A transient component in the pulse profile of PSR J0738−4042

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ABSTRACT

One of the tenets of the radio pulsar observational picture is that the integrated pulse profiles are constant with time. This assumption underpins much of the fantastic science made possible via pulsar timing. Over the past few years, however, this assumption has come under question with a number of pulsars showing pulse shape changes on a range of time-scales. Here, we show the dramatic appearance of a bright component in the pulse profile of PSR J0738−4042 (B0736−40). The component arises on the leading edge of the profile. It was not present in 2004 but strongly present in 2006 and all observations thereafter. A subsequent search through the literature shows that the additional component varies in flux density over time-scales of decades. We show that the polarization properties of the transient component are consistent with the picture of competing orthogonal polarization modes. Faced with the general problem of identifying and characterizing average profile changes, we outline and apply a statistical technique based on a hidden Markov model. The value of this technique is established through simulations and is shown to work successfully in the case of low signal-to-noise ratio profiles.

Key words: pulsars: individual: J0738−4042 – pulsars: individual: B0736−40.

1 INTRODUCTION

The radio emission from pulsars is characterized by a range of dynamic phenomena that take place on various time-scales. Microstructure is observed at the shortest (μs) time-scales, stochastic or organized changes in the pulse shape occur on time-scales of the rotational period P, while other phenomena, such as nulling (e.g. Lorimer & Kramer 2005), where radio emission totally switches off, may last significantly longer than one rotation. An examination of the average pulse properties of a given pulsar, however, demonstrates that the mean shape of a sufficiently large number of individual pulses remains remarkably constant over long periods of time. It is this quality of radio pulsars that makes them extremely useful tools: knowing the exact shape of the pulse profile increases the precision of the measurement of the pulse time of arrival, which is the basic quantity in pulsar timing experiments.

Although it is rare that the integrated profiles of pulsars change with time, it is not unprecedented. Time-scales of changes range from hours through to months and years. On short time-scales are the rotating radio transients (McLaughlin et al. 2006), which are thought to be neutron stars that only emit individual bursts of emission at irregular and infrequent intervals. A group of pulsars show mode changing, where two distinct and different pulse profiles are observed over time-scales of hours (e.g. Gil et al. 1994). The intermittent pulsar PSR B1931+24 (Kramer et al. 2006) is present for 5−10 d before its emission ceases for some 30 d. In this case, the derivative of the rotational period, P, changes between the on and off phases and is therefore correlated with changes in the radio pulse profile. Similar results associated with more subtle profile changes are reported in Lyne et al. (2010), and another intermittent pulsar (PSR J1832+0029) is discussed in Kramer (2008). In PSR J1119−6127, pulse changes were seen which appeared to be associated with glitch activity (Weltevrede, Johnston & Espinoza 2011). There is strong evidence that all these effects (nulling, mode changing and intermittency) are magnetospheric in origin.

A further long-term effect, due to geodetic precession of a pulsar in a binary orbit, can also cause pulse shape changes. These have been observed in e.g. PSR B1913+16 (Kramer 1998; Weisberg & Taylor 2002) and J1141−6545 (Manchester et al. 2010). Periodic changes in the average profile of PSR B1828−11 were interpreted as free precession by Stairs, Lyne & Shemar (2000); however, free precession of solitary neutron stars is considered unlikely (Sedrakian, Wasserman & Cordes 1999) on theoretical grounds. Changes in the pulse profile due to precession relate to changes in the viewing geometry rather than magnetospheric effects.
The average pulse profiles of pulsars are partially linearly polarized, to a lesser or higher degree. Highly energetic pulsars feature high degrees of linear polarization (e.g. Weltevrede & Johnston 2008). There is good evidence to suggest that the observed emission results from the superposition of two orthogonally polarized modes (OPMs), which arise and propagate inside the pulsar magnetosphere (e.g. McKinnon & Stinebring 2000; Karastergiou et al. 2002). Comparable intensities of the modes have been favoured observationally as the cause for reduced linear polarization in pulsars at typical ($\sim1$ GHz) observing frequencies. A further observational consequence is that the changes in the structure of the total power average profile with observing frequency are often coupled with particular changes in the degree of linear polarization, reflecting the spectral behaviour of the orthogonal polarization modes (as discussed in Karastergiou, Johnston & Manchester 2005; Smits et al. 2006); as the OPMs become more equal in strength, the total power increases and the polarization decreases.

Pulsar timing models need to incorporate all known physical phenomena (intrinsic to the pulsar or not) that affect the measured times-of-arrival, in order to achieve a floor of sensitivity that would enable the discovery of extremely weak components to the model, such as gravitational waves (e.g. Hobbs 2008). Pulsar timing uses template matching and relies on the average profile not varying with time. Any variability in the profile adversely affects the timing model. In the following, we present data from a significant change in the average pulse profile of PSR J0738–4042. We show how polarization data reveal details about the change and explore its potential physical origins.

2 TOTAL INTENSITY PROFILE OF PSR J0738–4042

PSR J0738–4042 was one of the first radio pulsars discovered (Large, Vaughan & Wielebinski 1968). It has a high dispersion measure of $160.8 \text{ cm}^{-3} \text{ pc}$, and its spin period of $P = 375 \text{ ms}$ and a period derivative of $\dot{P} = 1.61 \times 10^{-15}$ place it within the bulk of normal pulsars on the $P$–$\dot{P}$ diagram. Its relatively high flux density ($80 \text{ mJy}$ at 1.4 GHz) has made it a consistent observing target over the 40 yr since its discovery. The most recent polarimetric profiles of the pulsar over a wide range of frequencies have been published in Karastergiou & Johnston (2006) and Johnston et al. (2006); Johnston et al. (2007). Average profiles in three separate observing bands taken in 2004 are shown in Fig. 1 (thin line). The profile at 1.4 GHz shows one bright component with a shoulder component on its leading edge, on what appears to be a broad pedestal of emission on the leading and trailing edge. Subsequently, the pulsar was observed as part of a programme to measure accurate rotation measures (Noutsos et al. 2009). The 1.4-GHz profile, taken in 2006, is shown as the thick line in Fig. 1. An additional component, $\approx 15^\circ$ earlier than the main peak, can be seen on the leading edge of the 2006 profile, which is almost entirely absent in 2004. This component is present at all three observing frequencies.

Armed with this result, we looked through the literature for other published profiles of this pulsar. Table 1 includes a summary of available data, where the date and observing frequency are given with a note relating to the presence of the leading component. Two facts are immediately evident. First, there is a period between 1991 and 2005 where the component is totally absent. Secondly, the presence or absence of the leading component is a broad-band

![Figure 1](https://academic.oup.com/mnras/article-abstract/415/1/251/989104)

Figure 1. The average profile of PSR J0738–4042 as observed with the 50-, 20- and 10-cm receivers at Parkes, in the first half of 2004 (thin line) and the second half of 2006 (thick line). The change in the leading edge of the profile shape is visible at all frequencies.

| Date   | Frequency (MHz) | Component at $-15^\circ$ | Reference                                |
|--------|-----------------|--------------------------|------------------------------------------|
| <1970  | 1720            | Strong and discrete      | Komesaroff, Morris & Cooke (1970)        |
| <1975  | 1400            | Strong and discrete      | Backer (1976)                            |
| <1977  | 631             | Shoulder to main pulse   | McCulloch et al. (1978)                   |
| <1977  | 1612            | Strong and discrete      | Manchester, Hamilton & McCulloch (1980)   |
| 1979   | 950             | Strong and discrete      | van Ommen et al. (1997)                  |
| 1990   | 950             | Weak shoulder to main pulse | van Ommen et al. (1997)            |
| 1991   | 800             | Absent                   | van Ommen et al. (1997)                  |
| 1996   | 1375            | Absent                   | Unpublished                              |
| 1997   | 1375            | Absent                   | Unpublished                              |
| 2000   | 1375            | Absent                   | Karastergiou & Johnston (2006)           |
| 2004   | 1375            | Absent                   | Karastergiou & Johnston (2006)           |
| 2005   | 8400            | Absent                   | Johnston, Karastergiou & Willett (2006)   |
| 2005   | 3100            | Absent                   | Johnston et al. (2007)                   |
| 2006   | 1369            | Strong and discrete      | Noutsos et al. (2009)                    |
A transient component in PSR J0738−4042

Figure 2. A grey-scale representation of the intensity of 71 profiles, observed at irregular intervals between 2003 and 2011. The peak intensity of each profile is normalized to unity; the profiles are aligned by cross-correlation with a top-hat function. The change occurs at profile 23.

Figure 3. Three average profiles of PSR J0738−4042 in full polarization, from 2004, 2006 and 2010 (top to bottom). The total intensity, linear polarization and circular polarization are shown just below the PA curve (dotted line). The extra component in the 2006 and 2010 profiles is clearly responsible for the observed additional orthogonal jumps in the leading edge of that profile. These jumps coincide in phase with local minima in the linear polarization.

3 CHANGES IN THE POLARIZATION PROFILE

As mentioned in Section 1, polarization is a useful diagnostic in the interpretation of pulsar radio emissions. Fig. 3 shows three average profiles of PSR J0738−4042, from 2004, 2006 and 2010. It is immediately obvious that the additional component which appears between 2004 and 2006 is also associated with a different polarization state. Between pulse phases −20° and −10°, there are three orthogonal polarization jumps in the 2006 and 2010 profiles, as opposed to a single jump in the 2004 data. It is also evident that the degree of linear polarization in this region of the profile is related to the total power and that there are local minima directly related to the orthogonal position angle (PA) jumps. A comparison between the 2004 and 2006 data shows that as the total power increases around pulse phase −16°, the linear polarization drops.

We attempted to reproduce the observed changes in polarization using a simple model. The starting point of the model is the polarization profile obtained from observations in 2004 shown at the top of Fig. 3. To this, we added a Gaussian component centred at phase −15.47°, which is 100 per cent polarized. We computed the total intensity $I_c$ of the simulated component as

$$I_c(\phi) = A \exp[-(\phi - 15.47)^2/(2\sigma^2)],$$

where $A$ is the amplitude, $\sigma$ is the width of the Gaussian and $\phi$ is the pulse phase. For each pulse phase bin, we set the polarization of the simulated component to be orthogonal to the polarization of the 2004 profile, by computing its Stokes parameters ($I_o, Q_o, U_o, V_o$) relative to the Stokes parameters of the 2004 profile ($I_o, Q_o, U_o, V_o$), taking into account that

$$\frac{U_c}{Q_c} = \frac{U_o}{Q_o}, \quad I_c = \sqrt{Q_o^2 + U_o^2 + V_o^2}.$$
realization of a hidden Markov model (HMM) to automatically identify putative state changes in the data. HMMs (Rabiner 1989) have been widely used for inferring latent changes in sequential data. Consider a sequence of observations, $Y = \{y_t\}_{t=1}^{T}$, $y_t \in \mathbb{R}^d, \forall t$. The distribution of an observation, $y_t$, is determined by a corresponding hidden state, $s_t \in \{1, \ldots, J\}$, and a state-dependent observation probability.

The hidden state at time $t = 1$ is determined by a prior state vector, $\pi = [\pi_1, \ldots, \pi_J]^\top$, where $\pi_j = p(s_1 = j)$. The Markov property implies that a hidden state $s_{t-1}, s_t$ depends only on $s_{t-1}$ and not on those at time $t-2$ and before:

$$p(s_1 | s_{t-1}, \ldots, s_t) = p(s_1 | s_{t-1}).$$

(6)

State transitions are jointly determined by a transition matrix, $A = [a_{ij}]$, where $a_{ij} = p(s_t = j | s_{t-1} = i)$ and observation likelihoods. An observation $y_t$ depends only on the corresponding hidden state, $s_t$, and we utilize here a state-dependent Gaussian density, such that the predictive distribution over observations, conditioned on the hidden state, is given by

$$p(y_t | s_t = j) = \mathcal{N}(y_t; \mu_j, \Sigma_j),$$

(7)

where $\mu_j$ and $\Sigma_j$ are the mean vector and the covariance matrix for the $j$th state.

Inference in an HMM proceeds by evaluation of the posterior distribution over the parameters, $[\pi, A, \mu, \Sigma]$, as well as the posterior distributions of the hidden state variables, $p(s_t | Y)$. A two-stage maximum-likelihood algorithm is often adopted, such as the Baum–Welch algorithm (Baum et al. 1970), a special case of the expectation-maximization (EM) algorithm (Dempster, Laird & Rubin 1977). The most probable state sequence can be found using the Viterbi algorithm (Rabiner 1989). The maximum-likelihood approach, however, has major limitations, most notably overfitting and inference of underlying model complexity, such as determining the most probable number of states. In order to address these limitations, we employ a fully Bayesian approach, which exploits the tractable bounds of variational Bayes approximations (Jordan et al. 1999). The Bayesian methodology allows for uncertainty to be handled at all levels of inference, making the approach ideal for analysis of smaller data samples. Furthermore, the number of underlying states is inferred automatically such that sequences without significant state changes are modelled by a single state process. This deviates significantly from maximum-likelihood methods in which the data are forced into a set number of states.

As posterior state probabilities are inferred for each datum, we can not only investigate with ease the existence of state changes but also track the entropy associated with state determination at each point. The information entropy associated with the posterior over the states, conditioned on observation $y_t$, is hence given as

$$\mathcal{H}_t = - \sum_j p(s_t = j | y_t) \log p(s_t = j | y_t).$$

(8)

The advantage of utilizing entropy lies in the fact that increases in entropy will occur in locations in which a full state change is not supported by the data. If the logarithm is to base two, then the entropy is returned in bits, with 1 bit of entropy indicating the existence of a fully supported state change.

We use the Bayesian HMM to infer the posterior distribution over the state sequence for each bin of the pulse profile, using the total power amplitudes of each bin as our observables. Fig. 5 shows the entropy (in bits) of the state posterior applied to all bins of all profiles, in contours superposed on the raw data. The contours, which range from 0 to 1 in steps of 0.2, indicate very...
4.2 Sensitivity analysis

Although the HMM clearly and robustly identifies a state change in the average pulse profile, it is not surprising that this analysis performs well, given the large magnitude of the event (it can be picked out clearly by eye). We have performed a sensitivity analysis to test the performance of the HMM on noisier data. This involves adding increasing levels of white noise to the profiles and comparing the state-change identification with the original analysis. We have performed this analysis by means of a Monte Carlo simulation, producing 1000 versions of each profile with a given S/N and changing the noise from four to 100 times the original in steps of 4 (i.e. $25 \times 10^4$ simulated profiles for each observed profile). For each set of profiles at a given S/N, we run the HMM and count the fraction of sets in which a state change is detected, versus the S/N of the new component. The HMM performs perfectly for an S/N of 1 and above.

5 DISCUSSION AND CONCLUSIONS

We have shown that PSR J0738−4042 has undergone dramatic changes in its average pulse profile in the period between 2004 and 2006. The changes affect the total amplitude and polarization of a single component on the leading edge of the profile and are broad-band at least over the frequency range between 600 and 3100 MHz. Examination of the literature shows that the transient component was present between 1970 and 1990 and then absent until 2006 since when it has again been present up to the current epoch (2011 January). The ‘intermittency’ of this particular component can therefore be measured in tens of years compared to e.g. the tens of days in PSR B1931+24. This serves as a unique example of magnetospheric changes on very long time-scales. This is further proof that there remains a lot to be understood on the dynamic nature of pulsar magnetospheres on all time-scales.

The increase in intensity of the transient component is accompanied by an orthogonal transition in the position angle of the linear polarization and by a decrease in the fractional linear polarization of that part of the profile. When the extra component is absent, the leading part of the profile is almost completely polarized. Orthogonal jumps in the polarization angle are common in pulsars with medium or low levels of linear polarization, which implies that the degree of polarization is affected by the presence of the two modes. In the past, two models have been put forward to account for this behaviour: the observed pulsar radiation occurs either in two partially polarized orthogonal modes of emission which are emitted disjointly (e.g. Cordes, Rankin & Backer 1978) or in two entirely polarized orthogonal modes, the superposition of which sets the total polarization (e.g. McKinnon & Stinebring 2000). The data presented here strongly favour the latter, as this is the first example where we see two distinct states: a single mode and high polarization when the additional component is absent and low polarization associated with higher total intensity when it appears. We show the validity of this interpretation of the post-2006 data with a simple simulation.

Orthogonal polarization modes are thought to be related to propagation effects within the pulsar magnetosphere (e.g. Melrose 2000), which then strongly suggests a magnetospheric rather than geometrical origin for the observed profile changes. We consider a geometrical effect such as free precession to be extremely unlikely. Magnetospheric effects have been shown to be responsible for the profile changes seen in PSR B1931+24, and the correlations between the period derivative and the profile shape changes of a small
number of pulsars in Lyne et al. (2010) also point to magnetospheric effects. In PSR J1119–6127, profile changes seem to occur immediately following a glitch (Weltevrede et al. 2011). Although there are insufficient existing data to trace the behaviour of the timing of the pulsar over the long term, there is no evidence for glitch activity between 2004 and 2006. Also, unlike PSR J1119–6127, a long series of single pulses from PSR J0738–4042 taken after 2006 shows the transient component to be persistent in the single pulses with no more than typical variability.

We have presented a robust statistical technique based on an HMM that estimates the likelihood of state changes in the total power data and showed that this technique has great potential for substantially noisier data in which similar systematic changes occur. We plan to apply the HMM technique to a large number of pulsars for which regular observations have been conducted, to look for and characterize statistically significant profile variations. Most importantly, this technique provides a means of correlating changes in the pulse profile with other physical parameters, such as the period and period derivative, which could prove extremely useful in partially accounting for non-Gaussian timing residuals in pulsar timing models.

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