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40 Years of Pulsars: Millisecond Pulsars, Magnetars and More

Low Frequency Observations of Millisecond Pulsars with the WSRT

B. W. Stappers*,†, R. Karuppusamy*,† and J. W. T. Hessels†

*Stichting ASTRON, Postbus 2, 7990 AA Dwingeloo, The Netherlands
†Astronomical Institute "Anton Pannekoek", University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands

Abstract. With LOFAR beginning operation in 2008 there is huge potential for studying pulsars with high signal to noise at low frequencies. We present results of observations made with the Westerbork Synthesis Radio Telescope to revisit, with modern technology, this frequency range. Coherently dedispersed profiles of millisecond pulsars obtained simultaneously between 115-175 MHz are presented. We consider the detections and non-detections of 14 MSPs in light of previous observations and the fluxes, dispersion measures and spectral indices of these pulsars. The excellent prospects for LOFAR finding new MSPs and studying the existing systems are then discussed in light of these results.

Keywords: pulsars, radio, interstellar medium
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INTRODUCTION

There are a large number of new radio facilities currently in the planning or construction phase and it is important that we consider the impact of these telescopes on all aspects of pulsar research. The first of these facilities to come on line will be the low frequency telescopes like LOFAR, LWA and MWA, which from now on we will collectively refer to as low frequency radio arrays (LRAs). While these instruments differ somewhat in design and frequency range, they all work at frequencies below 300 MHz and will be used to study the existing pulsar population and to discover new pulsars. It is therefore appropriate to consider what we might expect from pulsars in this frequency range. As discussed elsewhere in this volume by van Leeuwen & Stappers **??** there is huge potential for finding new pulsars with LOFAR for example. Their study didn't consider the millisecond pulsars (MSPs) as less is presently known about their low-frequency properties. The main issues governing the potential the LRAs have for discovering new MSPs are; the steepness of the radio spectrum and whether it turns over in this frequency range and the magnitue of the scattering in the interstellar medium.

In the late nineties and earlier this decade Kuzmin & Losovsky [1, 2] published the first papers which took a statistical look at the MSPs in the frequency range of interest here. They first presented a number of pulse profiles at frequencies near 100 MHz and by comparing them with profiles at higher frequencies they concluded that unlike the normal radio pulsar population there was little evidence for broadening of the pulse profile as a function of frequency [1]. They then went on to show that the radio spectral index of the MSPs seemed not to show a turnover at frequencies at or near 120 MHz as do the majority of higher magnetic field pulsars [2]. This later result, combined with the relatively large number of MSPs they detected, indicated that the low frequency range could potentially be a valuable one for finding MSPs.

Kuzmin & Losovsky had to use very narrow bandwidths (32×5 kHz) to obtain their results due to the deleterious effects of dispersion in the interstellar medium and they had limited time resolution (at best 0.64 – 0.128 ms). We therefore decided to obtain higher resolution pulse profiles from a number of these MSPs in order to better determine the pulse profile changes and the influence of scattering. We first discuss the observations and present our results. We then discuss the implications for the properties of MSPs and scattering in the interstellar medium and for their future study and detection with the LRAs.

OBSERVATIONS AND DATA REDUCTION

We observed a total of 14 pulsars (see Table 1) using the low frequency front ends (LFFEs) on the Westerbork Synthesis Radio Telescope (WSRT). The LFFEs have good sensitivity in the frequency range 115-180 MHz, where the lower limit is defined by the FM band and the upper limit by the response of the feeds. The band does contain some interference which is especially troublesome because the data is only sampled with 2 bits. We therefore selected eight clean bands each of 2.5 MHz

TABLE 1. Pulsars observed so far with the LFFEs at the WSRT. The sixth column indicates whether a 100-MHz profile is presented either in [1] or on the EPN database. PSR B1957+20 was not previously observed at these frequencies.

Pulsar	Period (ms)	DM (cm^{-3} pc)	Flux (mJy)	Flux Error (mJy)	Profile	WSRT Detection
J0034-0534	1.87	13.7	250	120	y	y
J0218+4232	2.33	61.2	270	150	n	n
J0613-0200	3.06	38.8	240	100	n	n
J0621+1002	28.85	36.6	50	25	n	n
J1012+5307	5.25	9.0	30	15	y	y
J1022+1001	16.45	10.2	90	40	y	y
J1024-0719	5.16	6.4	200	100	y	n
B1257+12	6.21	10.1	150	50	y	y
J1713+0747	4.57	15.9	250	100	y	n
J1744-1134	4.09	3.1	220	100	n	y
J1911-1114	3.62	30.9	260	130	y	y
J2051-0827	4.51	20.7	250	100	n	n
J2145-0750	16.05	9.0	480	120	n	y
B1957+20	1.61	29.11				y

bandwidth distributed throughout the band at 116.75, 130, 139.75, 142.25, 147.5, 156, 163.5 and 173.75 MHz. The data were oversampled at 40 MHz, decimated in real-time to 2.5 MHz bandwidth and then baseband recorded using the PuMa II pulsar backend.

The data were reduced using the open source software package, DSP for Pulsars, DSPSR[1]. A coherent filterbank of either 32 or 64 channels in each of the 8 bands was formed offline. The data were coherently dedispersed in each of the 32 or 64 channels, leading to a final time resolution of 25.6 or 51.2 μs. The data was also folded offline with an average pulse profile being formed for every ten seconds of data. These time-frequency cubes for each ten seconds of data were then checked for interference using a median filtering technique based on the rms noise in each frequency channel. The cleaned ten-second average profiles from all 8 bands were then summed to form a profile for each band and these bands were subsequently combined. It soon became evident that the combination of a wide range of frequencies and the low central frequencies meant a very accurate, epoch specific, determination of the dispersion measure (DM) was required in order to properly combine the 8 bands. Each data set was therefore optimised for the best DM, by maximising the signal-to-noise ratio of the pulse profile, and the inter-channel and inter-band dispersion correction was redone with the new best DM value. Typically the DM values needed to be changed at the $10^{-3} - 10^{-4}$ level, indicating the importance of accurate DM determinations for these low frequency observations. It will be interesting to see if follow-up observations at these frequencies also indicate small differences in the DM and thus a small DM optimisation step will be required for any analysis at these frequencies. The potential for using these accurate determinations of the DM for other applications like high precision pulsar timing at higher frequencies needs to be investigated.

[1] http://sourceforge.net/projects/dspsr/

RESULTS AND DISCUSSION

We present the results of the observations with the LFFEs in Table 1. Of the 14 pulsars observed a clear detection of a pulse profile was made in 8 cases and of the 13 pulsars which overlapped with the sample of KL99/KL01 7 were detected. In Figure 1 the detections are plotted as a function of DM and flux in an attempt to determine whether there is a common reason for detection or non-detection. All the sources detected by KL99/KL01 are plotted with crosses, while those observed by us are indicated by the open squares. The closed squares correspond to our detections. Before considering the sources as a whole we'll discuss a couple of individual cases.

The pulsar with the worst period and DM combination and thus the one that is most likely to suffer from scattering is PSR J0218+4232 (top-leftmost point in the left hand plot of figure 1). Despite this KL01 claim to have detected it. It is unclear whether they detected pulsations as only a flux is quoted in their paper and it is well known that it is a bright point source all the way down to 30 MHz. However we do not detect it in our observations and also do not detect it in deep observations at 250 MHz. This suggests that this source is not seen at these frequencies due to scattering.

PSR B1957+21, like PSR J0218+4232, has one of the worst combinations of period and DM and yet we detected it with very high signal-to-noise. This is the only pulsar in our sample that was not observed by KL99/KL01 and this is probably because they had insuf-

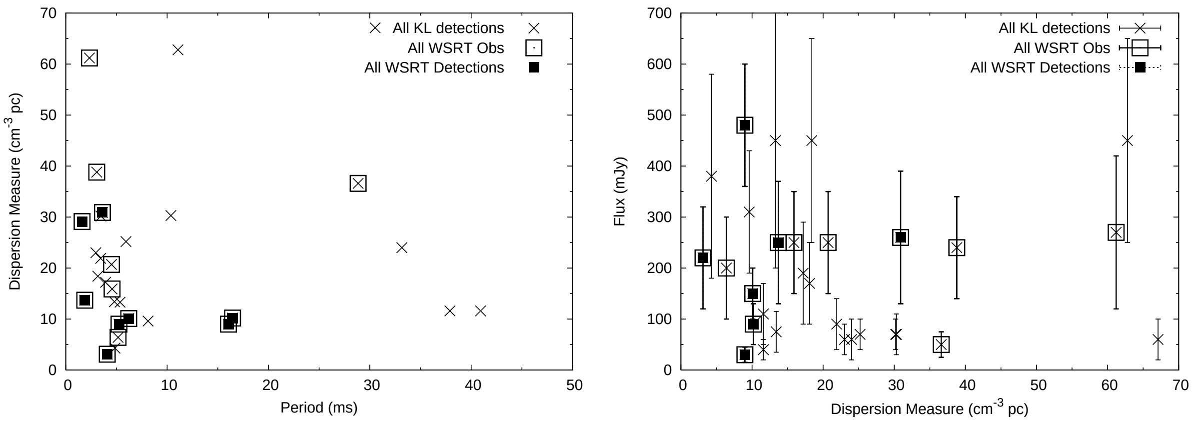

FIGURE 1. Plots comparing detections made with the LFFEs on the WSRT with the detections presented in KL99 and KL01.

ficient time resolution. Not only did we detect the source but the signal-to-noise ratio was sufficiently high that it was detected in every 10-second interval in each of the eight bands. Moreover the observations took place just as the pulsar was coming out of eclipse. The wide fractional frequency range simultaneously spanned by these data will provide an exciting opportunity to study the properties of the eclipses in this system.

It is apparent from Figure 1 that there is no clear relationship between detection of a source in our observations with any combination of period and DM nor with the quoted 100 MHz flux. However the majority of the non-detections are at the lower fluxes, although not all. Seven pulsars in our sample have published profiles either in KL99 or in the EPN database[2] and of those we detect five. It remains unclear why the other sources were not detected and if all the detections by KL99/KL01 are secure then it points to some time variable phenomenon.

It is unlikely to be due to scintillation, as the scintillation bandwidth decreases rapidly with frequency and the relatively wide bands used here mean that there are many scintles in each band. The average flux should therefore remain relatively constant. At these frequencies interference is always a concern and it is certainly variable on the timescales of our observations. However all of the sources we detected were seen in the individual 2.5 MHz bands and these are widely separated in frequency and therefore one would not expect them all to be affected by interference simultaneously. Moreover inspection of the data where pulsars were not seen does not show overly worse interference conditions than when pulsars were detected.

As discussed above, for the pulsars that we have detected, corrections had to be made to the DM in order not to have a broadened profile. Changes in DM are therefore another variable that might affect our ability to detect the MSPs at low frequencies. However, in order for the profile to be smeared by a large fraction of the pulse period across the 2.5 MHz band of each observing band then DM changes of the order of 0.1 are required. This is two to three orders of magnitude more than were detected above and is much larger than has been measured for any MSP [3]. It is therefore unlikely that this is the reason for the lack of detection of some of these sources.

While not thought to be highly variable, one of the main reasons why one might not expect to be able to detect some MSPs at these frequencies is scattering in the interstellar medium. The combination of the short rotational periods and the extreme frequency dependence of scattering mean that the pulse profiles may be scattered by more than a pulse period and thus it is no longer possible to detect them as pulsed sources. While there does appear to be an empirical relation between the DM and scattering (e.g. [4, 5]) the more than a couple of orders of magnitude variation about the relation means that it has litle predictive power (e.g. see Figure 4 of [5]). This, combined with the results of KL99/KL01 and this work show that it is basically only possible to determine which MSPs will be visible by actually observing them.

PSR J0034-0534 AND PSR J1713+0737

PSRs J0034-0534 and J1713+0737 are a pair of pulsars which illustrate the unpredictability of the degree of scattering. Both pulsars are claimed to be detected by KL99/KL01 and the pulse profiles can be found in the EPN database. A simple comparison of the two profiles suggests that they were both detected equally well, apart from the time resolution being better for PSR J1713+0747. The fluxes quoted for the two sources at these frequencies are also very similar. However,

[2] http://www.mpifr-bonn.mpg.de/div/pulsar/data/

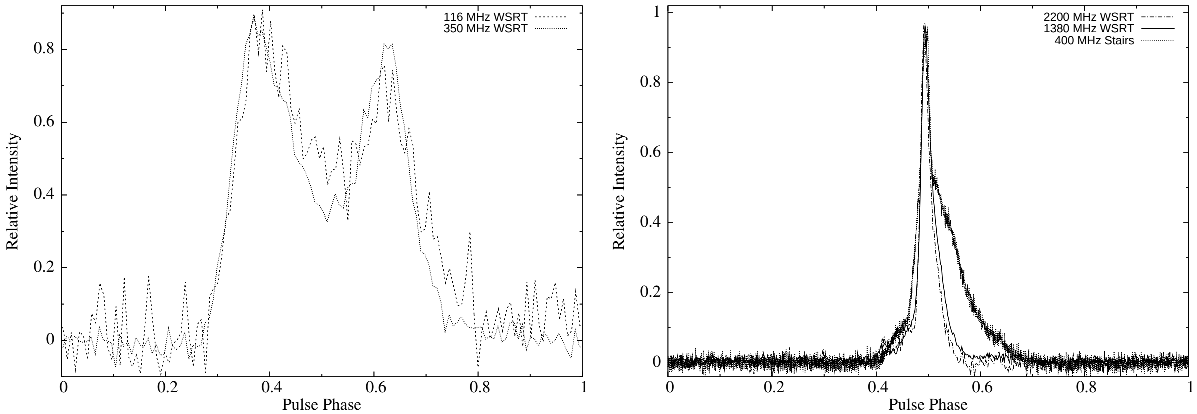

FIGURE 2. A comparison of the pulse profile evolution of PSR J0034-0534 (left) and PSR J1713+0737 (right). Both pulsars have similar DMs and the expected fluxes in the LFFE band are similar, however PSR J1713+0747 is not detected. There is some broadening of the profile of PSR J1713+0747 however it is not clear if this is due to scattering or profile evolution. The 400 MHz profile is from Arecibo data and is provided by I. H. Stairs.

we easily detect PSR J0034-0534 and do not see PSR J1713+0747 at all.

What could be the reason why we see one of these pulsars and not the other? As well as the fluxes being similar they also have very similar DMs, however we have already discussed the fact that there is not a very robust correlation between DM and the degree of scattering and so it may be that the profile of PSR J1713+0747 is too scattered to be detected (assuming also, with no explicit reason, that the detection by KL99 is not real). To test this we plot in Figure 2 the frequency evolution of the average pulse profiles of the two pulsars. The comparison between the 328 and 116 MHz pulse profiles of PSR J0034-0534 shows a small degree of broadening of the pulse profile due to scattering however it is still clearly detected at the lowest frequencies. The situation is a little bit more complicated for PSR J1713+0747 where at the higher frequencies there is some evidence for a broadening of the pulse profile but there is also, what appears to be, the development of a new component on the trailing edge of the profile at 400 MHz. It is therefore unclear whether scattering is the reason why the pulsar is undetected at these frequencies.

THE PULSE PROFILE OF PSR J2145-0750

PSR J2145-0750 is presently the brightest MSP observed at frequencies below 200 MHz. Kuzmin & Losovsky (1996; KL96) first detected the source near 100 MHz and they compared their observed profile with those obtained at higher frequencies. As a result of Gaussian fitting to the profiles at 102, 430 and 1520 MHz they find that the profile apparently broadens at higher frequencies. This is extremely unusual as the traditional view is that the profiles become narrower at higher observing frequencies and this is thought to indicate that the higher frequency emission comes from deeper in the, predominantly dipolar, magnetosphere. The authors then suggest that this may be interpreted as being evidence for a magnetic field where the quadrupole terms are also important. Multipole contributions might be expected in MSPs because they have much more compact magnetospheres and this was some of the first evidence that this might be observable.

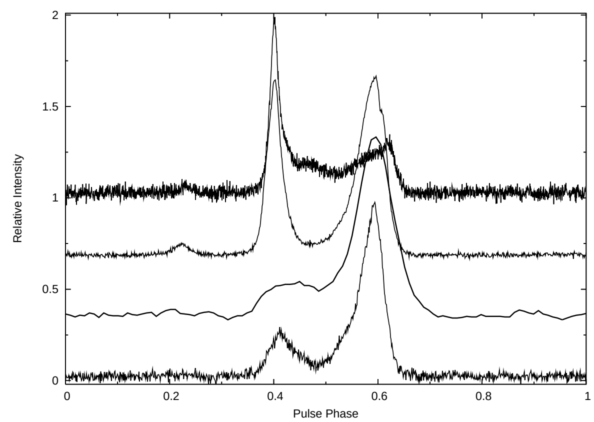

FIGURE 3. The profile evolution of PSR J2145-0750 as a function of frequency is shown. The topmost plot corresponds to a frequency of 1380 MHz, the second is 350 MHz, the third is the KL99 plot at 100 MHz and the lowest profile is the WSRT detection at 150 MHz.

In Figure 3 we present observations made at the WSRT using the PuMa II backend at frequencies of 150, 350 and 1380 MHz. In all cases the data were coherently dedispersed and the time resolution was at worst 25.6 μs. Also shown is the 102 MHz profile from KL96. One can see the advantages of the coherent dedispersion in our profile at 150 MHz which is significantly sharper. It is clear that the leading component (component I in KL96) has undergone significant frequency evolution and also that the the peak separation between it and the second large peak is reduced. However the shift is smaller than seen by KL96 as their profile seems to be slightly distorted, perhaps due to dispersive smearing. Moreover it is not clear that this is still component I as it has such a different shape. It now more resembles the trailing component of the high frequency profile. A multipole interpretation would require further observations at smaller frequency intervals to better track the component evolution.

CONCLUSIONS

We have used the LFFEs on the WSRT to make low frequency observations of 14 MSPs and successfully detected 8 of them. Using the PuMa II backend and coherent dedispersion we are able to get profiles with significantly higher time resolution than was previously possible. Previous work has suggested that we should have been able to detect the majority of these sources. We consider whether our failure to detect them is due to scattering or flux limits and find no clear factor which governs our ability to them. Taking the claimed detections in the literature at face value it would therefore suggest that there is some time dependent effect which is lowering the flux of them.

We consider diffractive scintillation, interference, and DM variations and find that neither can plausibly explain the non-detections. One possible explanation is refractive scintillation which causes flux modulation on long timescales. However further investigation into the long term flux stability of the sources would be required to confirm this effect as the modulation due to refractive scintillation is expected to be low [7].

What do these observations tell us about the prospects for observing and detecting MSPs with the LRAs? For LOFAR the sensitivity in the frequency range discussed above is expected to be at least 20 times better than the WSRT-LFFE combination. This means that we can expect to have the sensitivity to discover new MSPs with LOFAR. We need better statistics before being able to determine any sort of MSP luminosity function in this frequency range, but the initial results are very promising. It is also apparent that it will not be possible to determine a priori the DM out to which MSPs might be detected. The huge spread around the DM-scattering relationship precludes that and so a search out to DMs up to at least 100 will be a necessary component of searches for MSPs.

The greatly improved sensitivity of the LRAs over the existing telescopes, in general, means that they will also be able to study the single pulses from a large sample of MSPs for the first time. This will be essential for determining whether there are any changes in the single pulse properties of MSPs, with their significantly smaller magnetic fields, compared to the normal pulsar population. That is to say, do any of the known single pulse properties depend on rotation rate or magnetic field strength or even neutron star surface temperature.

The LRAs have the potential to not only increase the number of MSPs known but also to study their emission properties with unprecedented detail.

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