The Subpulse Modulation Properties of Pulsars and its Frequency Dependence

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Abstract. A large sample of about two hundred pulsars have been observed to study their subpulse modulation at an observing wavelength of (when achievable) both 21 and 92 cm using the Westerbork Synthesis Radio Telescope. For 57 pulsars drifting subpulses are discovered for the first time and are confirmed for many others. This leads to the conclusion that it could well be that the drifting subpulse mechanism is an intrinsic property of the emission mechanism itself, although for some pulsars it is difficult or impossible to detect. It appears that the youngest pulsars have the most disordered subpulses and the subpulses become more and more organized into drifting subpulses as the pulsar ages. Drifting subpulses are in general found at both frequencies and the measured values of $P_3$ at the two frequencies are highly correlated, showing the broadband nature of this phenomenon. Also the modulation indices measured at the two frequencies are clearly correlated, although at 92 cm they are on average possibly higher. The correlations with the modulation indices are argued to be consistent with the picture in which the radio emission is composed out of a drifting subpulse signal plus a quasi-steady signal which becomes, on average, stronger at high observing frequencies. There is no obvious correlation found between $P_3$ and the pulsar age (or any other pulsar parameter) contrary to reports in the past.

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INTRODUCTION

Although the pulse profiles of radio pulsars are in general very stable, the shape of their single pulses are often highly variable from pulse to pulse. For some pulsars the single pulses are modulated in a highly organized and fascinating way: they exhibit the phenomenon of drifting subpulses. An example is shown in the left panel of Fig. 1. In this so-called “pulse-stack” fifty successive pulses are displayed on top of one another and a beautiful pattern of diagonal “drift bands” emerges.

There are a few types of models that attempt to explain the drifting phenomenon. The most well known model is the carousel model (Ruderman and Sutherland [1]), which has been extended by many authors (e.g. Gil et al. [2]) making it the most developed model for explaining the drifting phenomenon. These models explain the drifting phenomenon by the generation of the radio emission via a rotating “carousel” of discharges which circulate around the magnetic axis due to an $E \times B$ drift. Alternative models to explain drifting subpulses are the model for non-radial pulsations of neutron stars (e.g. Clemens and Rosen [3]) and the feedback model proposed by Wright [4].

We have embarked on an extensive observational program to survey a large sample of pulsars to study their single pulse modulation using the Westerbork Synthesis Radio Telescope (WSRT) in the Netherlands. The main goals of this program are to determine what fraction of the pulsars have drifting subpulses, whether those pulsars share some physical properties and if subpulse modulation is frequency dependent. The sample of pulsars studied is selected based only on the predicted $S/N$ in a reasonable observing time, which makes the resulting statistics as unbiased as possible towards well-studied pulsars, pulse profile morphology or any particular pulsar characteristics. If possible, we observed the pulsars at two wavelengths around 21 and 92 cm.

The results of the pulsars observed at a wavelength of 21 and 92 cm are published in Weltevrede et al. [5] and Weltevrede et al. [6] respectively. All the plots of the two 21-cm and 92-cm observations can also be found side by side in the PhD. thesis of the main author [7]. In this proceedings we summarize the results of the observations and a comparison between the two observing frequencies is made.

1 The thesis of P. Weltevrede is online available via the following link: [http://dare.uva.nl/en/record/217315](http://dare.uva.nl/en/record/217315) or contact the author for a hardcopy.
FIGURE 1. An example of a pulse-stack of fifty successive pulses of PSR B0818–13 as observed by the WSRT at 92 cm. Two successive drift bands are vertically separated by $P_3$ and horizontally by $P_2$.

RESULTS

Drifting subpulses are very common

Our sample of pulsar is not biased on pulsar type or any particular pulsar characteristics. This allows us, first of all, to address the very basic question: what fraction of the pulsars show the drifting phenomenon? Of the 187 analyzed pulsars at 21 cm, 68 pulsars show the drifting phenomenon. At 92 cm this fraction is a little bit higher: for 76 of the 185 analyzed pulsars we found drifting subpulses. Most of the pulsars for which we detected drifting subpulses were not known to have them. This shows first of all that the used method to detect drifting subpulses (using fluctuation spectra; Edwards and Stappers [7]) works extremely well.

For about one in three pulsars we found drifting subpulses, and this is a lower limit for a number of reasons. The most important reason is that the chance of finding drifting subpulses was found to be correlated with the $S/N$ ratio of the observation. The probability of detecting drifting is higher for observations with a higher $S/N$. We estimate that at least half of the pulsars have drifting subpulses. There are many reasons why drifting is not expected to be detected for all pulsars. For instance for some pulsars the line of sight cuts the magnetic pole centrally and therefore longitude stationary subpulse modulation is expected. Also, refractive distortion in the pulsar magnetosphere or nulling (periods during which the pulsar emits no radio emission) will disrupt the drift bands, making it difficult or even impossible to detect drifting. Some pulsars are known to show organized drifting subpulses in bursts. In that case (or when $P_3$ is very large) some of our observations could be too short to detect the drifting.

With a lower limit of one in two it is clear that drifting is at the very least a common phenomenon for radio pulsars and it could well be that the drifting phenomenon is an intrinsic property of the emission mechanism although for some pulsars it is difficult or even impossible to detect.

Drifting subpulses become more organized when the pulsar ages

In Fig. 2 it can be seen that the population of pulsars that show the drifting phenomenon is on average older than the population of pulsars that do not show drifting. Moreover it seems that the population of pulsars that show coherent drifting (i.e. very regular drifting subpulses) is on average older than those who show less regular drifting subpulses. The same trend is found
both in the 21 and the 92 cm data. It is intriguing to think that drifting becomes more and more coherent for pulsars with a higher age. This correlation cannot be explained by nulling, because the nulling fraction is on average higher for older pulsars. Possibly the alignment of the magnetic dipole axis with the rotation axis has something to do with the observed trend. Observations seem to show that the angle $\alpha$ between the magnetic axis and the rotation axis is on average smaller for older pulsars and this angle is likely to be an important physical parameter in the mechanism that drives the drifting phenomenon. In this scenario as the pulsar gets older, the rotation axis and the magnetic axis grows more aligned, which makes the drifting mechanism more effective or regular.

**Subpulse modulation at the two frequencies**

An interesting quantity to consider is the modulation index, which is a measure of the factor by which the intensity varies from pulse to pulse. It is clear that the modulation index is a parameter that is closely related with the drifting phenomenon, because drifting subpulses imply an intensity modulation. However, it is somewhat arbitrary how the modulation should be defined, because the longitude-resolved modulation index is in most cases highly dependent on pulse longitude. We have used the minimum in the modulation index profile, which should be more independent of the $S/N$ of the observation.

In Fig. 3 it can be seen that the modulation indices measured at the two frequencies are not independent, but they are clearly correlated. If the modulation index was independent of observing frequency the points would be scattered symmetrically around the dotted line. However, there are more pulsars with a higher modulation index at 92 cm than visa versa.

This trend is also confirmed by making a straight line fit through the data. This is done by minimizing the $\chi^2$ incorporating the measurement errors of both coordinates (dashed line). To avoid the best fit being dominated by a few high $S/N$ observations, the fitting is also done by weighting the data-points equally. This fit also confirms that the modulation index at 92 cm is on average higher than at 21 cm (solid line).

**Properties of drift behavior**

It is generally thought that the value of $P_3$ is independent of the observing frequency, while the value of $P_2$ could vary. All pulsars with a measured $P_3$ at two frequencies are compared in Fig. 4 to test the absence of a dependency on the observing frequency of $P_3$. The correlation is indeed extremely tight. This correlation confirms the report for nine pulsars by Nowakowski et al. FIG 3. Moreover, many points that do not fall on the correlation can be explained. In the case of PSRs B0031−07 and B1819−22 drift-modes with different $P_3$ values dominate at the two frequencies. For others, such as PSRs...
B1738−08 and B1946+35 it seems not unlikely that longer observations will reveal that the $P_3$ values are consistent at the two frequencies.

There is no obvious correlation found between $P_3$ and the pulsar age contrary to reports in the past. The absence of a correlation with age in this large sample of pulsars with drifting subpulses (90) suggests that if such a correlation would exist, it must be a very weak correlation. Also, the evidence for a pulsar sub-population located close to the $P_3 = 2P_1$ Nyquist limit (Wright [4], Rankin [6]) is weak.

THE QUASI-STEADY EMISSION COMPONENT

Nowakowski et al. [8] concluded, based on a multi-frequency study of nine pulsars, that it is a common feature of pulsars to have a quasi-steady component in their emission which becomes stronger with increasing frequency. Our observations support this conclusion in several ways. First of all, a considerable fraction of the pulsars with drifting subpulses have a modulation index lower than $m = 1/\sqrt{2}$ (see Fig. 3). Such low modulation indices cannot be produced by a pure drifting subpulse signal. Fig. 3 also shows the trend that the modulation index is, on average, lower at 21 cm. This would be consistent with the idea that there is a quasi-steady component in the emission of pulsars which is relatively strong at higher frequencies. This picture may also explain why the chance of detecting drifting subpulses is slightly higher at low frequencies, because the drifting subpulse signal is relatively stronger at lower frequencies.

SUMMARY AND CONCLUSIONS

Drifting subpulses are at the very least a common phenomenon for radio pulsars, if not an intrinsic property of the emission mechanism. For 57 pulsars drifting subpulses are discovered for the first time, showing the success of this survey. It is estimated that at least half of the total population of pulsars will show drifting subpulses when observations with high enough $S/N$ would be available. The chance of detecting drifting subpulses at both frequencies is high, indicating that the drifting phenomenon is in general broadband.

Drifting subpulses are at the very least a common phenomenon for radio pulsars, which implies that the physical conditions required for the emission mechanism and the drifting mechanism to work are similar. This is consistent with the absence of a correlation with the surface magnetic field strength.

The measured values of $P_3$ at the two frequencies are highly correlated. These correlations are expected when the drifting subpulses share a common physical origin. A correlation between $P_3$ and other pulsar parameters is expected if the drift rate depends on any physical parameters of the pulsar and the strongest correlation is expected to be found when $P_2$ is identical for different pulsars. Such a correlation would be a very important observational restriction on pulsar emission models. However, there are no such correlations found. This could suggest that many pulsars in our sample are aliased or that $P_2$ is highly variable from pulsars to pulsar.

Our sample of pulsars is not biased on pulsar type or any particular pulsar characteristics, which allows us to do meaningful statistics on the drifting phenomenon. There is a weak trend found that pulsars with drifting subpulses are on average older, especially the very regular drifters. This correlation suggests that there is an evolutionary trend such that the youngest pulsars have the most disordered subpulses and that the subpulses become more and more organized into drifting subpulses when the pulsar ages. This trend could for instance be explained by the evolution of the angle between the magnetic axis and the rotation axis or the evolution of the pulse morphology. In the non-radial pulsations model (Clemens and Rosen [3]) this trend can also be explained, because the appearance of narrow drifting subpulses is favored in pulsars with an aligned magnetic axis. This trend cannot explained by nulling.

The modulation indices measured at the two frequencies are clearly correlated, although they tend to be higher at low frequencies. This is consistent with the picture in which the radio emission can be divided into a drifting subpulse signal plus a quasi-steady component which becomes stronger at high observing frequencies.

REFERENCES

1. M. A. Ruderman, and P. G. Sutherland, ApJ 196, 51–72 (1975).
2. J. Gil, G. I. Melikidze, and U. Geppert, A&A 407, 315–324 (2003).
3. J. C. Clemens, and R. Rosen, ApJ 609, 340–353 (2004).
4. G. A. E. Wright, MNRAS 344, 1041–1056 (2003).
5. P. Weltevrede, R. T. Edwards, and B. W. Stappers, A&A 445, 243–272 (2006).
6. P. Weltevrede, B. W. Stappers, and R. T. Edwards, A&A 469, 607–631 (2007).
7. R. T. Edwards, and B. W. Stappers, A&A 393, 733–748 (2002).
8. L. Nowakowski, J. Usowicz, A. Wolszczan, and A. Kępa, A&A 116, 158–163 (1982).
9. J. M. Rankin, ApJ 301, 901–922 (1986).