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A survey for millisecond pulsars at Molonglo

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Summary. A survey for millisecond pulsars in a zone along the southern galactic plane has been carried out at a frequency of 843 MHz using the Molonglo Observatory Synthesis Telescope. The area covered by the survey was from l=255° to l=360°, $b=\pm 1°$ in about 7000 separate pointings. Sampling was at 0.5 ms intervals, giving nominal sensitivity down to pulsar periods of one millisecond. For longer-period pulsars the limiting sensitivity was about 8 mJy for dispersion measures up to 400 cm^{-3} pc. The relatively high frequency of this survey ensured that any reduction in sensitivity owing to interstellar dispersion and scattering was not serious up to distances corresponding to DM values of about 200 cm^{-3} pc, allowing the search of a considerable volume for relatively bright millisecond pulsars. No millisecond pulsars were found, although some suspects remain under investigation. One new pulsar with a period 106 ms was discovered and parameters are given for this. The survey shows that luminous millisecond pulsars like PSR 1937+21 are not common objects in the disc of our Galaxy.

1 Introduction

The discovery of the original millisecond pulsar, PSR 1937+21, by Backer *et al.* (1982) has had a major impact on both physics and astronomy. Its very short period of 1.5 ms implies a neutron-star spin rate close to the maximum believed possible (Shapiro, Teukolsky & Wasserman 1983). The corresponding radius of the light-cylinder is small, putting important constraints on the pulse emission mechanism. Although millisecond pulsars have an extremely high rotational kinetic energy, the rate of loss of this energy is very small. The resulting stability of the pulsar as a clock is

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comparable to that of terrestrial time standards (Rawley *et al.* 1988), suggesting that millisecond pulsars may be useful in defining the long-term time standard. They may also be useful in the refinement of solar-system ephemerides and as detectors of a cosmological background of gravitational waves. Although PSR 1937+21 is a single pulsar, three of the five millisecond pulsars currently known are members of binary systems and further tests of relativity theories similar to those made using PSR 1913+16 (Weisberg & Taylor 1984) can be envisaged.

It is believed that the high rotation rate of millisecond pulsars originates from spin-up due to angular momentum transfer in a close binary system (van den Heuvel 1984). The recent discoveries of millisecond pulsars in the cores of the globular clusters M28 and M4 (Lyne *et al.* 1987; Lyne *et al.* 1988) provide strong support to this idea. It is worth noting that the idea of spinning-up or 'recycling' pulsars was suggested before the discovery of millisecond pulsars (Smarr & Blandford 1976) in order to explain the properties of PSR 1913+16.

Following the discovery of PSR 1937+21, many searches for further millisecond pulsars were made. Several of these searches were based on surveys of continuum radio sources with properties similar to those of 4C 21.53, the continuum source associated with PSR 1937+21 (Erickson 1983), namely steep radio spectrum and relatively high linear polarization. Until the recent discovery of the M28 pulsar, these searches were singularly unsuccessful (e.g. Heiles *et al.* 1984). On the other hand, the second millisecond pulsar, PSR 1953+29, was discovered in an effectively untargeted survey of a region of the sky (Boriakoff, Buccheri & Fauci 1983), suggesting that these objects might be fairly numerous in the Galaxy. It therefore appeared that a survey of a large portion of the galactic plane for millisecond pulsars would be worth while. This was subsequently reinforced by the discovery of PSR 1855+09 in an untargeted search (Segelstein *et al.* 1986).

The southern galactic plane was searched for pulsars at 408 MHz using the Molonglo radio telescope by Manchester *et al.* (1978). This survey had a sampling interval of 20 ms and hence was not sensitive to pulsars with periods shorter than about 100 ms. For longer-period pulsars, the limiting mean flux density was about 15 mJy. After this survey, the Molonglo telescope was converted into a synthesis instrument operating at 843 MHz (Mills 1981). This higher frequency reduces the beam size and hence the area of sky that can be searched in a given time, but has the advantage of reducing the effects of interstellar scattering, which can be an important limiting factor in searches for short-period pulsars (Clifton & Lyne 1986). A search for millisecond pulsars in steep-spectrum radio sources was carried out using the Molonglo telescope by D'Amico *et al.* (1985). This paper reports the first untargeted search of the southern galactic plane for millisecond pulsars.

2 Observations and analysis

Observations were made using the central beam of the Molonglo Observatory Synthesis Telescope (MOST) in total-power mode in several observing sessions in the period 1985 March to 1986 February. The telescope receives right-circular polarization with a frequency bandpass of 3.2 MHz centred at 843 MHz. On cold sky the system equivalent flux density is approximately 70 Jy. To allow removal of the effects of interstellar dispersion, the bandpass was split into 16 adjacent channels each of bandwidth 200 kHz. After passing through an automatic gain control amplifier and low-pass filters, the detected filter outputs were sampled at 0.5 ms intervals, two bits per sample, using a specially-built sampling system attached to the Observatory HP1000 computer. At 843 MHz, the total power beam has half-power widths of 40 arcsec in the meridian distance direction (hour angle at transit) by 2° in the zenith distance direction (declination at transit). Observations were made by tracking a point on or near the galactic equator for 132 s and writing the data along with header information directly to magnetic tape. The observation time was limited both by the desire to maintain sensitivity for pulsars in tight binary systems and by the

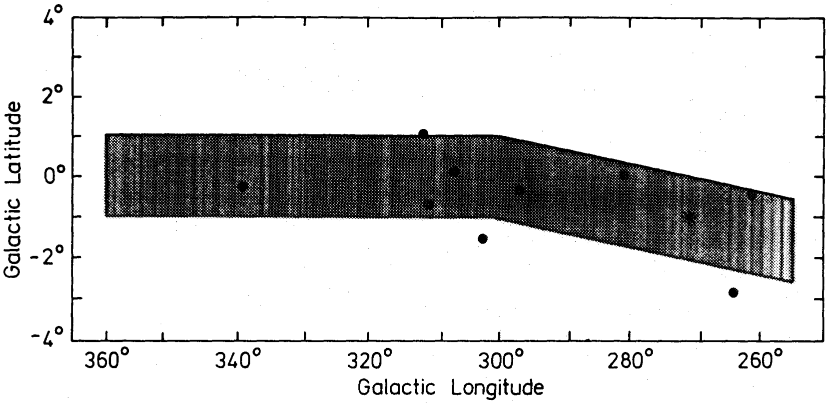

Figure 1. Area surveyed for millisecond pulsars at Molonglo. The shading represents the completeness of the survey (on a linear scale) with the darkest areas (e.g. l=298°–300°) representing complete coverage. Locations of detected pulsars are marked, previously known pulsars with a dot and a new pulsar PSR 0906−49 by an asterisk.

rotation of the beam on the sky. For an observation time of 132 s, sensitivity was maintained over the full 2° extent of the beam.

Observation positions were automatically selected by the on-line program from a disc file generated at the beginning of the survey and updated after each observation as the survey proceeded. The region surveyed was from l=255° to 360° as shown in Fig. 1, a total area of 210 square degrees given the 2° extent of the beam (which at most longitudes was roughly perpendicular to the galactic plane). The beam centre was at negative galactic latitudes from l=255° to l=300° to follow better the peak of the galactic continuum emission. All observations were made within 15° meridian distance of transit, starting at l=255° approximately an hour before transit and ending at l=360° approximately an hour after transit. Of the 7341 beam positions in the survey area, 6955 or nearly 95 per cent were successfully observed; the completeness of the survey is indicated in Fig. 1.

The sensitivity of the survey was estimated by observing known pulsars and, for millisecond periods, by injecting pulsed calibration signals into the system. The resulting function for the minimum detectable mean flux density versus the pulsar period for a duty cycle of 10 per cent and dispersion measures less than 200 cm^{-3} pc is shown in Fig. 2. For higher dispersion measures the short-period cut-off effectively moves toward longer periods. At long periods the limiting flux density is approximately 8 mJy at 843 MHz; for an assumed pulsar spectral index of −1.5, this

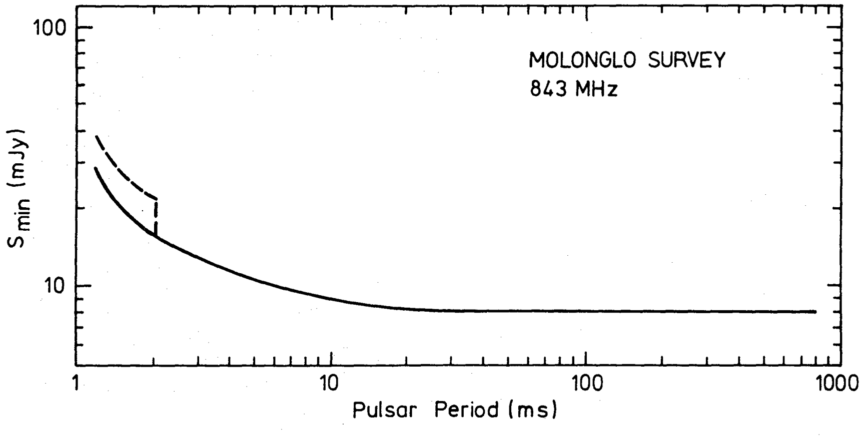

Figure 2. Minimum detectable mean flux density as a function of pulsar period for a mean duty cycle of 10 per cent and dispersion measures less than 200 cm^{-3} pc. The minimum detectable flux density scales as the square-root of the duty cycle. The reduced sensitivity of the Princeton analysis for short-period pulsars is indicated by the dashed line.

corresponds to a 400-MHz limit of about 24 mJy. This survey is therefore not as sensitive as the second Molonglo survey (Manchester *et al.* 1978) for long-period pulsars but is more sensitive for periods less than approximately 300 ms.

The resulting data were processed using two separate analysis systems. The first one operated on a VAX 11/750 at the CSIRO Division of Radiophysics and a VAX 11/780 at Siding Spring Observatory and processed about 20 per cent of the data, providing quick feedback on the quality of the data. The analysis procedure was essentially that employed in the second Molonglo survey. The data were first dedispersed for 12 different dispersion values ranging from 11 to 400 cm^{-3} pc using an optimized algorithm to avoid redundant additions. The resulting dedispersed time series were then transformed using an FFT algorithm (Fraser 1979) and searched for periodicities in the fundamental spectrum and the spectra resulting from the incoherent addition of 2, 4, 8 and 16 harmonics. For the five highest peaks in each of these spectra, a time-domain profile was formed by interpolating and transforming the complex spectral harmonics. Parameters for profiles with a signal/noise ratio greater than a threshold value were stored for subsequent evaluation. For periods less than 4 ms, spectral features having an amplitude in excess of ten times the rms amplitude were also selected as suspects.

The second analysis system operated on a Masscomp 5500 mini-computer with a floating-point array processor at Princeton University and used a two-dimensional FFT search procedure (Stokes *et al.* 1986). For the Molonglo data the maximum dispersion measure searched was 175 cm^{-3} pc for pulsar periods near 1 ms, increased linearly with period to 1750 cm^{-3} pc at 10 ms, and was constant at this value for longer periods. Approximately 80 per cent of the survey observations were processed on this machine. Unfortunately, because of software problems detected only after the analysis was complete, the 500–1000 Hz band was not searched in the fundamental. It was, however, effectively searched as the second harmonic of a signal in the 250–500 Hz band; we estimate that this lowered the effective sensivity for pulsars in the 500–1000 Hz band by about 30 per cent. Also, spurious signals at frequencies related to the Nyquist frequency were present at levels above the threshold in approximately 160 of the analysis outputs. Entries at these positions were deleted from the observation file, although a pulsar with signal/noise about 50 per cent above the normal threshold would probably still have been detected.

These analyses produced a list of approximately 120 suspects. These were graded according to signal/noise and profile quality into three categories (A, B and C) and reobserved at Molonglo between 1986 April and August. The confirmation observations were made using a modified version of the observing program and were of 264 s duration, centred at the sidereal time of the original observation. Class A suspects were observed on three different occasions, class B twice and class C once. The program automatically selected the next highest priority observation from a file. The confirmation observations were analysed in interleaved 132-s segments using both FFT and fast-folding analyses to search for a signal at or near the suspect period and dispersion measure.

3 Results and discussion

A total of ten pulsars were detected by the survey and of these only one was a new detection. The locations of the detected pulsars are shown on Fig. 1. All known pulsars whose expected flux densities were above the threshold of the survey were detected; the detected pulsars are PSRs 0833−45, 0835−41, 0959−54, 1154−62, 1240−64, 1323−62, 1353−62, 1356−60 and 1641−45. The one new pulsar, PSR 0906−49, has a fairly short period, 106 ms, but no millisecond pulsars were detected. Some suspects remain under investigation and will be reobserved with a more sensitive system.

As shown in Fig. 3, the pulse profile for PSR 0906−49 has a relatively strong interpulse, adding

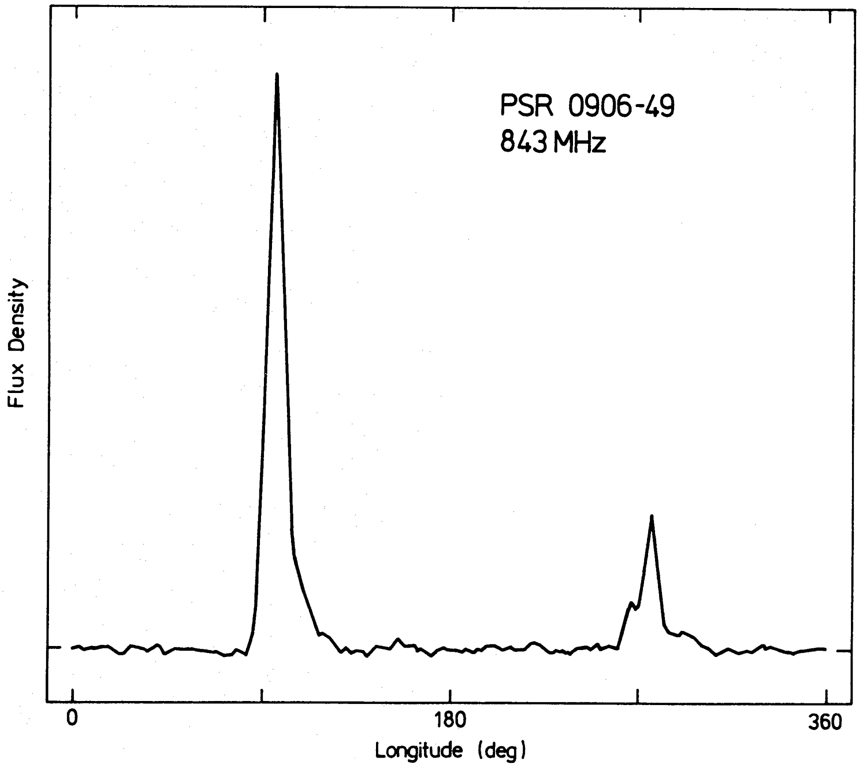

Figure 3. Mean pulse profile of PSR 0906−49 at 843 MHz and for right-circular polarization.

further weight to the conclusion that interpulses occur predominantly in short-period pulsars (e.g. Manchester & Lyne 1977; Gil 1985). The interpulse is situated midway between main pulses and has three distinct profile components. Since 1986 April, this pulsar has been observed in a timing program at Molonglo Observatory (*cf.* Manchester *et al.* 1985) and the profile shown in Fig. 3 is derived from these observations. A fit to the timing data to 1987 December gives the parameters for PSR 0906−49 listed in Table 1. The pulsar has a characteristic age ($P/2\dot{P}$) of slightly less than 10^5 yr and the dispersion measure indicates a distance of about 3 kpc. It is located near the edge of a small region of enhanced emission on the 2.7-GHz continuum map by Day, Caswell & Cook (1972). A MOST synthesis map of the region shows that the pulsar is located outside the continuum source and that the source has a relatively flat spectrum. It is therefore probably an H II region and not associated with the pulsar.

Fig. 4 is a plot of equivalent 400-MHz radio luminosity versus distance showing the five known

Table 1. Parameters for PSR 0906−49.

R.A.(1950)	$09^{\rm h}\,06^{\rm m}\,54^{\rm s}.46 \pm 0^{\rm s}.10$
Dec.(1950)	$-49^{\circ}\,00'\,54''.4 \pm 0''.9$
Galactic longitude	$270^{\circ}.27$
Galactic latitude	$-1.^{\circ}02$
Period	0.10675459250 ± 3 s
Period Derivative	$(1.5151 \pm 0.0002) \times 10^{-14}$ s s^{-1}
Epoch (J.D.)	2446546.7841
Dispersion measure	192 ± 12 cm^{-3} pc
Mean Flux Density (843 MHz)	25 mJy
Pulse width (50%) :main pulse	2.8 ms
:interpulse	2.6 ms
Interpulse - main pulse sepn	180°
Interpulse/main pulse energy	0.26

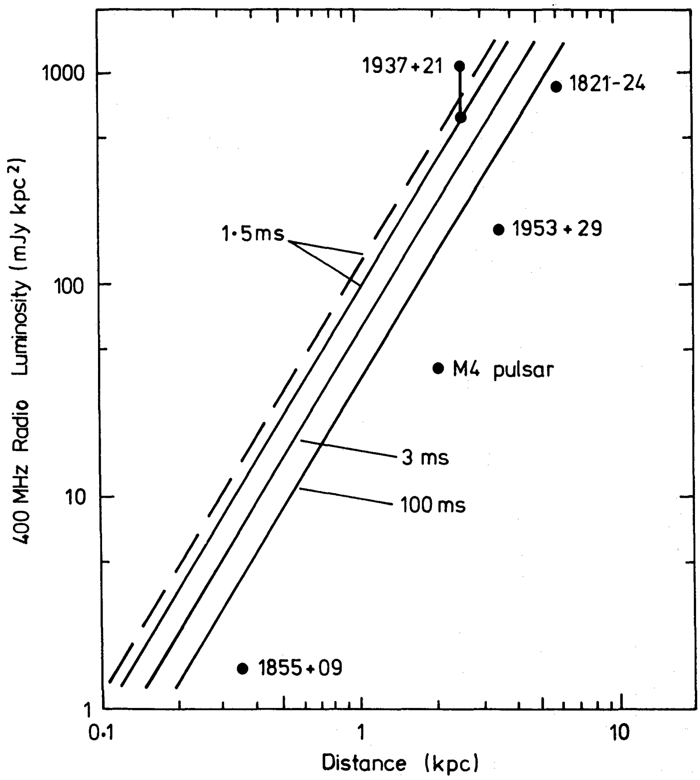

Figure 4. Minimum detectable radio luminosity for the Molonglo survey (400 MHz equivalent) as a function of pulsar distance and pulsar period. The dashed line indicates the reduced sensitivity of the Princeton analysis for pulsars of period between 1 and 2 ms. The locations of the five millisecond pulsars are marked. The effective reduction in sensitivity for PSR 1937+21 resulting from the presence of the strong interpulse is indicated by the lower point for this pulsar. For PSR 1821−24, which also has a strong interpulse, the reduction in sensitivity is much less, as the second harmonic frequency is less than the Nyquist frequency for this survey (1 kHz) and hence is included in the harmonic summing process.

millisecond pulsars. Also plotted are the limiting sensitivities of the present survey for pulsars of period 1.5, 3 and 100 ms. This figure shows that a pulsar with the period and luminosity of PSR 1937+21 and within the search area would have been detected provided it were at a distance of less than about 3 kpc. For a pulsar of this period with an interpulse as strong as that of PSR 1937+21, the limiting distance would be reduced to about 2 kpc. This suggests that the number of such pulsars in the galactic disc (with $|z|$ less than about 40 pc) is less than about $25/f$, where f is the beaming factor (the fraction of the celestial sphere swept out by the pulsar beams). For millisecond pulsars the beaming factor is probably close to unity (Narayan 1984; Lyne & Manchester 1988). If the lifetime of millisecond pulsars is greater than 10^9 yr (Kulkarni 1986), then the birthrate of luminous pulsars such as PSR 1937+21 in the galactic disc must be very low, less than one per 10^7 yr. Of course, there may be a much larger population of less luminous millisecond pulsars such as PSR 1855+09 in the disc. More sensitive searches covering a greater area of sky are required to detect such pulsars. The recent detections show that there is also a significant population of millisecond pulsars in the cores of globular clusters and more sensitive searches directed at these objects are clearly worth while.

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References

Backer, D. C., Kulkarni, S. R., Heiles, C., Davis, M. M. & Goss, W. M., 1982. *Nature,* **300,** 615.

Boriakoff, V., Buccheri, R. & Fauci, F., 1983. *Nature,* **304,** 417.

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

D'Amico, N., Manchester, R. N., Durdin, J. M. & Erickson, W. C., 1985. *Proc. astr. Soc. Aust.,* **6,** 174.

Day, G. A., Caswell, J. L. & Cooke, D. J., 1972. *Aust. J. Phys. Suppl.,* **25,** 1.

Erickson, W. C., 1983. *Astrophys. J.,* **264,** L13.

Fraser, D., 1979. *A.C.M. Trans. Math. Software,* **5,** 500.

Gil, J., 1985. *Astrophys. J.,* **299,** 154.

Heiles, C., Kulkarni, S. R., Purvis, A., Goss, W. M. & van Gorkom, J. H., 1984. In: *Millisecond Pulsars,* Proceedings of a Workshop held at the National Radio Astronomy Observatory, Green Bank, NRAO, Green Bank, p. 265, eds Reynolds, S. P. & Stinebring, D. R.

Kulkarni, S. R., 1986. *Astrophys. J.,* **306,** L85.

Lyne, A. G. & Manchester, R. N., 1988. *Mon. Not. R. astr. Soc.,* **234,** 477.

Lyne, A. G., Brinklow, A., Middleditch, J., Kulkarni, S. R., Backer, D. C. & Clifton, T. R., 1987. *Nature,* **328,** 399.

Lyne, A. G., Biggs, J. D., Brinklow, A., Ashworth, A. S. & McKenna, J., 1988. *Nature,* **332,** 45.

Manchester, R. N. & Lyne, A. G., 1977. *Mon. Not. R. ast. Soc.,* **181,** 761.

Manchester, R. N., Durdin, J. M. & Newton, L. M., 1985. *Nature,* **313,** 374.

Manchester, R. N., Lyne, A. G., Taylor, J. H., Durdin, J. M., Large, M. I. & Little, A. G., 1978. *Mon. Not. R. ast. Soc.,* **185,** 409.

Mills, B. Y., 1981. *Proc. astr. Soc. Aust.,* **4,** 156.

Narayan, R., 1984. In: *Millisecond Pulsars,* Proceedings of a Workshop held at the National Radio Astronomy Observatory, Green Bank, NRAO, Green Bank, p. 279, eds Reynolds, S. P. & Stinebring, D. R.

Rawley, L. A., Taylor, J. H., Davis, M. M. & Allan, D. W., 1988. *Science,* in press.

Segelstein, D. J., Rawley, L. A., Stinebring, D. R., Fruchter, A. S. & Taylor, J. H., 1986. *Nature,* **322,** 714.

Shapiro, S. L., Teukolsky, S. A. & Wasserman, I., 1983. *Astrophys. J.,* **272,** 702.

Smarr, L. L. & Blandford, R., 1976. *Astrophys. J.,* **207,** 574.

Stokes, G. H., Segelstein, D. J., Taylor, J. H. & Dewey, R. J., 1986. *Astrophys. J.,* **311,** 694.

van den Heuvel, E. P. J., 1984. *J. Astrophys. Astr.,* **5,** 209.

Weisberg, J. M. & Taylor, J. H., 1984. *Phys. Rev. Lett.,* **52,** 1348.