Statistics of the Drifting Subpulse Phenomenon

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Abstract We present the statistical results of a systematic, unbiased search for subpulse modulation of 187 pulsars performed with the Westerbork Synthesis Radio Telescope (WSRT) in the Netherlands at an observing wavelength of 21 cm (Weltevrede et al. 2006). We have increased the list of pulsars that show the drifting subpulse phenomenon by 42, indicating that more than 55% of the pulsars that show this phenomenon. The large number of new drifters we have found allows us, for the first time, to do meaningful statistics on the drifting phenomenon. We find that the drifting phenomenon is correlated with the pulsar age such that drifting is more likely to occur in older pulsars. Pulsars that drift more coherently seem to be older and have a lower modulation index. Contrary claims from older studies, both P_3 (the repetition period of the drifting subpulse pattern) and the drift direction are found to be uncorrelated with other pulsar parameters.

Key words: pulsars:general

1 INTRODUCTION

If one can detect single pulses one can see that in some pulsars they consist of subpulses and in some cases these subpulses drift in successive pulses in an organized fashion through the pulse window. If one plots a so-called "pulse-stack", a plot in which successive pulses are displayed on top of one another, the drifting phenomenon causes the subpulses to form "drift bands". In the left panel of Figure 1 one can see a sequence of 100 pulses of one of the new drifters we have found which clearly shows the drifting phenomenon. The pulse number is plotted vertically and the time within the pulses (i.e. the pulse longitude) horizontally. The drift bands are characterized by two numbers: the horizontal separation between them in pulse longitude (P_2) and the vertical separation in pulse periods (P_3). This complex, but highly regular intensity modulation in time is known in great detail for only a small number of well studied pulsars. Because the properties of the subpulses are most likely determined by the emission mechanism, we learn about the physics of the emission mechanism by studying them. That drifting is linked to the emission mechanism is suggested by the fact that drifting is affected by "nulls", where nulling is the phenomenon whereby the emission mechanism switches off for a number of successive pulses. The main goals of this unbiased search for pulsar subpulse modulation is to determine what percentage of the pulsars show the drifting phenomenon and to find out if these drifters share some physical properties. As a bonus of this observational program new, individually interesting drifting, subpulse systems are found (Weltevrede et al. 2006).

2 OBSERVATIONS AND DATA ANALYSIS

An important aspect when calculating the statistics of drifting is that one has to be as unbiased as possible, so we have selected our sample of pulsars based only on the predicted signal-to-noise (S/N) ratio in a

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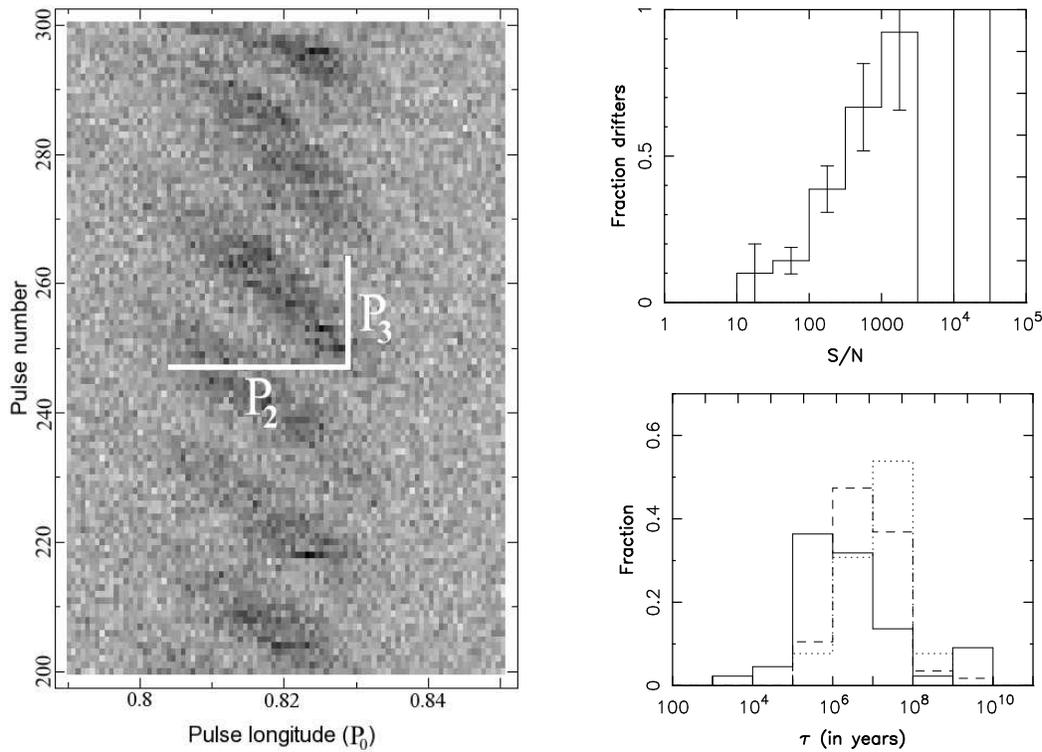
Fig. 1 Left: A pulse-stack of the new drifter PSR B1819−22. **Top right:** The fraction of pulsars we observe to show the drifting phenomenon versus the measured S/N ratio of the observation. **Bottom right:** The age distribution of the non-drifting pulsars (solid line), all the drifters (dashed line) and the coherent drifters (dotted line).

reasonable observing time. While this sample is obviously still luminosity biased, it is not biased towards well-studied pulsars, pulse profile morphology or any particular pulsar characteristics as were previous studies (e.g. Ashworth 1982; Backus 1981; Rankin 1986). Moreover, all the conclusions in this paper are based on observations at a single frequency. All the analyzed observations were collected with the WSRT in the Netherlands at an observation wavelength of 21 cm.

One basic method to find out if there is subpulse modulation is to calculate the modulation index, which is a measure of the factor by which the intensity varies from pulse to pulse and could therefore be an indication for the presence of subpulses. To determine if the subpulses are drifting, the Two-Dimensional Fluctuation Spectrum (2DFS; Edwards & Stappers 2002) is calculated. By analyzing the 2DFS it can be determined if this modulation is disordered or (quasi-)periodic and if there exists a systematic drift. The calculation of the 2DFS is an averaging process and this makes it a powerful tool to detect drifting subulses, even when the S/N is too low to detect single pulses. The drifting is classified as *coherent* when the drift has a well defined P_3 value. For more details about the observations and data analysis we refer to Weltevrede et al. (2006).

3 STATISTICS

3.1 The Numbers

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 68 pulsars show the drifting phenomenon, indicating that at least one in three pulsars drift. This is a lower limit for a number of reasons. First of all, not all the observations have the

expected S/N. This could be because of radio interference, interstellar scintillation, digitization effects, or because the flux or pulse width for some pulsars was wrong in the database used.

In the top right panel of Figure 1 the fraction of pulsars that show the drifting phenomenon is plotted versus the S/N ratio of the observation. One can see that the probability of detecting drifting is higher for observations with a higher S/N. To make the statistics more independent of the S/N ratio of the observations, the statistics are done with the 106 pulsars with a S/N$\geq$ 100. Of these pulsars 54% is detected to be drifters and from the top right panel of Figure 1 it is clear that the real drift percentage could even be higher. 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 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. This is consistent with the conclusion that the drifting phenomenon is only weakly correlated with (or even independent of) magnetic field strength (Weltevrede et al. 2006), because the drifting phenomenon is too common to require very special physical conditions. 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.

### 3.2 The Age Dependence Of The Drifting Phenomenon

Two directly measurable and therefore important physical parameters of the pulsar are the pulse period and its time derivative (spin-down parameter). From the pulsar age histograms (bottom right panel of Figure 1) 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 drifting is more coherent for older pulsars. It turns out that the drifters and nondrifters have significantly different age distributions and that the pulsars which drift coherently are likely to have a separate age distribution (Weltevrede et al. 2006). It is intriguing to think that drifting becomes more and more coherent for pulsars with a higher age. A possible mechanism to distort the drift bands is nulling. However it has been found that the nulling fraction is on average higher for older pulsars, showing that nulling cannot explain this correlation.

Another possible scenario is that 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 α 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. Also the pulse profile morphology seems to evolve when the pulsar ages what could make drifting subpulses more likely to be detected in older pulsars. In the non-radial pulsations model this trend can also be explained, because the appearance of narrow drifting subpulses is favored in pulsars with an aligned magnetic axis (Clemens & Rosen 2004).

3.3 The Drifting Phenomenon And The Modulation Index

The drifting phenomenon is a form of subpulse modulation, so the modulation index is an obvious parameter to try to correlate with the drifting phenomenon. Modulation index distributions are shown in the left panel of Figure 2. Readily apparent is the trend that pulsars that show the drifting phenomenon more coherently have on average a lower modulation index (not shown to be statistically significant).

To explain the trend, pulsars that drift coherently must either have on average more subpulses per pulse or the subpulse intensity distribution must be more narrow. The latter could be understood because coherent drifting could indicate that the electrodynamical conditions in the sparking gap are stable. Also the presence of subpulse phase steps results in a lower modulation index and could be explained as the result of interference between two superposed drifting subpulse signals that are out of phase (e.g. Edwards & Stappers 2003). It is not unlikely that this interference can only occur if the drifting is coherent, which could explained the trend. It is also found that many pulsars must have a non-varying component in their emission, consistent with the presence of superposed out of phase subpulse signals. Another explanation
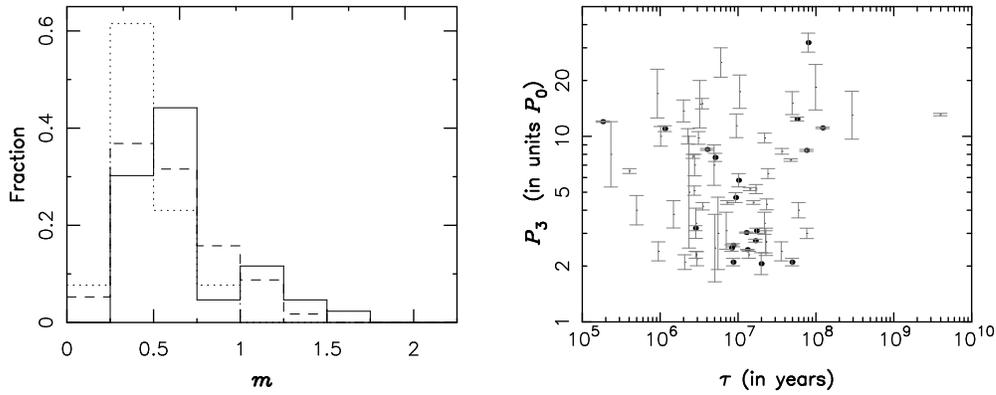
Fig. 2 Left: The modulation index distribution of the pulsars that do not show the drifting phenomenon (solid line), that do show the drifting phenomenon (dashed line) and of the pulsars that drift coherently (dotted line). **Right:** The measured value of the vertical drift band separation P_3 versus the pulsar age. The coherent drifters are the filled circles.

for this trend would be that for some pulsars the organized drifting subpulses are more refractively distorted than for others, causing the subpulses to appear more disordered in the pulse window. Moreover it could be expected that the intensities of the individual subpulses varies more because of lensing (e.g. Petrova 2000) and possible focusing of the radio emission (Weltevrede et al. 2003), causing the modulation index to be higher in those pulsars.

The modulation index of core type emission is observed to be in general lower than that of conal type of emission. This is also a consequence of the Gil & Sendyk (2000) model. In the sparking gap model, the drifting phenomenon is associated with conal emission and therefore expected to be seen in pulsars with an on average higher modulation index. If well organized coherent drifting is an exclusively conal phenomenon, it is expected that coherent drifters have an on average a higher modulation index, exactly opposite to the observed trend. No drifting is expected for pulsars classified as "core single stars". Although this may be true for many cases there are some exceptions, stressing the importance of being unbiased on pulsar type when studying the drifting phenomenon.

In the framework of the sparking gap model the subpulses are generated (indirectly) by discharges in the polar gap (i.e. sparks). The number of sparks that fits on the polar cap is quantified by the complexity parameter (Gil & Sendyk 2000), which is expected to be anti-correlated with the modulation index (Jenet & Gil 2003). The complexity parameter is a function of the pulse period and its derivative and its precise form depends on the model one assumes for the pulsar emission. By correlating the modulation index of a sample of pulsars with various complexity parameters as predicted by different emission models one could try to distinguish which model best fits the data. We have correlated the modulation indices in our sample of pulsars with the complexity parameter of four different emission models as derived by Jenet & Gil (2003). Unfortunately none of the models can be ruled out based on these observations.

3.4 Properties Of The Drift Behavior

A significant correlation between P_3 and the pulsar age has been reported in the past (e.g. Rankin 1986). As one can see in the right panel of Figure 2 there is no clear correlation found in our data, which is confirmed by χ^2-fitting. There is no correlation found between P_3 and the magnetic field strength or the pulse period as well as between the drift direction and the pulsar spin-down as reported in the past (Ritchings & Lyne 1975). The evidence for a pulsar subpopulation located close to the $P_3 = 2P_0$ Nyquist limit also seems to be weak.

In a sparking gap model one would expect that the spark-associated plasma columns drift because of an $\boldsymbol{E} \times \boldsymbol{B}$ drift, which depends on both the pulse period and its derivative. The absence of any correlation between P_3 and a physical pulsar parameter is difficult to explain in this model, unless many pulsars in our sample are aliased. Because the emission entities are only sampled once per rotation period of the star, it is very difficult to determine if the subpulses in one drift band correspond to the same emission entity

for successive pulses. For instance for PSR B1819−22 (see left panel of Figure 1) we do not know if the emission entities drift slowly toward the leading part of the pulse profile (not aliased) or faster toward the trailing part of the pulse profile (aliased). If a pulsar is aliased a higher $\boldsymbol{E} \times \boldsymbol{B}$ drift can result in a lower P_3 value and visa versa, making P_3 not a direct measure of the $\boldsymbol{E} \times \boldsymbol{B}$ drift. Also if P_2 is highly variable from pulsars to pulsar, any correlation with P_3 is expected to be weaker.

4 CONCLUSIONS

The number of pulsars that are known to show the drifting phenomenon is significantly expanded by 42 and the fraction of pulsars that show the drifting phenomenon is likely to be larger than 55%. This implies that the physical conditions required for the drifting mechanism to work cannot be very different than the required physical conditions for the emission mechanism of radio pulsars. It could well be that the drifting phenomenon is an intrinsic property of the emission mechanism, although drifting could in some cases be very difficult to detect.

Our results seem to suggest that drifting is not exclusively related to conal emission. 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. Although significant correlations between P_3 and the pulsar age, the magnetic field strength and the pulse period have been reported, we find no such correlations in our enlarged sample. The absence of a correlation between P_3 and any physical pulsar parameter is difficult to explain, unless many pulsars in our sample are aliased or if P_2 is highly variable from pulsar to pulsar.

The population of pulsars that show the drifting phenomenon are on average older than the population of pulsars that do not show drifting and it seems that drifting is more coherent for older pulsars. The evolutionary trend found seems to suggest that the mechanism that generates the drifting subpulses gets more and more stable as the pulsar ages.

If subpulse phase steps are exclusively (or at least more likely) to occur in pulsars with coherently drifting subpulses, their modulation index is expected to be on average lower. This is indeed the trend the we observe. Another possible scenario to explain this trend is that coherent drifting indicates that the electrodynamical conditions in the sparking gap are stable or that refraction in the magnetosphere is stronger for pulsars that do not show the drifting phenomenon coherently.

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