SPECTRA OF SOUTHERN PULSARS

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1. INTRODUCTION

In the early 1980s, attention was focused on the enigmatic radio complex at the position of 4C21.53. In particular, the object to the west of this position, named 4C21.53W, was resolved into two components, an extended flat-spectrum source ~1° north of a compact steep-spectrum object. The steep spectrum and interplanetary scintillation of the compact source suggested that it was a radio pulsar. Several searches, sensitive only to periods greater than a few milliseconds, failed to detect any pulsations, but Backer et al. (1982) announced that the source was the first millisecond pulsar (MSP), PSR B1937+21, with a rotation period of just 1.5 ms. Spurred on by this exciting discovery, Hamilton, Helfand, & Becker (1985) made a spectral survey in 12 nearby globular clusters for unresolved objects that might be MSPs. Their best candidate, in the core of M28, was shown to be a highly linearly polarized, steep-spectrum object (Erickson et al. 1987). This steep-spectrum source was later found to be the fourth MSP (PSR B1821-24) and the first globular cluster pulsar discovered (Lyne et al. 1987). A search aimed at a further 24 nearby globular clusters resulted in the discovery of yet another steep-spectrum pulsar, PSR B1620-26, in M24 (Lyne et al. 1988).

The first detailed spectral study of MSPs was made by Foster, Fairhead, & Backer (1991, hereafter FFB). Their study included the three pulsars mentioned above, as well as PSR B1855+09. The latter was discovered in a 430 MHz pulsar survey conducted at Arecibo (Segelstein et al. 1986; Fruchter 1989). Except for PSR B1855+09, all the MSPs had spectral indices steeper than −2.3. Although the sample of four pulsars was not very statistically significant, this paper helped reinforce the growing belief that MSPs had spectra that were significantly steeper than their slower counterparts.

Since then there have been a number of large-scale surveys for pulsars (e.g., Biggs & Lyne 1992; Clifton et al. 1992; Foster et al. 1995; Camilo, Nice, & Taylor 1993). As a result there are now some 60 known pulsars with periods less than 20 ms. The high-frequency surveys of Clifton & Lyne (1986) and Johnston et al. (1992) were mildly sensitive to MSPs but found none in their surveys of the Galactic plane. This restricted the population of very luminous high-frequency MSPs, but offered little insight into the number of low-luminosity MSPs detectable at high frequencies. On the other hand, the Parkes 70 cm survey (Manchester et al. 1996; Lyne et al. 1998) detected 19 MSPs, 17 of which were new discoveries. The history of MSP searching with its focus on steep-spectrum objects, and the comparative success of low-frequency surveys compared with high-frequency surveys, might lead one to conclude that there are good reasons to conduct MSP searches exclusively at low frequencies.

The major works on pulsar spectra are those of Lorimer et al. (1995) and Kramer et al. (1998). Lorimer et al. derived a mean spectral index for millisecond and slow pulsars of −2 and −1.6, respectively. Their study included all of the pulsars regularly observed from Jodrell Bank and did not differentiate between those found in high- or low-frequency surveys. Kramer et al. attempted to reduce observational biases by selected spectra only from pulsars out to a distance of 1.5 kpc. They found the average spectra of MSPs and slow pulsars to be essentially the same, with mean indices of −1.6 and −1.7, respectively. As noted by Kramer et al., the Parkes survey, with its large number of detections of both millisecond and slow pulsars, provides an excellent sample from which to discuss the spectral properties of pulsars in a more unbiased way.

All of the 19 MSPs detected in the Parkes survey have been either timed regularly at Parkes or observed for polarization studies with the Caltech pulsar correlator (Navarro 1994). The correlator provides accurate fluxes suitable for a spectral study. The aim of this paper is to compare the spectra of the millisecond and slow pulsars detected in the Parkes survey. In § 2 of this paper we describe the observations and data reduction techniques used in obtaining the spectra, § 3 presents the average flux density measurements and spectral indices for the MSPs, and in § 4 we compare the spectral index distribution of these MSPs and the slow pulsars detected by the survey. This demonstrates that MSPs found in a large-scale, low-frequency survey have

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spectra that are only slightly steeper than their slower counterparts, and it supports the case for high-frequency surveys for MSPs. In § 5 we present the results of a simulated high-frequency search for MSPs near the Galactic plane, which suggests that MSPs will be found in significant numbers by the current Parkes multibeam survey.

2. OBSERVATIONS AND DATA REDUCTION

The 19 MSPs detected in the Parkes survey were observed using the 64 m radio telescope at Parkes in 12 sessions between 1996 February and October. These observations form a subset of data taken in a continuing pulsar timing program. PSR B1620−26 is not timed regularly at Parkes, but it was observed on 10 occasions. The remaining 18 MSPs were observed much more frequently, and our data set consists of approximately 1700 observations, each of 24 minute duration. The large number of observations and their spread over an extended time span should reduce the observational biases introduced by refractive and diffractive scintillation.

Our observations were made using three dual-channel cryogenic receiver systems with center frequencies of 436, 660, and 1500 MHz. At the lower frequencies the system bandwidth was 32 MHz, but for the highest frequency system, two bands of 128 MHz bandwidth centered at 1400 and 1660 MHz were used. System equivalent flux densities for the three receivers were approximately 100, 90, and 40 Jy, respectively. The flux-density scale was established using observations of Hydra A, which was assumed to have a flux density of 134.60 Jy at 400 MHz and a spectral index of $-0.909$ (Baars et al. 1977). The system gain of all three receivers was monitored using a linearly polarized pulse calibration signal, injected at 45° to the two feed probes.

The data were two-bit digitized, and autocorrelation functions (ACF) were computed using the Caltech correlator. These were integrated at the apparent pulsar period in memory giving 1024 samples per pulsar period for each of 512 lags. Data were typically integrated for 90 s in the hardware integrator and then transferred to a Sun Sparc-20 computer for further processing. The ACF data were corrected for nonlinearities resulting from the two-bit digitization and Fourier-transformed to form power spectra for each of the 90 s integrations and pulse phase bins; the spectra were dedispersed into 16 or 32 frequency channels and stored on disk.

A typical observation provided us with sixteen, 90 s integrations in each of two polarizations and several frequency sub-bands. The number of bins across each profile was dependent upon the amount of dispersion smearing across the band and the duty cycle of the pulsar. To obtain flux densities, profiles were added in time and frequency and the two polarizations summed. After baseline removal, the mean flux density for that observation was computed.

For each pulsar, the unweighted mean flux density of the measurements at a particular observing frequency was computed, as well as the standard error, $\sigma_g = \sigma/(N - 1)^{1/2}$,
where $\sigma$ is the standard deviation of the $N$ measurements about their mean. We found that the spectra of the MSPs in our sample were often well described by a power-law distribution of the form $S = S_0 \nu^\alpha$, as illustrated in the plot of typical spectra in Figure 1. A $\chi^2$ minimization technique was used to fit for the spectral index, $\alpha$, for each pulsar. We calculated the standard error, $\sigma_\alpha$, for each spectral index from the variance in $\alpha$ returned by the least-squares fitting program.

To make a meaningful comparison with the slow pulsars, we limited our sample of slow pulsars to those detected in the Parkes 70 cm survey: 279 in total. In this way, we are able to compare in a relatively unbiased manner the spectral indices of slow and MSPs. Follow-up observations of the slow pulsars have not been as thorough as for the MSPs, and 63 of them have flux density measurements only at frequencies near 430 MHz. Of the remaining 216 for which we have calculated spectral indices, 117 had measurements at three or more frequencies.

3. RESULTS

Table 1 shows the flux densities measured for southern MSPs. The average number of individual integrations included in each data point varied with observational frequency, but it was typically 10 at 436 MHz and 25 or more at the higher frequencies. The last two columns of Table 1 give the spectral index and error for each pulsar. Figure 1 shows typical spectral plots, and Figure 2 shows comparative histograms of the spectral index distributions for the slow and MSPs detected in the 70 cm survey.

For PSR B1620 – 26 (PSR J1623 – 2631), the 660 MHz flux density is similar to that of FFB, but the 1400 MHz flux density is higher, giving a flatter spectrum (spectral index –1.5 compared to –2.5). For this and other pulsars in the FFB study, their steeper spectral indices result mainly from the inclusion of data points near 100 MHz. We also note that our total integration time was similar to that used by FFB, and so we consider our value of similar statistical significance.

4. DISCUSSION

Interstellar scintillation results in variations of the pulse intensity as a function of time and frequency. Diffraective interstellar scintillation (DISS) has a time scale, $T_{\text{DISS}}$, that is dependent upon the distance to the pulsar, the observing frequency and the pulsar’s transverse velocity (e.g., Stinebring & Condon 1990). The timescale and bandwidth of these intensity modulations increase as the observing frequency increases. For MSPs at the lower frequencies, the typical $T_{\text{DISS}}$ was ~ 10 minutes, and the typical diffraective bandwidth was less than 1 MHz. By using a bandwidth of 32 MHz and integration times of 24 minutes at these low frequencies, we have averaged over many scintils to obtain our flux density measurements. The timescale for refractive interstellar scintillation (RISS), $T_{\text{RISS}}$, is typically of the order of a few days. We have made sufficient observations to have averaged out the effects of RISS in almost all of the
pulsars. The effects of DISS are more evident in the higher moments of the flux density distributions. Typically, the flux density distribution shows some positive skewness and kurtosis, consistent with the exponential probability density function expected to arise from scintillation. An effort was made to include all observations of the highly scintillating pulsars to avoid the observational bias that arises by observing pulsars only when they are at a scintillation maximum.

Until the recent publication of MSP spectra by Kramer et al. (1998), it was commonly accepted that the mean spectral index of MSPs was steeper than that of slow pulsars. The evidence for this had largely been based on flux density data presented in discovery papers. For example, the MSP spectral indices quoted by Lorimer et al. (1995 and references therein) have a mean of $-2.0 \pm 0.2$. The spectral index distribution for the 19 MSPs considered here has a mean spectral index of $-1.9 \pm 0.1$, while the mean value for the slow pulsars in our sample of $-1.72 \pm 0.04$ is slightly steeper than the $-1.6$ obtained by Lorimer et al. The difference between these two values can be understood in terms of selection effects. Lorimer's sample included all pulsars, including those found in high-frequency surveys, whereas the Parkes sample included only those detected at 436 MHz. Flat-spectrum pulsars are much easier to detect at high frequencies because of reduced dispersion measure (DM) smearing, scattering, and lower sky background temperatures. Johnston et al. (1992) found, for example, that the median spectral index for their 1500 MHz survey at Parkes was only $-1.0$.

Our results agree well with Kramer et al.'s (1998) comparison of the spectra of the slow pulsars and many of the MSPs detected in the Parkes 70 cm survey. They determined the mean spectral indices to be $-1.8 \pm 0.2$ (MSPs) and $-1.7 \pm 0.1$ (slow pulsars). Although the individual spectra of MSPs published by Kramer et al. and those presented here show significant differences, the mean MSP spectral indices are within errors, while the mean spectra of slow pulsars are in excellent agreement.

By combining flux density measurements taken at frequencies above 1400 MHz with published data, Malofeev et al. (1994 and references therein) were able to derive accurate spectral indices for 45 slow pulsars. If we consider only the 20 of these pulsars that show no evidence for a break in their spectra, then the mean spectral index for these pulsars is $-1.9$. Kijak et al. (1998) have done similar work with flux densities at frequencies between 1.41 and 4.85 GHz, deriving a mean spectral index of $-1.9$ for a sample of 144 slow pulsars. PSR J0437–4715, with a flux density of $11.6 \pm 0.1$ mJy at 4.8 GHz was the only MSP for which we had flux density data above 1600 MHz. With a spectral index of $-2.1$ between 1.4 and 4.8 GHz compared to $-1.1$ at lower frequencies, PSR J0437–4715 follows the same trend as the slow pulsars in Kijak et al.'s sample.

The mean spectral index of the MSPs in our sample is $\sim 10\%$ steeper than that of the slow pulsars. To compare the distributions in more detail, we did a Kolmogorov-Smirnov test that showed that there is a 28% probability that the two samples are drawn from the same distribution. Therefore, the evidence that MSPs are intrinsically steeper spectrum objects is fairly weak. Similarly, there is little evidence when one compares the distributions directly, as in Figure 2. We therefore suggest, in agreement with Kramer et al.'s (1998) study, that the widely held view that MSP spectra are much steeper is unfounded, and due, in part, to the early methods for finding MSPs that required candidates to have steep spectra.

5. A SIMULATED MSP HIGH-FREQUENCY SURVEY

Most of the more than 700 pulsars known today were discovered in searches conducted at frequencies near 400 MHz, where pulsars are relatively bright. The last decade has seen concerted efforts to search for pulsars at higher frequencies where sensitivity is better, because DM smearing and scattering in the interstellar medium (ISM) are reduced. One such survey is currently under way at the Parkes observatory using the 13 beam $\text{H}^1$ multibeam receiver system (Camilo 1997). The survey plans to cover the Galactic plane at 1400 MHz ($-5^\circ \leq b \leq +5^\circ$ and $260^\circ \leq l \leq 20^\circ$). In the light of the new spectral results presented in this paper, we have modeled the pulsar population and investigated the possible results of similar high-frequency surveys. The primary aim of our simulations was to study the spatial distribution of detectable MSPs in high-frequency surveys.

The pulsar population synthesis modeling software we used was developed by Lorimer et al. (1993). The model generates an evolved population of $10^5$ pulsars and conducts a search for these pulsars after taking into account selection effects. Our selection of initial Galactocentric radii and heights above the Galactic plane for each pulsar were drawn from Gaussian probability distributions, with a scale length of 4.8 kpc for the disk and a z-height of 500 pc. The effects of the ISM on the pulsar signals were simulated using the Cordes et al. (1991) electron distribution model. The pulse broadening caused by scattering by the ISM, scattering time $\tau_{\text{scatt}}$, was estimated by a power-law fitted to the DM-$\tau_{\text{scatt}}$ correlation (Bhattacharya et al. 1992) and a simple $v^{-4.4}$ scaling. The periods of MSPs were drawn from a Gaussian distribution about a mean value of log $P$ corresponding to 3.1 ms and a standard deviation in the log of 0.3. Lorimer et al. (1993) used a power-law expression of the form $L = \gamma P^{1+P}$ to derive each pulsar's luminosity, $L$, where $P$ is the pulsar's period in seconds, $P$ its period derivative, and $\gamma$ is a scale constant (Emmering & Chevalier 1989). The spread in luminosity about the luminosity law was modeled by convolving this distribution with a Gaussian in the log. We found that the pulsar population synthesized in this way was very sensitive to the form of the luminosity law. Instead, we used a simplified luminosity law in which we set $L = \gamma$, i.e., independent of $P$ and $P$.

In order to model a realistic population, we scaled the constant $\gamma$ and the standard deviation of log $L$, $\sigma_{\text{log}L}$, until the detailed model of the Parkes 70 cm survey detected 19 MSPs. The initial spectral index distribution was varied until the observed MSP spectral index distribution matched that presented in this paper. The mean spectral index of the evolved population was $-1.95$, with a standard deviation of 0.50, and $\gamma$ was set to 1.55 mJy kpc$^{-2}$, with $\sigma_{\text{log}L}$ set to 0.65.

We conducted a simulated 1400 MHz all-sky search of the evolved population of MSPs. The search involved 35 minute pointings of the 13 beam receiver assumed to have an effective receiver temperature of 30 K. The back-end recording system had $2 \times 288$ MHz of bandwidth, 3 MHz channels, and a sampling rate of 4 kHz, as described in Camilo (1997). To investigate the likely spatial distribution, our first model searched the entire sky. This model search resulted in the discovery of 172 MSPs with a minimum flux
density of \(~0.7\) \text{mJy}. This result suggests that such a survey would result in a threefold increase in MSPs known. Figure 3 shows that the distribution of the detected MSPs is far more concentrated on the plane than previous surveys. In fact, \(50\%\) of the detected MSPs are within \(11^\circ\) of the Galactic plane. This is easily understood in terms of the higher space density of MSPs in that region due to geometrical effects and the relative insensitivity to scattering and high sky background temperatures of high-frequency surveys.

We modeled the current multibeam survey by restricting the search to within \(\pm 5^\circ\) of the plane and \(260^\circ \leq l \leq 20^\circ\). Our model survey detected 26 MSPs, 24 of which were new discoveries. Uncertainties in the MSP luminosity function and total Galactic population, not to mention our simplified model of the Galaxy and multibeam survey system, mean that the above estimate could be uncertain by a factor of 2. Figure 4 shows the distribution of MSP DMs extends to a DM value of \(~310\ \text{pc cm}^{-3}\). To date, the only known MSPs with such high DMs were found in globular clusters. The high-DM tail shows that a high-frequency survey will have a significant effect on the known population of MSPs in the near future.

6. CONCLUSION

We have obtained reliable multifrequency flux density measurements for the 19 southern MSPs discovered in the Parkes 70 cm survey, enabling us to determine the spectral index distribution for this sample. We have compared this spectral index distribution with that of slow pulsars. A Kolmogorov-Smirnov test suggests only a \(72\%\) probability of the distributions differing. This result adds to the growing evidence that MSPs have spectral properties similar to slow pulsars. Our simulation of high-frequency surveys, similar to the Parkes multibeam survey, using the data presented in this paper, suggests that they will discover a large number of MSPs. High-frequency surveys are therefore likely to have a significant effect on the known population of MSPs in the near future.

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