Part 1
The Pulsar Population

Section A
Surveys and Instruments

https://doi.org/10.1017/S0252921100040860 Published online by Cambridge University Press

Pulsars : Problems & Progress
ASP Conference Series, Vol. 105, 1996
S. Johnston, M. A. Walker and M. Bailes, eds.

Millisecond Pulsar Surveys

M. Bailes

Physics Department, University of Melbourne, Parkville, Victoria 3052, Australia. email: mbailes@physics.unimelb.edu.au

Abstract. There are now more than 30 millisecond pulsars known to be associated with the Galactic disk. The majority of these have been discovered in just the last few years as the result of large-scale all-sky surveys. The properties of the population vary tremendously. One unique object hosts a planetary system, more than half of those discovered possess white dwarf companions, two have extremely low-mass companions that are undergoing mass-loss and several others appear to be solitary. In this review I discuss the methods employed to find these millisecond pulsars, the parallels with early surveys for "normal" pulsars, and possible strategies for future searches.

1. Introduction

There have been several articles providing the details of specific large-scale millisecond pulsar surveys in recent years. I refer interested readers to papers by Manchester et al. (1996), Camilo, Nice & Taylor (1993), and Foster et al. (1995). For an excellent summary of the most recent surveys and the objects found readers should consult Camilo (1996), and for an overview of pulsar surveys over the last decade or so see Bailes & Johnston (1993).

Pulsar astronomy began in Cambridge when Jocelyn Bell noticed peculiar "scruff" present on her chart record in 1967. Since then, the search techniques have greatly increased in sophistication. There are now over 700 pulsars known and only a few of the brighter pulsars were discovered in the same manner as the first. Pulsar surveys are no longer limited to pulsars where the flux of an individual pulse is several times the noise. If the detected output of a telescope is sampled at regular intervals then long integrations can be searched for periodic signals using Fourier techniques. Equation 1 gives an expression for the minimum mean pulsar flux ($S_{\rm min}$) detectable by a telescope with gain G in an integration time τ across a bandwidth B (Dewey et al. 1984). The number of polarisations is $N_{\rm p}$ and T is the combined receiver and sky temperature plus any contributions due to spillover.

$$S_{\rm min} \sim 10 \frac{T}{G\sqrt{N_{\rm p}B\tau}}\sqrt{\frac{w}{P-w}} \tag{1}$$

Equation 1 differs from the normal sensitivity equation for a radiometer by the factor of 10 and the square root term involving the pulsar's period P and the apparent width w. The factor of ~10 arises because in a blind survey we do

https://doi.org/10.1017/S0252921100040860 Published online by Cambridge University Press

not have any *a priori* knowledge of the pulsar's period and dispersion measure and must search through all possible combinations. Equation 1 does not take into account the finite number of harmonics that can be summed, for a more rigorous discussion one should consult Camilo, Nice & Taylor (1996).

There is potential for a large increase in sensitivity if the apparent pulse width is small compared to the pulse period. Modern surveys therefore make every attempt to minimise any smearing of the pulse. All pulsar observations suffer from the effects of interstellar dispersion, and pulses are smeared by an amount

$$t_{\rm DM} = \frac{8.3BDM}{\nu^3}\mu s \qquad (2)$$

where B is the bandpass, in MHz, over which the signal is being detected, DM is the pulsar's dispersion measure in the units pc cm^{-3} and ν is the centre frequency of the observation in GHz. To minimize smearing, multi-channel filterbanks are used.

Pulsars are steep-spectrum objects, with typical spectral indices of -2. At 400 MHz where most pulsar surveys are conducted, a one second pulsar with a DM of 100 pc cm^{-3} is only smeared by 20 % across a 16 MHz bandpass. However a 200 ms pulsar is rendered invisible. Surveys in the 1970's began breaking up the total receiver bandpass into several independent channels in order to combat the effects of pulse dispersion and searched in dispersion measure as well as pulse frequency (eg. Hulse & Taylor 1975). These surveys clearly demonstrated that the pulsar period distribution fell away rapidly at periods below 100 ms. However a search by Hulse & Taylor at Arecibo in 1974 discovered the 59 ms pulsar B1913+16 in a 7.75 hour orbit around another neutron star. This pulsar had one of the weakest known magnetic field strengths, and shortest periods. In retrospect, this fascinating system was a beacon pointing the way towards the location of the millisecond pulsars in the $B-P$ diagram (see Fig 1). The short pulse period was only a few times the sampling time of the Arecibo survey, and had it not been found it is interesting to speculate about whether the field of pulsar astronomy would have endured long enough for the millisecond pulsars to have been found.

The histogram of pulsar periods is now clearly bimodal (see Fig 1), but before the discovery of the 1.6 ms pulsar PSR B1937+21 by Backer et al. (1982) there was no reason to suspect that more than a handful of pulsars would exist in the Galaxy with periods shorter than that of the Crab. All pulsars were believed to begin their lives with short periods and large magnetic field strengths and quickly spin down to slower periods (Manchester & Taylor 1977). The 33 ms Crab pulsar, after all, was only a little over 900 years old and the supernova rate thought to only be at most a few per century.

After its discovery in 1981 by Backer et al. (1982) PSR B1937+21 came as a great shock to the pulsar community. Its properties proved to be fascinating. Unlike normal pulsars, it was able to have its arrival times measured to sub-μs accuracy, but even more importantly it showed very little, if any, "timing noise" - presumably as a consequence of its low magnetic field strength. This opened up a whole new era in pulsar timing. Any binary system containing a millisecond pulsar could be mapped to extraordinary precision. The pulsar itself rivalled the Earth's best clocks for accuracy and searches explicitly targeting millisecond pulsars began.

https://doi.org/10.1017/S0252921100040860 Published online by Cambridge University Press

Figure 1

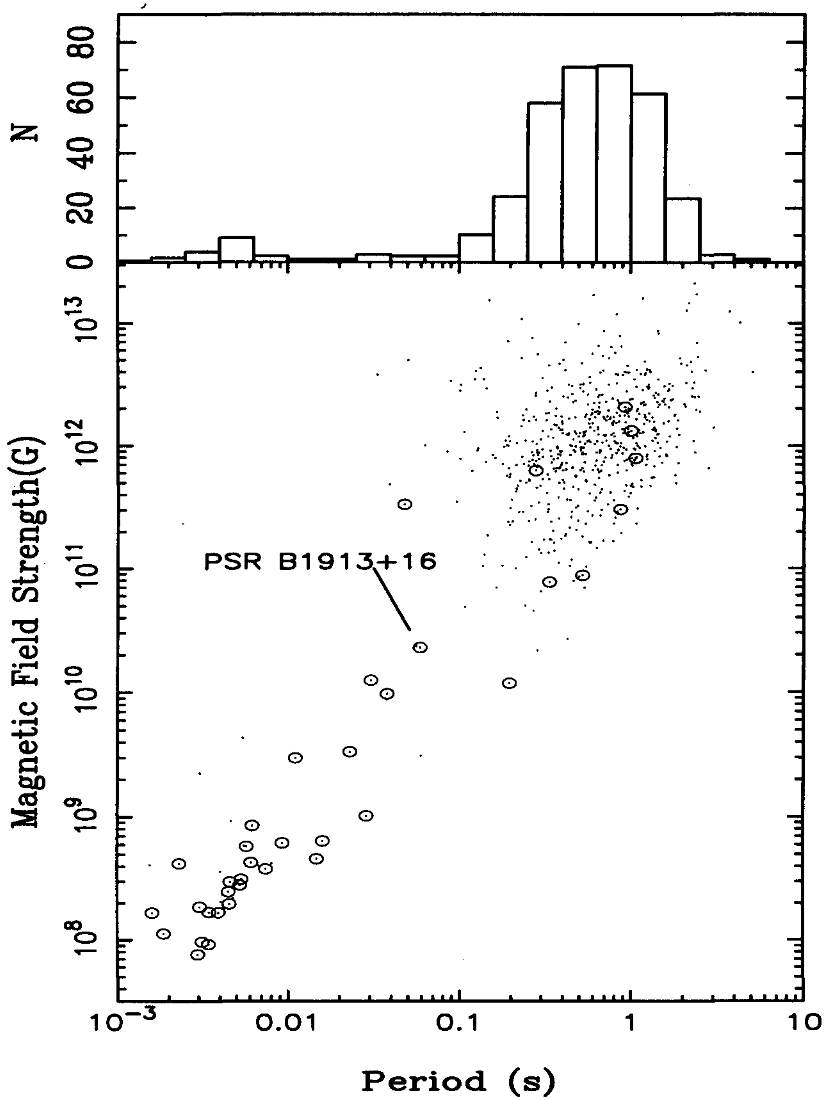

Figure 1. The period distribution of pulsars with known period derivatives (upper panel) and the magnetic field period diagram (lower panel). Binary pulsars are indicated by circles. The binary pulsar PSR B1913+16, discovered in 1974, had the weakest-known magnetic field strength and the second-shortest period at the time of its discovery (see text).

https://doi.org/10.1017/S0252921100040860 Published online by Cambridge University Press

2. Millisecond Pulsar Surveys

Early surveys concentrated on the Galactic plane. The survey by Segelstein et al. (1986) was the first to discover a millisecond pulsar in a survey. The next "disk" millisecond pulsar to be discovered was the eclipsing pulsar PSR 1957+20 by Fruchter et al. (1988). However it was not until Wolszczan surveyed 150 square degrees off the Galactic plane (Wolszczan 1990) and found two exciting recycled pulsars that observers began looking off the disk in earnest. It was soon demonstrated that the distribution of low-luminosity millisecond pulsars would be largely isotropic (Johnston & Bailes 1991). The continued advance in computer technology made the processing of large-scale surveys a real possibility without the need for supercomputer facilities. Equally important, the introduction of 8mm tape systems capable of recording over 2 GB of information made the transportation and storage of enormous amounts of information trivial compared to the previous generation of mass-storage media (round tapes). Many groups from around the world began large-scale surveys.

Millisecond pulsar surveys are extremely prone to the effects of not only pulse dispersion by the interstellar medium but also interstellar scattering. This is demonstrated by a comparison of the distribution of their dispersion measures compared to that of the normal pulsars (Fig 2). Distant millisecond pulsars are too smeared to be detected.

The entire Southern sky has now been surveyed for millisecond pulsars and much of the North. The recent Parkes survey (Manchester et al. 1996) discovered 17 pulsars with periods less than 20 ms. Although this represented a tremendous increase over the number of previously known millisecond pulsars (6 when the survey began), the penetration of the survey was still quite shallow with many of the newly-discovered millisecond pulsars being quite nearby (within $\sim$1 kpc). This is primarily due to the dispersion of the pulses across the individual filter channels increasing their apparent width, and from Eqn 1 decreasing the sensitivity of the survey at larger dispersion measures. Until very recently the minimum filter width employed in surveys has been 125 kHz. This leads to a smearing of 0.3 ms for every 25 units of dispersion measure at 430 MHz, thus increasing minimum detectable flux. Once the smearing is larger than the pulse period, the pulsar becomes invisible. The Parkes survey used an extremely wide bandwidth of 32 MHz centred on 430 MHz. The detected outputs of $2 \times 256 \times 125$ kHz channels were sampled every 300 μs. In theory, a 6 ms pulsar at a DM of 250 cm^3 pc^{-1} is only smeared by 50 % in such a system. There are some more subtle effects at play here though. Over the past few years the radio frequency environment at Parkes has become more and more polluted by man-made signals, many of which resemble pulsars with wide duty-cycles. There are so many of these interfering signals present that it is difficult for even relatively sophisticated algorithms to completely eliminate them, particularly at low levels. As a result the survey produced many 100s of "significant" candidates whose profiles had a remarkably sinusoidal appearance (almost certainly due to "birdies"). Although many of these were reobserved, candidate pulsars with narrow duty cycles were far more likely to be real pulsars, and the sheer number of short-period candidates with only one or two harmonics meant that only a small percentage of them could be reobserved. In the final analysis, the shortest period pulsar found was PSR J0034–0534 with a period of 1.87 ms and a DM of

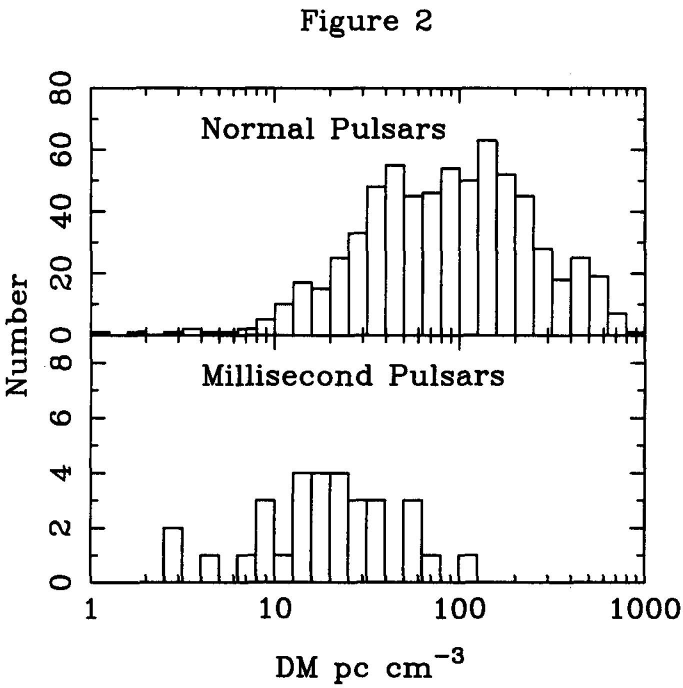

Figure 2. Histograms showing the distribution in dispersion measure for the millisecond and normal pulsars. The known millisecond pulsars are comparatively local objects, partly due to selection effects (see text).

https://doi.org/10.1017/S0252921100040860 Published online by Cambridge University Press

13. Unfortunately, increasing commercial use of the radio spectrum will only get worse in at least the short-term future and make the discovery of millisecond pulsars, and statistical inferences about the Galactic population increasingly difficult.

There have been a number of other surveys conducted over recent years. After Parkes, the most successful have been reasonably generic surveys conducted by at least 4 separate groups using the Arecibo 305m antenna. These surveys have discovered of order 15 millisecond pulsars (depending upon what is deemed to be a "millisecond" pulsar). Unlike the Southern skies, there are still "unchartered waters" within reach of the Arecibo telescope which should yield still further millisecond pulsars in coming years.

At Jodrell Bank a survey of the Northern sky between $+35^o$ and $+90^o$ has found the potentially youthful millisecond pulsar PSR J1012+5307 and is of order 50 % complete (Nicastro et al. 1995). A short-period, high-dispersion measure pulsar (PSR J0218+4232) was found using the Jodrell Bank 76m telescope as the result of a follow-up of a steep-spectrum object discovered at Westerbork by Navarro et al. (1995). Observations of an unrelated gamma-ray point source led to the discovery of another (Lundgren et al. 1995). A large scale survey of the Northern sky was performed by Sayer, Nice & Taylor (1996) using the Green Bank 140 ft antenna and discovered an unusual binary pulsar in a mildly relativistic system.

At Parkes the millisecond discovery rate is of order $\sim$1/1200 square deg compared to $\sim$1/500 square deg at Arecibo. We expect when the current round of surveys at Arecibo are over, the total population of "disk" millisecond pulsars should be of order 50. Apart from those millisecond pulsars which have been discovered in targeted searches all of the "disk" (as opposed to globular cluster) millisecond pulsars have been found in surveys conducted at an observing frequency of $\sim$ 430 MHz. Earlier surveys at high frequencies by Clifton and Lyne (1986) and Johnston et al. (1992) at high frequencies failed to find any millisecond pulsars, although the sampling time of the former survey was 2 ms and the Johnston et al. (1992) survey had a bandwidth of only 80 MHz in its narrow-channel system.

3. More millisecond pulsars?

The properties of the Galactic population of millisecond pulsars are becoming clear. The binary fraction (>50%) is almost two orders of magnitude greater than that of the normal pulsars. This is extremely strong evidence that millisecond pulsars are formed as the result of accreting matter from a binary companion as proposed by Alpar et al. (1982) shortly after the discovery of the original (solitary) millisecond pulsar. The active Galactic population is over 40000 (Lorimer et al. 1994). This number may need to be revised upwards with the discovery of several extremely low luminosity millisecond pulsars by the Parkes survey (Bailes et al. 1996). In one special case, a millisecond pulsar possesses its own planetary system (see Wolszczan's contribution to these proceedings). The discovery of another pulsar planetary system would be more than adequate reward for future millisecond pulsar surveys.

Compared to normal pulsars, millisecond pulsars offer much greater timing precision. This has led to applications involving constraints on cosmological models (Stinebring et al. 1990), limits on the time rate of change on Newton's constant (Nice, Taylor & Fruchter 1993), proof of the existence of gravitational waves (Weisberg & Taylor 1984), and observations of the Shapiro delay (Ryba & Taylor 1991). In the future we expect several of the recently-discovered millisecond pulsars to yield timing parallaxes and proper motions, providing information about the free electron density of the interstellar medium and millisecond pulsar kinematics. Millisecond pulsars also provide the opportunity to tie the planetary, radio and optical reference frames. The spin-down ages of pulsars can be used to constrain white dwarf cooling models and the discovery of a sub-ms pulsar would place severe constraints on the equation of state of nuclear matter. More radical applications involve the use of millisecond pulsars as a gravity wave telescope to search for the signature of extremely massive black hole binaries in the Universe (Romani 1989). The Galactic population of neutron star-neutron star binaries that will coalesce in a Hubble time is vital for the predictions of detectable sources of gravitational wave emission (Phinney 1991, Curran & Lorimer 1995) . Surveys sensitive to short period pulsars are the best way to constrain the population of such systems.

4. Millisecond pulsar surveys of the future.

Plans are already underway for still further surveys. The upgraded Arecibo telescope will be more sensitive and find still fainter pulsars in the same regions that have already been surveyed. At Parkes a 13-beam system is just being commissioned that will allow surveys of an extremely large area of sky to be undertaken at 1400 MHz. Plans are also afoot to use the Giant Metre-Wave Telescope in India for pulsar searches. All of these new surveys are expected to find several millisecond pulsars.

The backend is as important as the receiver temperature and telescope Gain however. At Arecibo the Penn State group has developed a new filterbank system with 60 kHz filters. At Jodrell Bank, a massive $13 \times 2 \times 96 \times 3$ MHz filterbank system has been developed for the Parkes multibeam survey. At Caltech a novel technique is being developed to expand the frequency resolution of existing filterbank systems. In the future we expect baseband recording to be employed in combination with powerful computers to synthesize filterbanks with still finer resolution.

The success or otherwise of the new high-frequency Parkes multibeam survey for millisecond pulsars will be crucial in the future search strategies of groups around the world. Even baseband recording techniques cannot combat interstellar scattering. Searching at higher frequencies is the only way to prevent significant smearing of the individual pulses for more distant millisecond pulsars. The Parkes multibeam survey is relatively immune to scattering due to the high power-law dependence of scattering on frequency. Like the Clifton & Lyne survey, I predict that it will discover a quite different population of pulsars than the previous 430 MHz surveys of the same region. Where the most science will ultimately come from is not yet clear. Deeper searches will tend to find fainter pulsars which are more difficult to time accurately either due to smaller flux densities or large dispersion measures. Many of the applications listed above require microsecond precision arrival times which may not be possible on these fainter objects with existing telescopes.

References

Alpar, A. et al. 1982, Nature, 300, 728.

Backer D. C. et al. 1982, Nature, 300, 615.

Bailes, M. & Johnston, S., 1993, in "Review of Radio Science 1990-1992", ed W. R. Stone, Oxford University Press, p 677

Bailes et al., 1996, ApJ, in prep.

Camilo, F., Nice, D. & Taylor, J. H., 1993, ApJ, 412, L37.

Camilo, F. 1996, in "High Sensitivity Radio Astronomy", Cambridge University Press.

Clifton, T. R., & Lyne, A. G., 1986, Nature, 320, 43.

Curran, & Lorimer, D. R., 1995, MNRAS, 276, 347.

Dewey, R. J. et al., 1984, in "Millisecond Pulsars", eds S. P. Reynolds & D. R. Stinebring, NRAO Green Bank, p. 234

Foster, R. S., Cadwell, B. J., Wolszczan, A. & Anderson, S. B., 1995, ApJ, 454, 826.

Fruchter, A. S., Stinebring, D. R. & Taylor, J. H., 1988, Nature, 333, 237.

Hulse, R. A. & Taylor, J. H., 1975, ApJ, 201 L55.

Johnston, S. & Bailes, M., 1991, MNRAS, 252, 277.

Johnston et al. 1992, MNRAS, 255, 401.

Lorimer et al. 1995, ApJ, 439, 933.

Lundgren, S. C., Zepka, A. F., & Cordes, J. M., 1995, ApJ, 453, 419.

Manchester et al. 1996, MNRAS, 279, 1235.

Manchester, R. N. & Taylor, J. H., 1977, "Pulsars", Freeman, San Francisco.

Navarro J. N. et al., 1995, ApJ, 455, L55.

Nicastro, L. et al., 1995, MNRAS, 273, L68.

Nice, D., Taylor, J. H. & Fruchter, A. S., 1993, ApJ, 402, L49.

Phinney, E. S., 1991, ApJ, 380, L17.

Romani, R. 1989, in "Timing Neutron Stars", Kluwer, eds Ögelman & van den Heuvel, p 113.

Ryba, M. & Taylor, J. H., 1991, ApJ, 371, 739.

Sayer, R. W., Nice, D. J. & Taylor, J. H., 1996, ApJ, submitted.

Segelstein et al., 1986, Nature, 322, 714.

Stinebring et al., 1990, Phys.Rev.Lett, 65, 285.

Weisberg & Taylor, J. H., 1984, Phys. Rev. L., 52, 1348.

Wolszczan, A., 1990, IAU circular 5073.

https://doi.org/10.1017/S0252921100040860 Published online by Cambridge University Press