch *et al* (2013) along with complete timing solutions. An additional 11 pulsars have been discovered since this first round of detailed follow-up and are still being studied.

2.2.1. Current surveys. The PTA experiments and advancements in data recording have driven the development of many large pulsar surveys which are currently underway.

The Arecibo observatory 327 MHz drift-scan (AO327) survey (Deneva *et al* 2013) is an ongoing survey using the Arecibo observatory, which is intended to search the entire sky visible by the telescope for new radio pulsars at 327 MHz. In this survey, the telescope is fixed at a particular azimuthal and zenith position while the rotation of the Earth moves the sky overhead. Due to the nature of this survey (it is sometimes performed when telescope pointing is not functional), it covers right ascension ranges spread throughout the declination range $-1^\circ < \delta < 38^\circ$. To date, the survey has discovered 22 new pulsars including 3 MSPs.

The Green Bank North Celestial Cap (GBNCC) survey (Stovall *et al* 2013, in preparation) is the successor to the aforementioned GBT 350-MHz drift-scan survey and is also carried out at 350 MHz, giving it excellent sensitivity to nearby, steep spectrum pulsars. It uses twice the bandwidth of the former survey, 120-s pointed observations, and the newer Green Bank Ultimate Pulsar Processor back-end (DuPlain *et al* 2008). The science goals are the same, but with a particular emphasis on northern declinations, where there are fewer high-precisions MSPs known, especially in the first stage of the survey. This is important for increasing the number of wide-separation baselines in PTAs and also probes a region of the Galaxy that has not been studied in as much detail as the galactic plane. Stage I of the survey covered the north celestial cap ($\delta > 38^\circ$) and data taking was completed in 2011. The second stage, which covers the remaining GBT visible sky, is currently underway. Data processing is being carried out at the Texas Advanced Computing Center and the Guillimin supercomputer operated by CLUMEQ. To date, the survey has discovered 62 new pulsars, including nine new MSPs. Further analysis of candidates from the GBNCC survey, as well as ongoing data taking and processing, will undoubtedly result in the discovery of many more pulsars.

The High Time Resolution Universe (HTRU) pulsar survey (Keith *et al* 2010) is currently underway at the Parkes telescope, using the same multibeam system as was used by the PMPS. Data acquisition is being carried out using updated spectrometers which provide order-of-magnitude increases in time and frequency resolution over the previous generation of Parkes multibeam surveys. The HTRU surveys are divided into three sky areas; the low, intermediate, and high galactic latitude regions. These three regions have integration times of 4300 s, 540 s, and 270 s, respectively. To date, the HTRU survey has resulted in the discovery of close to 150 pulsars, including about 30 new MSPs. A similar survey (HTRU-N) is also being conducted in the northern sky using a new seven beam system at the Effelsberg radio telescope (Barr *et al* 2013).

In recent years, low frequency observatories such as the Low Frequency Array (LOFAR, Stappers *et al* 2011), the Long Wavelength Array (LWA, Taylor *et al* 2012), and the Murchison Widefield Array (MWA, Bowman *et al* 2013) have begun to become operational. These instruments are beginning to be used for large-area pulsar surveys, which may lead to the detection of new MSPs. However, searches conducted at these low frequencies ($\sim$100 MHz) are more challenging due to the effects of the interstellar medium. The effects of dispersion are so strong below 100 MHz, that searches for MSPs at even moderate DMs require high frequency resolution to adequately account for dispersion broadening effects. Additionally, the detectable MSP population is reduced at these frequencies due to scattering by the ISM.

In summary, the various technical developments over the past decade have led to the discoveries of over 150 MSPs in the galactic disk. In addition to finding MSPs in large numbers, and therefore increasing the chances of uncovering one that times well, the same developments have led to a dramatic improvement in time and frequency resolution available for follow-up timing experiments. MSPs can now be routinely timed to μs precision or better with 100-m class telescopes. A decade ago, such a statement could only be made for pulsars timed with the large collecting area (and, hence, excellent signal-to-noise ratio) of the 305-m Arecibo telescope (Camilo 1999).

3. Search method

The pulsar surveys and targeted searches use slightly varying techniques for discovering new pulsars. Here we discuss the basic methods performed. Information on other search methods as well as a more in-depth discussion of the methods described below can be found in Lorimer and Kramer (2005). Standard software packages capable of performing many of the following tasks are available online. These packages include `PRESTO`, `SIGPROC`, and `PSRCHIVE`. Links to these packages are included in the appendix.

3.1. Radio Frequency Interference excision

One of the challenges faced by pulsar searches is the increasing levels of radio frequency interference (RFI) created by a technologically growing world. Pulsar searchers use several techniques to mitigate the effects of RFI. There are two main types of RFI, strong bursts and low-level, continuous signals. In order to remove bursts of RFI, the data are generally analyzed in sections to identify periods of time with increased power, or specific frequency channels which contain significantly more power than the others for the same observation. The time periods and frequency channels with too much power are then identified and either not used in analysis or the data for that time period/frequency channel are replaced with the mean of the observation. The removal of low-level, continuous signals is often done by removing power from specific Fourier bins, which are known to generally have increased power due to RFI.

3.2. De-dispersion

Prior to searching data for pulsars, we must remove the effects of dispersion, which will smear the signal out as a function of frequency. In order to remove this effect, the typical method for pulsar searching is to obtain data which is divided into a number of frequency channels. The number of frequency channels depends on observing frequency and is chosen such that the dispersive smearing time over individual channels is much less than the period of the pulsars you wish to find out to some DM. When performing the searches, we do not know the DM of our pulsars, so we must search over a wide range of trial DMs. The range and step sizes used are dependent on the observing frequency, bandwidth, number of frequency channels, direction of search, and available computational resources. A typical method is to create a set of DMs such that smearing due to DM error is less than the smearing within the frequency channels. Also, when the smearing time within the frequency channels is 2^N times the sample time, the time series is down-sampled by a factor of 2^N.

3.3. Search algorithms

There are various search methods for finding new MSPs. The most common is to perform an FFT and then incoherently sum harmonics (Taylor and Huguenin 1969). Binary pulsars' periods will change due to the Doppler shift from orbital motion. If the period change is significant over the length of an observation, then the pulsars' signal will be smeared across multiple Fourier bins. In order to mitigate this smearing, techniques assuming a constant acceleration such as the correlation method (Ransom *et al* 2001) or the stack/slide technique (Faulkner *et al* 2004) are often used. These techniques are effective for orbital periods much larger than the observation time. In the case of the current large sky surveys, which have observing times of a few minutes, these linear acceleration techniques are adequate.

3.4. Sifting and folding

After each of the de-dispersed time series have been searched, the resulting candidate signals must be sifted through in order to determine the likely pulsar candidates and remove ones which are unlikely to be real. Typical tactics used are to remove candidates which have periods of known RFI, do not appear at contiguous trial DMs, or are detected at only a single DM value. The candidates which make it through the sifting process are then made into diagnostic plots of the form shown in figure 3. In some cases, the resulting number of candidates can be too large for all candidates to be plotted, in which case only the top candidates are plotted.

3.5. Candidate analysis

Over the years, the instruments used to perform pulsar searches have improved drastically in frequency coverage, frequency resolution, and time resolution. One of the effects of these improvements is a drastic increase in the number of candidates generated by a search. This increase in candidates generated by pulsar surveys must be handled in some way by each of the survey groups. In recent years, there have been two major approaches to dealing with the large number of pulsar candidates. One is to develop automatic algorithms which are used to classify the candidates in such a way that real pulsars are distinguished from the RFI and noise. The other is to increase the number of people analyzing the data by training high school and undergraduate students to recognize pulsar signals. These two methods are described in detail below.

3.6. Automatic search algorithms

A majority of the search algorithms currently in use and being developed for distinguishing real pulsars from RFI and noise are based on what humans typically look for in the diagnostic plots created for each candidate. Some basic heuristics which are looked for in a candidate are: whether the signal is broadband, is detected throughout the observation, has a similar pulse profile to most known pulsars, has a DM curve shaped as expected, etc. Two tools which calculate these heuristics and provide methods for initial sorting are the JReaper tool (Keith *et al* 2009) and the PEACE algorithm (Lee *et al* 2013). Other techniques that take the heuristics calculated by tools like JReaper and PEACE and pass them to machine learning algorithms have also been developed or are currently being developed. The HTRU survey applied an artificial neural network which recovered 92% of known pulsars from ∼2.5 million candidates (Eatough *et al* 2010).

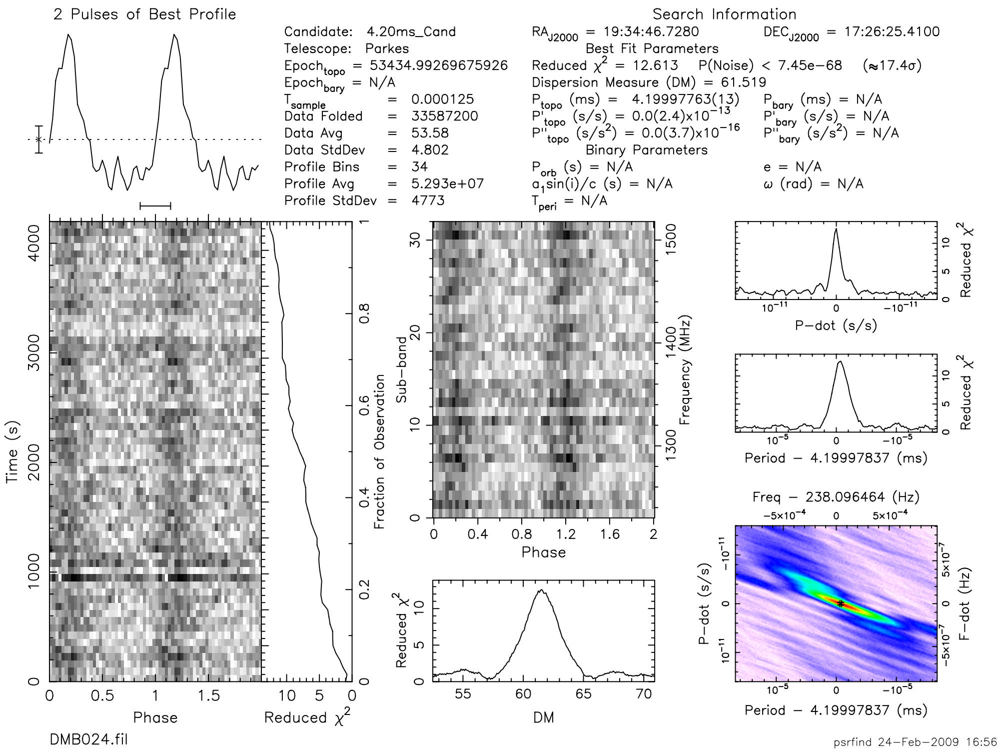

Figure 3. Example periodicity search output plot showing the discovery observation of the 4.2-ms pulsar J1935+1726 (Lorimer *et al* 2013) folded in time (lower left) and radio frequency (upper center) as well as the integrated pulse profile (upper left) and optimal DM search (lower center). The statistical significance of the signal in each of these diagrams is measured in terms of the reduced χ^2 square value computed from the integrated pulse profiles. A χ^2 value close to unity would be found for a profile that is consistent with Gaussian random noise.

3.7. Who searches for pulsars?

Pulsar searching has traditionally been the purview of graduate students as part of their thesis work[8]. In recent years, however, a number of groups have involved other groups through innovative outreach projects. In Australia the Pulse@Parkes project (Hobbs *et al* 2009) gives high school students the opportunity to carry out regular timing observations of pulsars using the Parkes radio telescope and learn about their properties. In Germany, the Einstein@Home project (Allen *et al* 2013) allows citizen scientists across the world the opportunity to participate in the discovery process by donating idle cycles on their home computers. Based on the Seti@Home infrastructure, Einstein@Home volunteers have so far discovered over 20 pulsars in searches of Arecibo and Parkes survey data (Knispel *et al* 2011, 2013).

In the US, two main pulsar searching outreach projects exist. The Arecibo Remote Command Center (ARCC) is a group of high school, undergraduate, and graduate students who work with university professors and local high school teachers in a program to detect new radio pulsars. The group was formed to get undergraduate students involved in research early in their careers, assist in controlling radio telescopes during pulsar survey observations, and to create a

[8] All three of the authors of the current paper spent a substantial fraction of their time sifting through pulsar search output!

large group of people to inspect the candidates from the pulsar surveys described in section 2.2. Students in this program have found a total of 46 pulsars over the past three years. There are currently ARCC centers at the University of Texas at Brownsville and the University of Wisconsin-Milwaukee. Another outreach effort which focuses on high school and middle-school students is the Pulsar Search Collaboratory (PSC), an NSF-funded project involving students and teachers analyzing 2800 deg^2 of the GBT drift-scan survey in partnership with the National Radio Astronomy Observatory and West Virginia University. Since the PSC began in 2008, nearly 800 students and 100 teachers have been involved in over 90 schools spread across 18 states in America. To date, students have inspected over 1.5 million search diagnostic plots and found a total of six new pulsars and identified previously known pulsars at a rate that is consistent with professional astronomers (Rosen *et al* 2013). Evaluation studies indicate that the PSC significantly increases student interest in science, engineering and computer science careers.

4. The MSP population

Understanding the origin and evolution of MSPs has provided a wealth of information and interesting puzzles over the years. One of the first efforts to quantify the MSP population was the work of Kulkarni and Narayan (1988). With a sample of only three MSPs, their study was subject to large uncertainties, but it began a significant discussion on the so-called 'birthrate problem' for MSPs. Based on their results Kulkarni and Narayan claimed that the birthrate of MSPs was substantially greater than that of their proposed progenitors, the low-mass x-ray binaries. Although this problem was alleviated as better constraints became available from larger samples (Lorimer 2008), very recently MSP population study (Levin *et al* 2013) suggested that the birthrate problem persists.

Following the 400 MHz MSPs surveys that took place during the 1990s, studies of the scale height, velocity distribution and luminosity function were performed (Lorimer 1995, Cordes and Chernoff 1997, Lyne *et al* 1998) and it was found that the local (within a few kpc) MSP population potentially observable was comparable in size to the equivalent population of normal pulsars. One conclusion from these studies is that the populations of millisecond and normal pulsars are consistent with a single velocity distribution applied to all neutron stars at birth (Tauris and Bailes 1996).

We are now in an era where the sample of MSPs is numerous enough to gain further insights into the population. As recently shown (Lorimer 2013), the MSP population can be described by a model in which the population of 30,000 potential observable MSPs has a luminosity function that is log-normal (Faucher-Giguère and Kaspi 2006, Bagchi *et al* 2011, consistent with the normal pulsars and recycled pulsars in globular clusters), an exponential scale height of 500 pc and a Gaussian radial distribution with a standard deviation of 7.5 kpc. Further work in this area is needed to quantify more subtle effects. Of particular interest are studies of the motion of MSPs in the $P - \dot{P}$ diagram and the relationship to the low-mass x-ray binary population. Additional work, along the lines of the population syntheses carried out by Story *et al* (2007), seems to be the next logical step. Significant progress is now being made in modeling the binary evolutionary steps and predicting distributions for orbital parameters for the binary population (see, for example, Belczynski *et al* 2008). Combining all these elements into an all-encompassing synthesis of the MSP population which accounts (as far as possible) for the observational selection effects is now a major goal of future studies. As part of this effort, a significant problem is to incorporate the gamma-ray/radio-selected sample of MSPs revealed by *Fermi* (Ray *et al* 2012). Are these pulsars more energetic than other MSPs? Are the spin periods of these MSPs shorter than the rest of the population? The answers are currently not clear and a careful study of the selection effects impacting this sample should now be undertaken in order to fully understand the impact of these discoveries on our knowledge of the MSP population.

5. Future surveys and prospects

The currently ongoing pulsar surveys are close to the most sensitive surveys possible with the current set of telescopes. So, in order to make significant leaps in sensitivity, instruments with larger collecting areas must be built. The next generation of telescopes are currently being planned and in some cases constructed. In the near future, MeerKAT and FAST will begin to come online. MeerKAT, an array of sixty-four 13.5 m dishes, will have about the equivalent sensitivity of a 100-m telescope. This will be an increase of about 2.5 over the existing telescopes in the southern hemisphere. The Five hundred meter Aperture Spherical Telescope (FAST) telescope is an Arecibo-like telescope which will have a diameter of 500 m. It will provide an increase in sensitivity of about a factor of two in regions of the sky visible by Arecibo and an increase by a factor of ten in other areas of the sky.

In the long term, the initial phase of the Square Kilometer Array (SKA) is expected to be built and will provide an increased sensitivity of about a factor of 1.3 in regions overlapping with FAST and a factor of more than 10 times in other regions of the sky. The field-of-view of the SKA will be significantly larger than that of the FAST telescope and therefore will have a much faster survey speed.

Other than FAST, the current trend in radio telescope development is to build large numbers of smaller antennas operating together as an array. These arrays alter the way that pulsar surveys are done (Stappers *et al* 2011, Coenen 2013). The time required to survey the entire sky is significantly reduced, since the beams of individual telescopes are quite large and multiple sky beams can be taken at once. However, the computational requirements and amount of data will also be significantly larger.

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Appendix. Useful resources

URL	Description
www.atnf.csiro.au/people/pulsar/psrcat	ATNF pulsar catalog
astro.phys.wvu.edu/GalacticMSPs	Galactic MSPs
www.naic.edu/~pfreire/GCpsr.html	Pulsars in globular clusters
www.naic.edu/~palfa/newpulsars	PALFA survey discoveries
astro.phys.wvu.edu/pmps	PMPS reprocessing at WVU
albert.phys.uwm.edu/radiopulsar/html/PMPS_discoveries	PMPS (Einstein@Home)
astro.phys.wvu.edu/GBTdrift350	GBT 350 MHz drift scan
arcc.phys.utb.edu/gbncc	GBNCC
www.naic.edu/~deneva/drift-search	Arecibo 327 MHz drift scan
www.astron.nl/pulsars/lofar/surveys/lotas	LOFAR Pilot Pulsar Survey
www.pulsarsearchcollaboratory.com	Pulsar Search Collaboratory
arcc.phys.utb.edu	Arecibo Remote Command Center
outreach.atnf.csiro.au/education/pulseatparkes	Pulse@Parkes
www.pulsarastronomy.net/wiki/Software/PulsarHunter	JREAPER
psrchive.sourceforge.net	PSRCHIVE
http://www.cv.nrao.edu/~sransom/presto	PRESTO
sigproc.sourceforge.net	SIGPROC

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