Pulsar polarimetry with the Parkes ultra-wideband receiver

Lucy Oswald, University of Oxford

Contact: lucy.oswald@physics.ox.ac.uk

Abstract

We create visualizations of broadband polarimetric data of two pulsars observed with the new Parkes ultra-wideband receiver. We use a Markov chain Monte Carlo to align the angle of linear polarization (PA) across frequency and so correct for the effects of the Interstellar Medium.

For both pulsars, aligning the angle of linear polarization (PA) does not align the total intensity. One explanation, aberration/retardation (A/R), implies low frequency emission is produced higher above the pulsar surface. Our height predictions agree with a theory of how height range may evolve with spin-down energy loss rate.

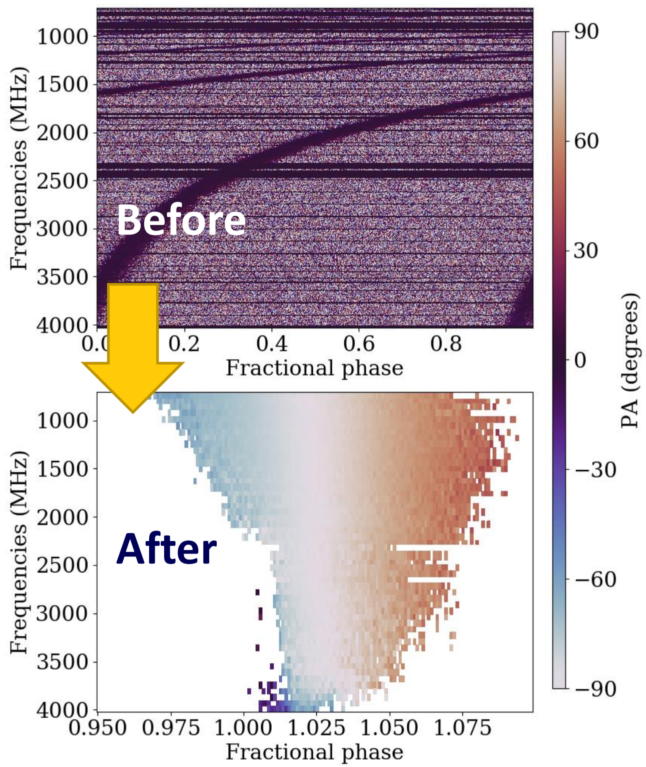
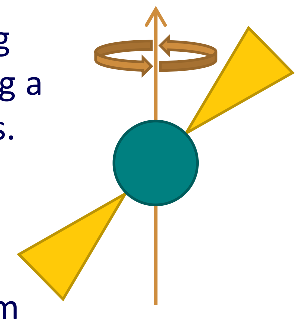


Figure 1. Plot of PA across phase and frequency for PSR J1056–6258, before and after alignment.

Radio pulsars

A pulsar is a spinning neutron star emitting a beam of radio waves. We detect the radio beam as a series of pulses as the pulsar rotates and the beam sweeps through space.



Summing them together produces an integrated profile that is stable over time. This profile is unique for each pulsar, but they all have common features: they are made up of one or more components, there is some degree of polarization, and the shape evolves so that it appears different at different observing frequencies.

Related publication – Oswald L., Karastergiou A., Johnston S., 2020, *MNRAS*, 496, 1418

Context

Pulsar polarization

The angle of linear polarization of a pulsar profile, called the position angle or PA, has a shape that results from the pulsar geometry. This means that, whereas the total intensity evolves across the observing band, the shape of the PA is predominantly independent of frequency (although deviations are known to exist). Fig. 2 shows the intensity and PA profiles for PSR J1359–6038. It has strong linear polarization (red line) and some circular (blue line).

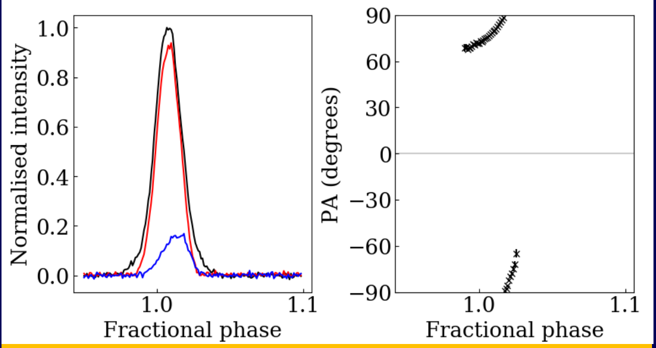


Figure 2. PSR J1359–6038, 1410 MHz profile with linear and circular polarization (left), and PA (right).

Frequency evolution

The frequency evolution of pulse profiles is key to understanding the 3D structure of the beam. For example, aberration/retardation (A/R) effects cause the observed intensity and PA to misalign. Emission generated higher above the pulsar surface is misaligned more.

However, the Interstellar Medium (ISM) also introduces frequency evolution:

- **Dispersion** delays pulse arrival. The delay follows a quadratic frequency relationship, so that lower frequencies arrive later (Fig. 3).
- **Faraday rotation** shifts the PA, again with a quadratic frequency relationship.
- **Scattering** smears out the pulse profile and the PA. Its effect is usually small except at low frequencies.

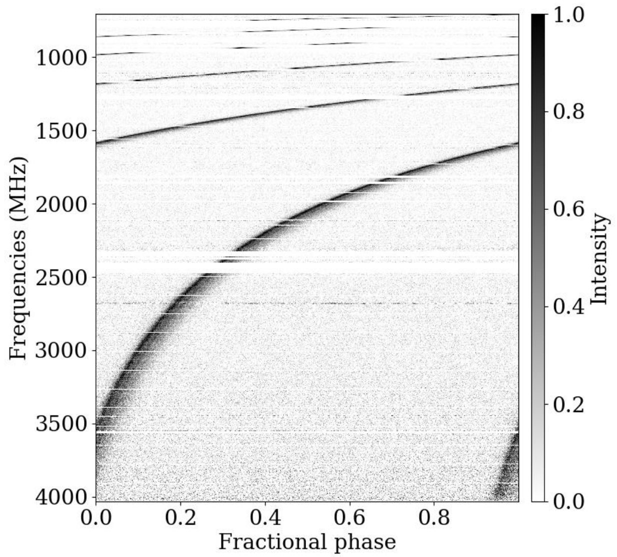


Figure 3. Intensity profile of PSR J1056–6258 across phase and frequency, with dispersion delay.

DM and RM

The proportionality constants of the frequency relationships of dispersion and Faraday rotation are called the **dispersion measure (DM)** and **rotation measure (RM)** respectively. If we know their true values, we can remove these effects correctly.

Method

Correcting effects of the ISM

To study the properties of broadband observations made with the new ultra-wideband receiver on the Parkes telescope, we must first identify the correct **DM** and **RM**.

What we use:

- The constancy of the PA shape means we can align it across the observing band.
- The best fit RM (shifting in angle) will depend on the choice of DM (shifting in phase) so we must find both together.

Method: We search for the best fit corrections to rough initial values of DM and RM. We calculate the likelihood function for alignment of the PA profiles at different frequencies (excluding profiles smeared by scattering). We use a Markov chain Monte Carlo to sample the log-likelihood over the parameter space of ΔDM and ΔRM.

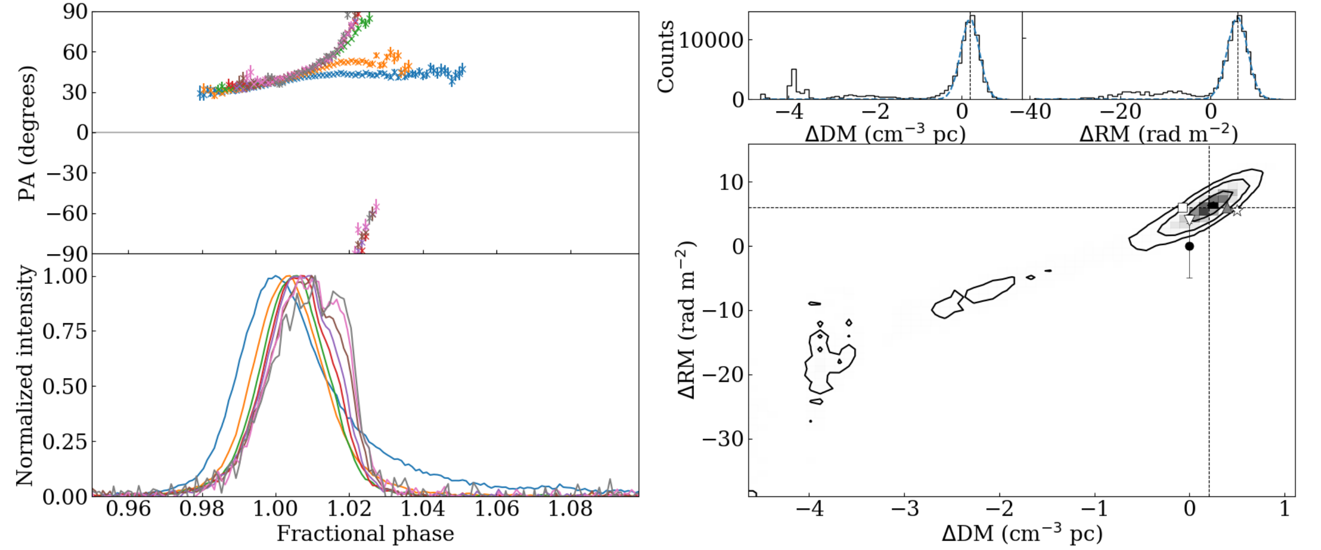


Figure 4. Left: aligned pulsar profiles for PSR J1369–6038 (PA above, total intensity below), frequencies overlaid from lowest (blue) to highest (grey). Right: alignment probability distribution for ΔRM and ΔDM.

Aligning the PA

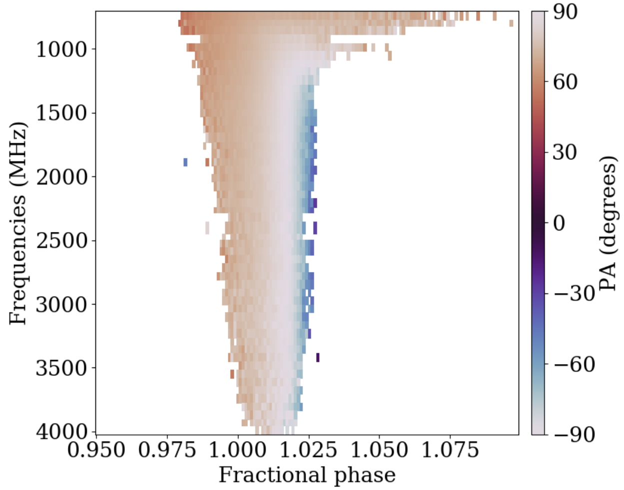
We see in Fig. 4 that our best fit values result in the PA profiles being well aligned. Even the scattered profiles (blue, orange, green), which weren't included in the fit, are successfully lined up. However, the intensity profiles (shown beneath) are not.

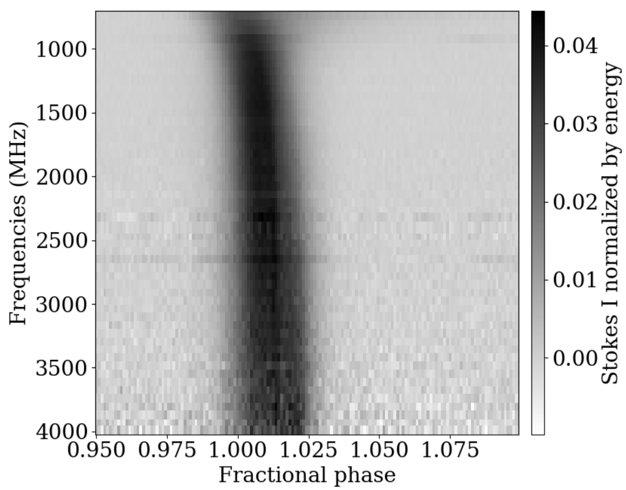
Intensity vs. PA: misaligned

The total intensity profiles are not lined up and the misalignment is larger at lower frequencies. If we assume this is due to A/R it implies that the 700 MHz emission is be produced 120 ± 120km higher up than that at 4000 MHz. This is comparable to theoretical predictions.

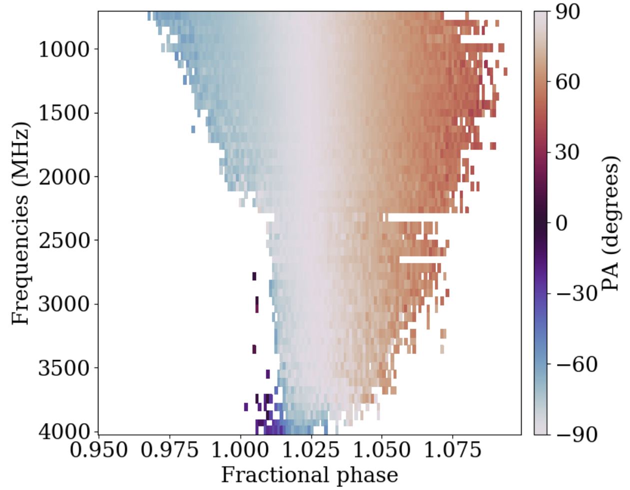
Results

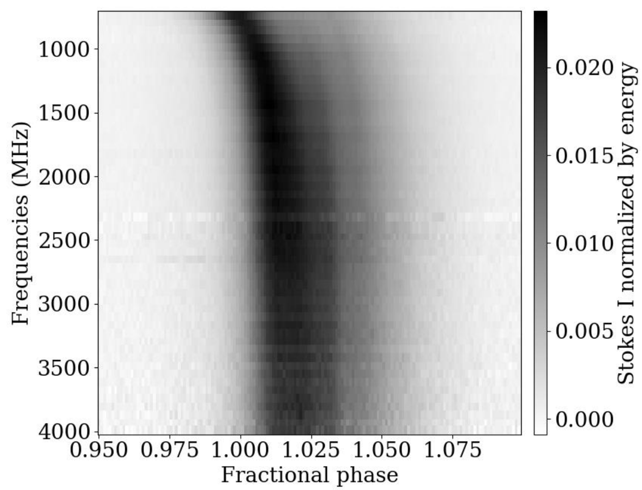
PSR J1359–6038





PSR J1056–6258





Interpretation

The figures show the aligned profiles across the observing band for two pulsars, both PA (coloured) and total intensity (greyscale). The total intensity plots have been normalized by total flux in each frequency channel, to highlight pulse shape over brightness.

Just as we saw for J1359–6038, the intensity profile for PSR J1056–6258 is visibly misaligned when the PA is well aligned. Performing the same calculation, we obtain 430 ± 350km for its emission height range.

One theory postulates that narrow emission height range is linked to low spin-down energy loss rate ($\dot{E}$) and vice versa. This fits with our calculations: PSR J1359–6038 has high $\dot{E}$ and a smaller height range, whilst PSR J1056–6258 has a larger height range and a low $\dot{E}$.