Recycled Pulsars

Bryan Anthony Jacoby

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Bryan Anthony Jacoby

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This thesis is dedicated to my wonderful wife Megan, whose love and support have sustained me throughout this work.

Abstract

We present the results of a large-area survey for millisecond pulsars (MSPs) at moderately high galactic latitudes with the 64-m Parkes radio telescope, along with follow-up timing and optical studies of the newly-discovered pulsars and several others. Major results include the first precise measurement of the mass of a fully recycled pulsar and measurement of orbital period decay in a double neutron star binary system allowing a test of general relativity along with improved measurements of the neutron star masses.

In a survey of $\sim 4,150$ square degrees, we discovered 26 previously unknown pulsars, including 7 "recycled" millisecond or binary pulsars. Several of these recycled pulsars are particularly interesting: PSR J1528−3146 is in a circular orbit with a companion of at least $0.94\,M_\odot$; it is a member of the recently recognized class of intermediate mass binary pulsar (IMBP) systems with massive white dwarf companions. We have detected optical counterparts for this and one other IMBP system; taken together with optical detections and non-detections of several similar systems, our results indicate that the characteristic age $\tau_c = P/2\,\dot{P}$ consistently overestimates the time since the end of mass accretion in these recycled systems. This result implies that the pulsar spin period at the end of the accretion phase is not dramatically shorter than the observed period as is generally assumed. PSR J1600−3053 is among the best high-precision timing pulsars known and should be very useful as part of an ensemble of pulsars used to detect very low frequency gravitational waves. PSR J1738+0333 has an optical counterpart which, although not yet well-studied, has already allowed a preliminary measurement of the system's mass ratio. The most significant discovery of this survey is PSR J1909−3744, a 2.95 ms pulsar in an extremely circular 1.5 d orbit with a low-mass white dwarf companion. Though this system is a fairly typical low-mass binary pulsar (LMBP) system, it has several exceptional qualities: an extremely narrow pulse profile and stable rotation have enabled the most precise long-term timing ever reported, and a nearly edge-on orbit gives rise to a strong Shapiro delay signature in

the pulse timing data which has allowed the most precise measurement of the mass of a millisecond pulsar: $m_p = (1.438 \pm 0.024)\,M_\odot$. Our accurate parallax distance measurement, $d_\pi = (1.14^{+0.08}_{-0.07})$ kpc, combined with the mass of the optically-detected companion, $m_c = (0.2038 \pm 0.0022)\,M_\odot$, will provide an important calibration for white dwarf models relevant to other LMBP companions.

We have measured the decay of the binary period of the double neutron star system PSR B2127+11C in the globular cluster M15. This has allowed an improved measurement of the mass of the pulsar, $m_p = (1.3584 \pm 0.0097)\,M_\odot$, and companion, $m_c = (1.3544 \pm 0.0097)\,M_\odot$, as well as a test of general relativity at the 3% level. We find that the proper motions of this pulsar as well as PSR B2127+11A and PSR B2127+11B are consistent with each other and with one published measurement of the cluster proper motion.

We have discovered three binary millisecond pulsars in the globular cluster M62 using the 100-m Green Bank Telescope (GBT). These pulsars are the first objects discovered with the GBT.

We briefly describe a wide-bandwidth coherent dedispersion backend used for some of the high precision pulsar timing observations presented here.

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Chapter 1

Introduction

The story of the study of pulsars begins in 1054 A.D., when Chinese astronomers observed the appearance of a bright object in the sky, the Crab supernova. We now know that supernovae like the Crab are the death cries of massive stars. Nearly 900 years later, Baade & Zwicky (1934) hypothesized that a very compact, dense remnant — a dead star composed almost entirely of neutrons — could be produced in a supernova explosion. However, it was assumed that these small neutron stars would not emit enough thermal radiation to be detected by optical telescopes. In 1967, Jocelyn Bell was observing interplanetary scintillation of celestial radio sources and found periodic bursts of radio noise unlike anything that had ever been seen before. These pulses, repeating every 1.3 s and visible each day in the same part of the sky, turned out to be the pulsar PSR B1919+21 (Hewish et al., 1968), a spinning, highly-magnetized neutron star sending out beams of radio waves along its magnetic axis. When these beams sweep past the earth, we see the pulsar blink on and then off, much like a rotating lighthouse beacon. Soon thereafter, Staelin & Reifenstein (1968) discovered a pulsar spinning 30 times per second at the heart of the Crab supernova remnant.

The discovery of the first binary pulsar, PSR B1913+16 (Hulse & Taylor, 1975), and of the first millisecond pulsar (MSP), PSR B1937+21 (Backer et al., 1982), ushered in the era of recycled pulsars and high-precision timing. After a neutron star is born, it gradually slows and eventually ceases to shine. In some circumstances, the neutron star can be recycled and begin a new life by accreting matter and angular momentum from a binary companion, spinning the neutron star up to fantastic rates. To the chagrin of many pulsar astronomers, after over twenty years of searching for more MSPs, PSR B1937+21 is still the most rapidly rotating pulsar known, spinning over 640 times per second! MSPs, with more than the mass of the sun packed into an object the size of a small city, a magnetic field 10^8 times stronger than that of the earth, and spinning faster than the blades of a kitchen blender or the crankshaft of a Formula 1 race car engine, are among the most exotic objects known in the universe. Well over 100 recycled pulsars are known today (out of over 1,500 pulsars total) — many in globular star clusters.

With incredible rotational stability rivaling that of atomic clocks, recycled pulsars provide ideal laboratories for a variety of physical experiments. Binary pulsars with massive companions can be used to test theories of gravity (Taylor & Weisberg, 1989; Stairs et al., 2002), and by timing the most stable MSPs, it will be possible to constrain or possibly even detect low-frequency gravitational waves emitted by massive black hole binary systems (Jaffe & Backer, 2003; Lomen et al., 2003). The ability to conduct these ultra-precise experiments with stars scattered across the galaxy with precision far exceeding almost every other type of astronomical observation comes from the technique of pulsar timing. Briefly, the arrival times of pulses obtained from a given set of observations are compared with a model or mathematical description of the expected pulsar behavior, and in turn, used to improve our knowledge of the model parameters. The power of this technique comes from the ability to count exactly how many rotations of the pulsar have taken place between one observation and the next over a long period of time, leading to very small fractional uncertainties in the model parameters (see Bell, 1998 for a detailed overview). A large part of the motivation for present and future pulsar search efforts is finding objects that will improve the quality of these timing experiments, or allow completely new experiments as in the case of the recently-discovered double pulsar system (Burgay et al., 2003; Lyne et al., 2004). Another primary motivation is the detection of an object spinning substantially faster than PSR B1937+21, whose very existence would provide direct constraints to theoretical models describing the mass – radius relation of nuclear matter (Fig. 2.11).

Motivated by these considerations, we have surveyed a large area of the sky at moderately high galactic latitudes for pulsars (Chapter 2). This effort resulted in the discovery of 7 recycled pulsars (Chapters 3 and 4), including one remarkable object which has allowed the first precise measurement of the mass of an MSP (Chapter 5). We have completed a series of optical observations of pulsars with massive white dwarf binary companions (Chapter 6), one of which was discovered in the pulsar survey. Through long-term timing observations of the double neutron star binary PSR B2127+11C in the globular cluster M15, we have verified that general relativity provides a correct description of gravity at the 3% level, improved upon the previous mass measurements of the pulsar and its companion, and verified the proper motion of M15 (Chapter 7). We have discovered three binary MSPs in the globular cluster M62 (Appendix A) as part of a study of globular cluster pulsars which is still in progress. Finally, we describe the design of an observing system used for some of the observations presented here (Appendix B).

Chapter 2

A Large-Area Survey for Radio Pulsars at High Galactic Latitudes†

B. A. Jacoby[a], M. Bailes[b], S. Ord[b], H. Knight[b,c], A. Hotan[b,c], R. T. Edwards[c], and S. R. Kulkarni[a]

[a]Department of Astronomy, California Institute of Technology, MS 105-24, Pasadena, CA 91125; baj@astro.caltech.edu, srk@astro.caltech.edu.

[b]Centre for Astrophysics and Supercomputing, Swinburne University of Technology, P.O. Box 218, Hawthorn, VIC 31122, Australia; mbailes@swin.edu.au, sord@swin.edu.au, ahotan@swin.edu.au.

[c]Australia Telescope National Facility, CSIRO, P.O. Box 76, Epping, NSW 1710, Australia; Russell.Edwards@csiro.au.

Abstract

We have completed a survey for pulsars at high galactic latitudes with the 64-m Parkes radio telescope. Observing with the 13-beam multibeam receiver at a frequency of 1374 MHz, we covered $\sim 4,150$ square degrees in the region $-100^\circ \leq l \leq 50^\circ$, $15^\circ \leq |b| \leq 30^\circ$ with 7,232 pointings of 265 s each. The signal from each beam was processed by a $96-$channel $\times$ $3\,$MHz $\times\, 2-$polarization filterbank, with the detected power in the two polarizations of each frequency channel summed and digitized with 1-bit resolution every $125\,\mu$s, giving good sensitivity to millisecond pulsars with low or moderate dispersion measure. The resulting 2.4 TB data set was processed using standard pulsar search techniques with the workstation cluster at the Swinburne Centre for Astrophysics and Supercomputing. This survey resulted

†Part of a manuscript in preparation for publication in *The Astrophysical Journal*

in the discovery of 26 new pulsars including 7 binary or millisecond "recycled" pulsars, and re-detected 36 previously known pulsars. We describe the survey methodology and results, and present timing solutions for the 19 newly discovered slow pulsars.

2.1 Introduction

Since the discovery of the first radio pulsar (Hewish et al., 1968), a great deal of effort in radio astronomy has been expended searching for pulsars, with about 1,500 pulsars known today. Until the late 1990s, most pulsars surveys focused on the region of sky near the plane of our galaxy since that is where the density of pulsars is highest. Also, early surveys usually were conducted at frequencies around 400 MHz because of pulsars' steep radio spectra, and because the larger beam produced by a given telescope at lower frequencies allowed for more rapid coverage of the sky, or conversely, longer integration on a given point in the sky, given a region of sky to cover and a fixed allocation of observing time.

However, there are clear advantages to searching for pulsars at higher frequencies. Most notably, dispersion and scattering are mitigated, allowing for better time resolution and sensitivity to pulsars with large dispersion measures (DMs). Also, the galactic synchrotron background has a steep spectrum and contributes little to the total system temperature at higher frequencies. The final disadvantage of high-frequency surveys, namely the slow sky coverage resulting from a small telescope beam, has been overcome by the innovative 13-beam multibeam receiver package at the Parkes radio telescope (Staveley-Smith et al., 1996) and 13 accompanying analog filterbanks which provide a combined beam area on the sky about 25% larger than the 70-cm system used in the Parkes Southern Pulsar Survey (Manchester et al., 1996). The Parkes Multibeam Pulsar Survey covering $\sim 1,500$ square degrees within 5° of the galactic plane has used this system to great effect, roughly doubling the number of pulsars known before this survey began (Manchester et al., 2001; Hobbs et al., 2004).

While pulsars descend from short-lived massive stars which are born and die in the galactic disk, older pulsars have had time to migrate to moderate to high galactic latitudes. Millisecond pulsars (MSPs) which spin roughly a hundred times or more each second are in this older group, having lived a life as a "normal" pulsar, then later being "recycled" to very fast rotation rates by accreting matter from an evolved binary companion. It is these objects which promise to reveal the neutron star equation of state: discovering ever faster spinning pulsars constrains the size of neutron stars, and measuring effects predicted by Einstein's general relativity allows us to determine their masses. Although the density of pulsars is less at high galactic latitudes than in the plane of the galaxy, a shallow survey of this relatively neglected part of the sky provides an efficient means for discovering recycled pulsars, as demonstrated by the Swinburne Intermediate Latitude Pulsar Survey in a region between 5° and 15° from the galactic plane (Edwards & Bailes, 2001b; Edwards et al., 2001). Here, we describe the results of a 21-cm multibeam survey for pulsars at higher galactic latitudes between 15° and 30° from the galactic plane.

2.2 Observations and Analysis

Between 2001 January and 2002 December, we observed roughly 4,150 square degrees in the region $-100^\circ \leq l \leq 50^\circ$, $15^\circ \leq |b| \leq 30^\circ$ in 7,232 individual pointings of 265 s with the 64-m Parkes radio telescope at a frequency of 1374 MHz. Using the 13-beam multibeam receiver system, the signal from each beam was processed by a 96 MHz $\times$ 2 filterbank, the powers from each polarization pair summed, and the result 1-bit sampled at 125 μs intervals. The resulting 94,016 survey beams comprising 2.4 TB in total were written to 98 DLT tapes for later analysis. The observing and data processing procedures were virtually identical to those described by Edwards et al. (2001). Our observing hardware and methodology were identical to the Parkes Multibeam Pulsar Survey, except that our integration time per pointing was shorter (265 s compared to 2,100 s) and our sampling interval was half as long (125 μs compared to 250 μs).

The minimum detectable flux $S_{\rm min}$ for a radio periodicity search can be calculated by a modified form of the radiometer equation,

$$S_{\rm min} = \frac{\alpha\,\beta\,(T_{\rm rec} + T_{\rm sky})}{G\,(2\,\Delta\nu\,t_{\rm int})^{1/2}} \left(\frac{\delta}{1-\delta}\right)^{1/2}, \tag{2.1}$$

where α is the threshold signal-to-noise ratio (S/N), $\beta \approx 1.5$ is an efficiency factor taking account of losses such as quantization error, G is the telescope gain, $\Delta\nu$ is the observed bandwidth, $t_{\rm int}$ is the integration time, $T_{\rm rec}$ and $T_{\rm sky}$ are the receiver and sky contributions to the system noise temperature, and δ is the effective fractional duty cycle of the periodic signal, including contributions from the sample period, dispersion smearing, finite DM search step size, and scattering. Figure 2.1 shows representative sensitivity curves for this survey. In our calculations, we have assumed that the pulsar signal contains $(2\,\delta)^{-1}$ equally significant harmonics in the frequency domain.

Our large data set was analyzed with the cluster of 64 Compaq Alpha workstations at Swinburne University of Technology's Centre for Astrophysics and Supercomputing. The filterbank data from each survey beam were padded with 32 empty channels with appropriate frequency spacing so that dispersion was a linear function of channel number in this 128-channel space. First, each channel was searched for strong, narrow-band radio frequency interference (RFI), and affected channels were masked. We then used the "tree" dedispersion algorithm (Taylor, 1974) to break the 128 channels into 16 sub-bands, each dedispersed at a range of different DMs. This sub-band data could then be efficiently dedispersed and summed to form one of 374 trial DMs up to a maximum $562.5\,\mathrm{pc\,cm^{-3}}$. Once the sub-band DM reached twice the diagonal DM of $17\,\mathrm{pc\,cm^{-3}}$ (when roughly one sample period of smearing occurs within an individual channel), adjacent samples were summed (thereby doubling the diagonal DM) and the process repeated until the maximum search DM was reached.

The periodicity search used an adaptation of the search software from the Parkes Southern Pulsar Survey (Manchester et al., 1996) and followed standard pulsar search procedures. Briefly, the Fourier transform was computed for a given trial DM and searched for harmonically related patterns with a fundamental frequency greater than $1/12\,\mathrm{Hz}$, summing up to 16 harmonics of a given frequency. The large list of possible candidates in the three-dimensional space of repetition frequency, number of harmonics summed, and DM was consolidated into a list of the best 99 suspects from each survey beam. Each of these was then subjected to a time-domain optimization in spin period (P) and DM. For each beam, the 48 most promising suspects from this optimization were saved for further scrutiny.

Candidate pulsars were selected from 1.2 million search suspects using a variety of fixed and adaptive filters, and finally, by human examination. Typically, the roughly 45,000 suspects from a given tape were considered together. Filters were constructed to eliminate known interference frequencies and to enforce criteria to eliminate other low-quality suspects such as short-period suspects with large relative DM error. The S/N threshold was set at 9 for suspects with $P \geq 20\,\mathrm{ms}$ and 9.5 for shorter-period suspects to help eliminate the many

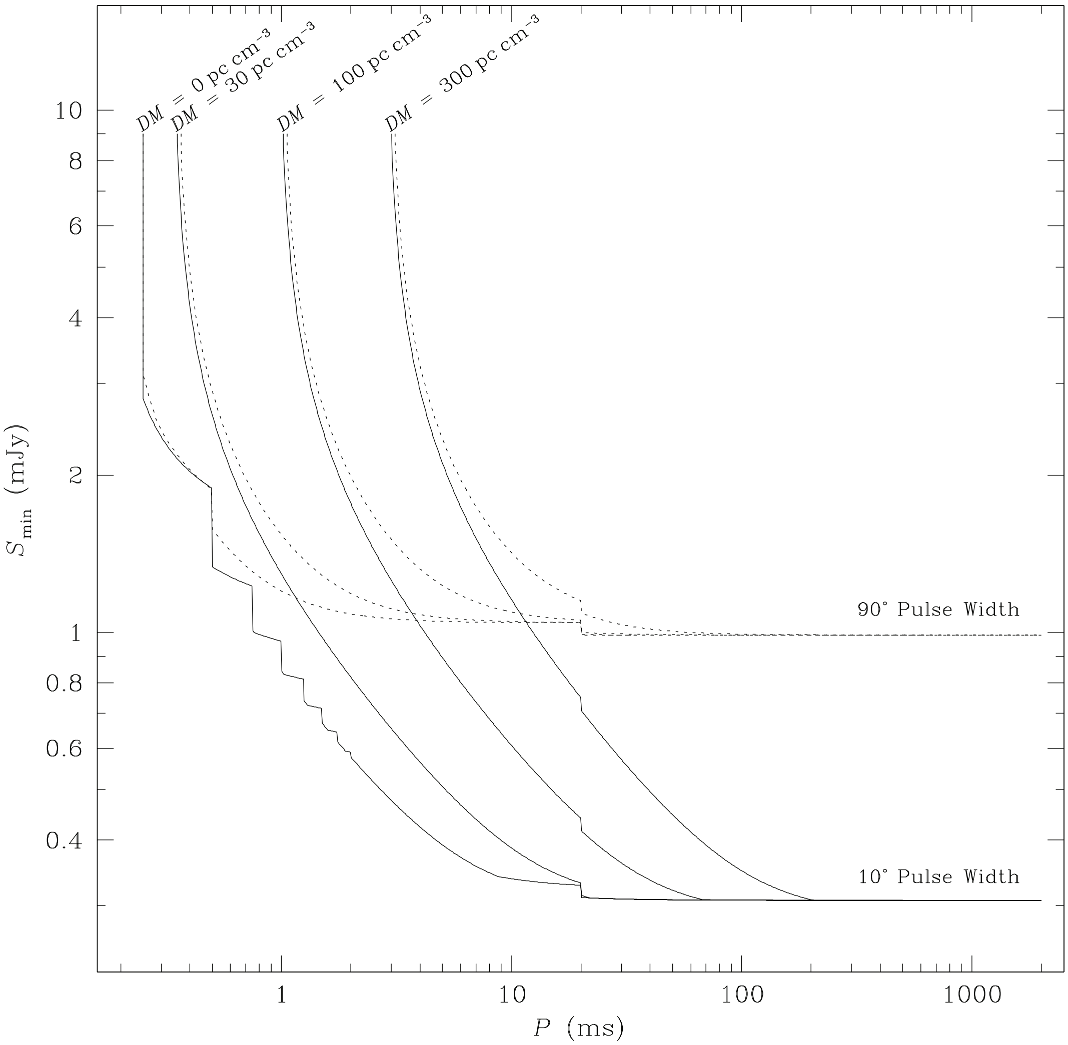

Figure 2.1: Survey sensitivity. Curves show minimum detectable 1400 MHz flux density as a function of spin period for pulsars with large (dotted curves) and small (solid curves) duty cycles for a range of dispersion measures as labeled.

spurious short-period signals found in our data. Finally, adaptive filters were used to allow signals that appeared at nearly the same period separated by many telescope beam widths many times on one tape. These automated parameter-based filters and screens allowed us to cull the suspect list to fewer than 10,000, each of which was then given much more human attention than would have been possible for the full set of suspects. Diagnostic information for two example candidate pulsars which were eventually confirmed is shown in Figures 2.2 and 2.3. Plausible pulsar candidates were re-observed, with the observation time depending on the strength of the candidate.

We note that in the case of one extremely convincing MSP candidate — later confirmed as PSR J1741+13 — it took four re-observations before it appeared again. This experience highlights the important role played by scintillation in pulsar surveys. Many other candidates which were not as convincing or interesting as this one were, of course, not afforded four confirmation attempts, and there are doubtless other pulsars in the survey region which were not visible at the time of the survey observation. We have no doubt that re-observing regions which have previously been surveyed will yield new discoveries, even when a new observing capability or strategy is not brought to bear.

2.3 Detected Pulsars

In addition to the seven recycled pulsars described in Chapters 3 and 4, this survey discovered 19 new slow pulsars. After confirmation, we began a roughly monthly timing program to determine phase-connected timing solutions for all slow pulsars using the Parkes $512 \times 0.5\,\mathrm{MHz} \times 2$ filterbank in conjunction with the center beam of the multibeam receiver centered on 1390 MHz. Following standard pulse timing procedures, folded profiles were cross-correlated with a template profile to determine times of arrival (TOAs). We used the standard pulsar timing package TEMPO[1], along with the Jet Propulsion Laboratory's DE405 ephemeris for all timing analysis. TOA uncertainties for each pulsar were scaled to achieve reduced $\chi^2 \simeq 1$ in order to improve the estimation of parameter uncertainties. Timing solutions for these pulsars are given in Table 2.1 and derived parameters are given in Table 2.2. Average pulse profiles are shown in Figure 3.1, and timing residuals relative to the models in Table 2.1 are shown in Figures 2.5 and 2.6.

[1]http://pulsar.princeton.edu/tempo

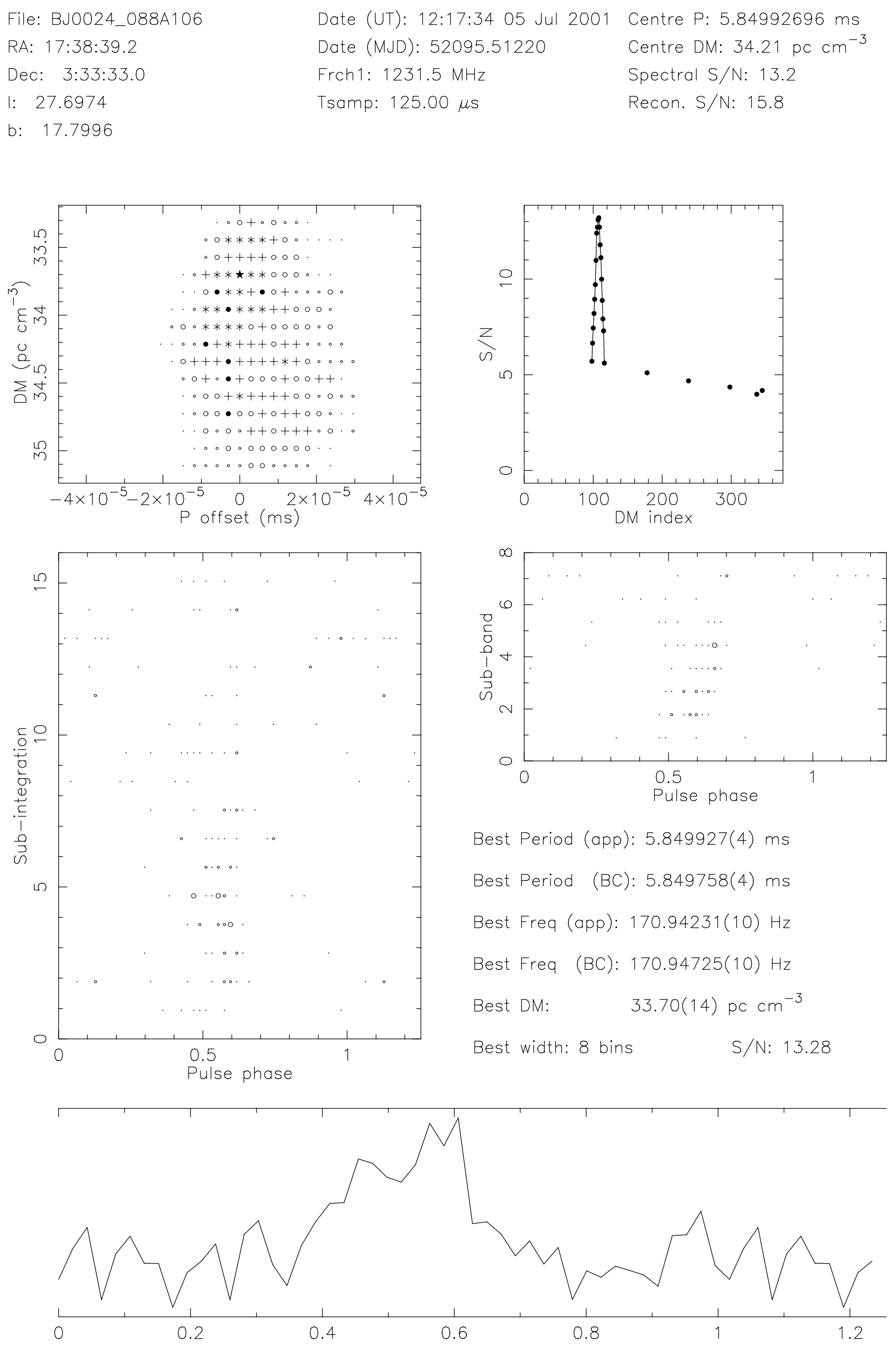

Figure 2.2: Example millisecond pulsar candidate. Shown clockwise from top left are the optimized period and dispersion measure relative to the values found in the frequency domain search, signal-to-noise ratio as a function of dispersion measure trial, folded pulse profile in each of several frequency sub-bands, best folded pulse profile, and folded pulse profile in each of several time sub-integrations. This candidate was confirmed as PSR J1738+0333.