Simultaneous single-pulse observations of radio pulsars

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Abstract

We present the first results from a programme of multi-frequency simultaneous single pulse observations carried out as part of the European Pulsar Network. We detail the main data analysis methods and apply them to simultaneous observations of the strong pulsar B0329+54 at 1.4 and 2.7 GHz using the Jodrell Bank and Effelsberg radio telescopes respectively. The pulses at different frequencies are highly correlated in their total intensity, as seen in previous experiments, and generally show consistent position angles of the linearly polarized component. In contrast, the circularly polarized emission sometimes shows clear differences between pulses received at different frequencies. These results are unexpected and warrant further follow-up studies to interpret them in the context of the intrinsic bandwidth of pulsar radiation.

1 Introduction

In 1995, a large scale project was launched by the European Pulsar Network. Simultaneous observations of individual pulses were conducted between various collaborating observatories across Europe and the world (Effelsberg, Jodrell Bank, Bologna, Westerbork, Puchshino, Ooty, Torun, Arecibo), as individual experiments. The data presented in this talk were obtained during such a polarimetric experiment between the Jodrell Bank and Effelsberg radio telescopes observing at the frequencies of 1.41 GHz and 2.70 GHz, respectively. This talk also provides an introduction into the polarimetric properties of pulsar radio emission.

2 The polarization characteristics of pulsar radio emission

Simply stated, pulsars emit polarized radio-waves. The ratio of the linearly polarized power to the total emitted power is extremely high, at some instants for some pulsars even 100%. Even more amazing is the degree of circular polarization, which, although significantly lower than its linear counterpart, is still one of the highest known amongst astrophysical sources. There are cases where the circularly polarized power may reach or even exceed 30% of the total emitted power.

2.1 Linear polarization

Pulsar emission is highly linearly polarized. According to the Rotating-Vector-Model (RVM) of Radhakrishnan and Cooke (1969), the position angle (PA) of the linearly polarized component is tied to the magnetic field lines of the pulsar magnetosphere. It is for this reason that the observed PA swings across an S-shaped curve as the line of sight intersects the emission cone. For many pulsars, the PA might jump by $\approx 90^o$ and back again during this S-shaped curve. This is due to the presence of an Orthogonal Polarization Mode (OPM) at some phase of the pulse (Manchester et al. 1975). In fact, the OPM is not always present and single-pulse observations help to determine when this is the case. It is not clear from pulsar emission theory where OPMs come from (see McKinnon & Stinebring

1998). However, OPMs are very important to pulsar physics. It is not possible to fit a correct RVM curve unless one correctly accounts for the presence of both polarization modes. Fitting an RVM curve is a good way of determining the pulsar geometry [1]. At higher frequencies, OPMs seem to become more frequent and the degree of linear polarization becomes smaller.

2.2 Circular polarization

The degree of circular polarization is also very high in pulsar emission. Circular polarization has been used in the past as a defining feature between core (originating from longitudes close to the magnetic axis) and conal (originating from the highest curvature magnetic field lines) emission. However, it is shown here that the average circular polarization of the conal components for PSR B0329+54 is small in comparison to the core due to the switching in the handedness observed in single-pulses. The degree of circular polarization has been noticed to increase with frequency for some pulsars (von Hoensbroech 1999).

3 The observations

A sequence of 1912 pulses of very good signal-to-noise ratio (S/N) were recorded simultaneously between the 76-m Lovell radio telescope at Jodrell Bank at 1.408 GHz and the 100-m Effelsberg radio telescope at 2.695 GHz, on the 13^{th} of July, 1997 (for a detailed description see Karastergiou et al. 2001).

3.1 Alignment

Every pulse emitted from the neutron star does not arrive simultaneously at different telescopes observing at different frequencies due to interstellar dispersion, which causes the high frequency radiation of the pulses to arrive earlier, relative to its lower frequency complement. Further variations arise from the different path-lengths to the telescopes. To eliminate such effects, the time of arrival of each pulse was referred to the time of arrival of the pulse at the solar system barycentre, at infinite frequency. The data with the appropriate time stamps were re-binned to the coarsest time-resolution, in order to compare phase bins one by one. The data was finally converted into the flexible EPN format (Lorimer et al. 1998).

4 Results

4.1 Cross-Correlation of Phase Bins

In order to study the correlation between the two observing frequencies, we conduct a cross-correlation analysis of the pulse-to-pulse variations of all individual phase bins, following Popov (1986). This yields a two-dimensional correlation array $c_{i,j}$. Each point (i,j) is the correlation coefficient between the time series $f_i(k)$ of bin i at one frequency and the time series $g_j(k)$ of bin j at the other frequency with k being the pulse number. For n pulses, $c_{i,j}$ is obtained through

$$c_{i,j} = \frac{1}{n \cdot \sigma_{f,i} \cdot \sigma_{g,j}} \sum_{k=1}^{n} [f_i(k) \cdot g_j(k) - < f_i >< g_j >] \ , \tag{1}$$

where $\sigma_{f,i}$ and $\sigma_{g,j}$ represent the *rms* deviations of the time series $f_i(k)$ and $g_j(k)$ respectively.
Figure 1 shows contour plots of the correlation arrays for I, L, V and |V|. The

[1] mainly the inclination of the magnetic axis w.r.t. the rotation axis and the impact parameter

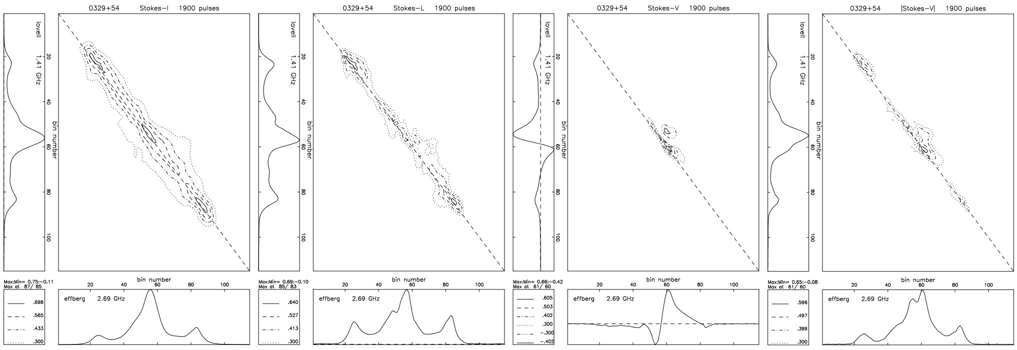

Figure 1: Contour plots of a bin-by-bin cross correlation function in total intensity, linear power, circular power and absolute circular (ignoring the handedness). The pulse-to-pulse fluctuations of each bin at one frequency are correlated against each bin at the other frequency. The profiles in the bottom- and left panel represent the integrated intensities of the respective Stokes parameter. The contour lines correspond to constant correlation coefficients, their representations are plotted in the box on the bottom-left.

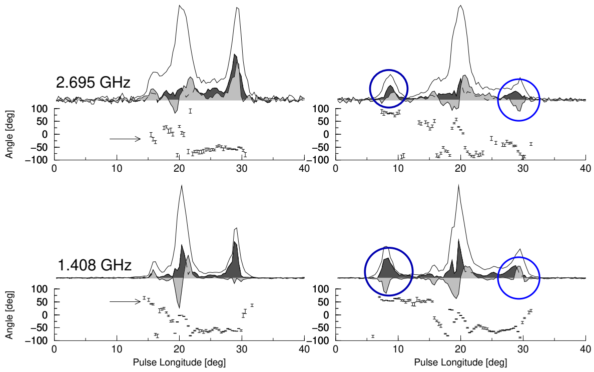

Figure 2: Two examples of individual pulse pairs of PSR B0329+54, observed in full polarization. The dark-shaded area represents linearly polarized power and the light-shaded area circularly polarized power.

distribution of the correlation maxima is quite distinct between the different polarizations. In total power (Fig. 1, first plot) three maxima can be identified, which correspond to the three main components of the pulse profile. In linear polarization however (Fig. 1, second plot), the correlation finds its maxima only in the outer components of the profile. Throughout the middle component— which is the strongest also in linear polarization, as can be seen from the integrated profiles on the bottom and the side—the correlation remains significantly lower.

The circular polarization on the other hand shows the opposite characteristic. Regarding the "non-absolute" plot (Fig. 1, third plot), the maximum is clearly situated in the profile centre. The outer components are completely uncorrelated. This is mainly caused by heavy frequency dependent fluctuations in these components and especially the opposite handedness, which can be frequently observed (Fig. 2). This can be obviously seen in the analysis of the absolute circular polarization (Fig. 1, right plot), where the difference in handedness is ignored. Some correlation in the outer profile components is now clearly visible.

4.2 Individual Pulse Pairs

Fig. 2 shows two pulse pairs of PSR B0329+54. The overall morphology of the pulses is very similar, especially in total power. However, regarding the polarization characteristics, larger deviations are observed, as revealed by the cross-correlation plots, especially concerning the circular polarization but also the polarization position angle.

- *Polarization position angle (PPA).* At some localized phases, significant differences between the PPAs are measured (e.g. arrows in Fig. 2). These differences indicate the simultaneous presence of both OPMs at the two frequencies observed. It is worth noting that the PA difference between the two modes is not always 90^o as noted also by Gil & Lyne (1995) and von Hoensbroech et al. (1998).
- *Circular polarization.* The most prominent differences observed concern the intensity and handedness of the circularly polarized component of the radiation. In the trailing component of the left pulse pair in Fig. 2 a high degree of circular polarization is measured at 2.7 GHz, but none at 1.4 GHz. The cross correlation plot in Fig. 1 indicates that these differences occur preferentially in the outer components, while the central component is well correlated. In the right pulse pair the encircled regions show opposite handedness between the two frequencies. Note that the handedness is in fact swapped in both the leading and trailing outer components. At the same time, however, the swing of the circularly polarized power is identical at the two frequencies for the central component where we see a change from negative to positive handedness.

5 Conclusions

We can summarize the results of our analysis as follows:

- the total intensity is well correlated between the two frequencies
- linear polarization is correlated principally in the outer components of the profile
- the two different orthogonal polarization modes can appear simultaneously at the same longitude at different radio frequencies
- in some parts of the profile the sense of circular polarization can change from one frequency to the other while it simultaneously remains unchanged at other parts of the profile

The good total intensity correlation implies that a single event at the bottom of the pulsar magnetosphere is responsible for a emission observed across the spectrum. This can be explained by a single plasma column streaming along the field lines and radiating with a large bandwidth. This wide-bandwidth picture seems to be in some contradiction to a radius-to-frequency mapping (RFM) model which assumes that the emission at higher frequencies is created closer to the neutron star than that at lower frequencies. This apparent conflict, for a frequency dependent emission height and radiation with a bandwidth much larger than the usual observational spacing, can be solved if the particles creating the radiation at separate frequencies are part of the same plasma column.

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