ON THE SEPARATION OF THE COMPONENTS IN THE MEAN PULSE PROFILE OF PSR 1451−68 AND THEIR SPECTRAL BEHAVIOR

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Abstract

We have developed a method to understand the detailed structure of the mean pulse profile of pulsars, namely, the Gaussian fit separation of the average profile (GFSAP) method, in which we assume the total profile is the superposition of several individual Gaussian-distributed components. Linear polarization data is used to simplify the fitting. The components of PSR 1451−68 are separated and their spectral indices calculated. We find that the profile of PSR 1451−68 is actually quintuple instead of triple, which is in agreement with the idea that quintuple is the prototype shape of pulsar profiles. The core component is shown to have the steepest spectrum, while the inner cone has the flattest. Another conclusion from PSR 1451−68 is that the core width does not change with frequency.

Introduction

The mean pulse profile and polarization of PSR 1451−68 have been studied at six frequencies: 170 MHz, 271 MHz [see Rankin (1983a)], 400 MHz (Hamilton *et al.* 1977b), 649 MHz (McCulloch *et al.* 1978), 950 MHz, and 1612 MHz (Manchester, Hamilton, and McCulloch 1980). At low frequencies the profiles appear to be triple. At higher frequencies the components merge into each other, but the linear polarization parts remain separable. It is generally believed that the three components of a triple profile are the core and cone components. It is of considerable interest to examine the quantitative spectral behavior of the core and conal components. The problem is that the components overlap each other, especially at high frequencies. Therefore, we must find a method to separate the components. All pulsar emission profiles represent a dynamic superposition of distinct contributions from various emitting regions within the beam. This is the physical basis behind the concept of a component. A statistical study of the apparent beam width by Wu and Manchester (1990) shows that mean pulse profiles have a Gaussian form. We are thus on solid ground in assuming that the total profile consists of a superposition of several individual Gaussian components.

Separation of components in the mean pulse profile

PSR 1451−68 exhibits an apparent triple profile which at high frequencies is barely resolved into three distinct components. We now consider how these three components might be separated and whether there are more than three components in the profile. Rankin (1988) has described a technique of polarization-mode separation in connection with PSR 1604−00 which there had the effect of separating three closely spaced components. Here we develop another method.

The method of Gaussian fit separation of the average profile (GFSAP)

We suppose that all pulsar emission profiles represent a dynamic superposition of distinct contributions from various emitting regions within the beam. These emitting regions then appear as Gaussian-shaped components within the profile. We thus assume that the total profile is the superposition of several individual Gaussian-shaped components in our GFSAP analysis.

We assume that there exist two distinct physical types of pulsar emission and two corresponding prototypical species of profile component, quasi-axial or "core" emission and the more familiar conal emission. Profile categories can be generated by cuts through a cone and core beam configuration. Multiple profiles prototypically exhibit five components and thus clearly involve both a core component and distinct inner and outer conal emission zones (*cf.* figure 21 in Rankin 1983a). We adopt the following formula as the general form of our fitting equation

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Table 1 The results of Gaussian fit separation of PSR 1451−68

f_{MHz}	170	271	400	649	950	1612
A_0(Jy)	22.3	16.1	6.4	12.9	4.3	1.3
A_{L}	3.4	2.6	1.0	2.6	1.0	0.5
A_{T}	4.7	3.5	2.1	4.7	1.6	0.3
$A_{\mathrm{L'}}$	1.8	1.6	1.4	1.6	0.5	0.4
$A_{\mathrm{T'}}$	1.5	1.0	0.6	1.5	1.1	0.3
Δx_0	4.5	4.3	5.3	4.7	4.8	5.2
Δx_{L}	5.4	5.3	5.3	6.1	5.3	4.3
Δx_{T}	5.7	6.6	6.3	6.0	3.8	5.2
$\Delta x_{\mathrm{L'}}$	3.0	2.5	3.2	3.5	2.9	3.5
$\Delta x_{\mathrm{T'}}$	5.0	5.0	5.3	3.6	2.4	2.6
x_{L}	−21.6	−17.2	−13.7	−13.3	−11.5	−13.0
x_{T}	20.1	17.0	13.0	12.3	12.5	8.7
$x_{\mathrm{L'}}$	−7.0	−7.0	−7.4	−6.1	−6.7	−6.9
$x_{\mathrm{T'}}$	3.0	3.0	4.2	7.1	7.7	8.7

$$\begin{aligned} f \;=\; & A_0 \exp\{-c[x/\Delta x_0]^2\} + \\ & A_{\mathrm{L}} \exp\{-c[(x - x_{\mathrm{L}})/\Delta x_{\mathrm{L}}]^2\} + \\ & A_{\mathrm{T}} \exp\{-c[(x - x_{\mathrm{T}})/\Delta x_{\mathrm{T}}]^2\} + \\ & A_{\mathrm{L'}} \exp\{-c[(x - x_{\mathrm{L'}})/\Delta x_{\mathrm{L'}}]^2\} + \\ & A_{\mathrm{T'}} \exp\{-c[(x - x_{\mathrm{T'}})/\Delta x_{\mathrm{T'}}]^2\} \end{aligned} \qquad (1)$$

in which the subscripts 0, L, T, L′, T′ stand for Core, and Leading and Trailing cone, respectively. Δx is the half-power, half-width of a component, x_{L}, x_{T}, $x_{\mathrm{L'}}$, $x_{\mathrm{T'}}$ are the peak positions, and $c = \ln 2 \cong 0.693$. There are 14 parameters in eq.(1), which is the generalized fitting equation. We can also use eq.(1) to analyze cases with fewer than five components.

Appropriate initial parameters for fitting

Appropriate initial fitting parameters such as the location, width and amplitude can be obtained by analysis of the total intensity and linear polarization profiles. Because the PSR 1451−68 profile is ostensibly triple, we need only give initial values for 8 parameters. The initial values of x_{L}, x_{T} and A_0, A_{T}, and A_{L} can be determined from the total intensity profiles at low frequencies and from the linear polarization observations at high frequencies. To obtain the initial widths, we assume that the conal components are symmetrical, so that the total width can be estimated as twice the peak to outer half-power value. Then subtracting this conal component pair from the total profile, we can get an initial estimate of the width and amplitude of the core component. Any residual power remaining when this estimated core component is subtracted will then give us some idea of whether other components are present in the profile. Finally, we use eq.(1) to fit the observed profiles and obtain a fitted solution.

We collect the results in table 1. Although PSR 1451−68 has usually been regarded as having a triple structure, it is intriguing that our results indicate that it has a five-component structure. This may support the view that five components are prototypical of pulsar emission in the largest sense (Rankin 1983a). Many other important conclusions can be drawn from table 1, however. In particular the separation technique facilitates study of the widths and spectra of the individual components and thus enlarges the body of information available about pulsar emission.

We could apply this technique to other pulsars. Many ambiguities in the pulsar profile need to be clarified, which may lead us to a new picture of pulsar profile components and a new understanding of the taxonomy of profiles.

Discussion of the separated results

The five-component (M) profile

In profile classification, the cone must be conceived as divided into several (probably two) distinct quasi-annular zones: an inner and outer zone are required to account for M class profiles (Rankin 1983a). The outer conal zone is usually more intense than the inner one and becomes more so at low frequencies. The five-component (quintuple) profile represents a distinct and coherent morphological class with about 20 known members [see Rankin (1992) below].

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Our analysis for PSR 1451−68 shows a pair of weak, symmetrical components in addition to the usual three. The linear polarization data indicate clear minor components inside the conal outrider pair. There is also evidence in our fits for the presence of this inner pair of conal components. If we assume three instead of five components for PSR 1451−68, the fitting results have a larger error. This is illustrated in figure 1.

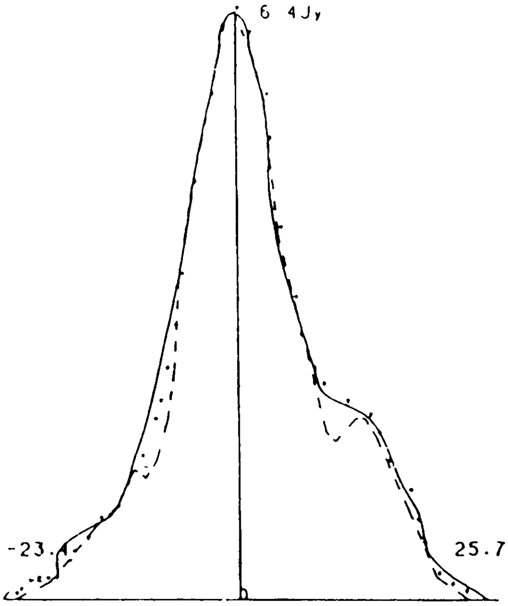

Figure 1 The profile (solid line) at 400 MHz of PSR 1451−68 and two fitted curves. The dotted line shows the fit of eq.(1), and the dashed line shows the fit using a triple profile, *i.e.* with $A_{L'} = A_{T'} = 0$ in eq.(1).

A drop in emission strength will always occur between the core and conal components when only three components are fitted for. The "bridge" regions (*cf.* 170- and 271-MHz profiles) between the core and the conal components require an additional pair of inner conal components to account for this emission. We obtain an irremediably poor fit if we assume a triple structure in the fitting, which cannot be corrected by any adjustment of the parameters. This clearly indicates the existence of another pair of components in this region, and the residuals to the fit greatly diminish when a five-component structure is assumed. We thus conclude that the PSR 1451−68 profiles have five components (the core and the inner and outer conal component pairs). Consequently, we wish to raise the question of whether the five-component (**M**) structure is the prototype of all the other morphological classes (Triple, Double and Single). Eq.(1) may provide an analytical basis for exploring the current classification system—that is, the **T**, **D**, $\mathbf{S_d}$ and $\mathbf{S_t}$ species all have a close relationship to the five-component **M** class.

Comparison with the hollow-cone model

Now that we have obtained the individual component information, we can do some statistical work concerning the spectral behavior. In a typical RS model (Ruderman and Sutherland 1975) the pulsar emission has a hollow-cone geometry, with its outer edge determined by the outermost open magnetic field line of the pulsar, $\theta_{\max} = 16° P^{-0.7} \omega_{10}^{-1/3}$, and its inner edge is given by a similar condition, $\theta_{\min} = 16° P^{0.9} \omega_{10}^{1/3}$, where ω_{10} is the angular radio frequency is units of $10^{10}\,\mathrm{s}^{-1}$. When applied to PSR 1451−68, the outer and inner edge of the hollow cone are given by

$$\rho_{\max} = 550° f_{\mathrm{MHz}}^{-1/3} \tag{2}$$

$$\rho_{\min} = 57.6° f_{\mathrm{MHz}}^{1/3} \tag{3}$$

where ρ is the cone radius. We take the outer half-power point of our separated conal component as the outer edge. Because of asymmetry, an average value is used

$$\Delta\phi = (|x_{\mathrm{L}}| + \Delta x_{\mathrm{L}} + x_{\mathrm{T}} + \Delta x_{\mathrm{T}})/2 \tag{4}$$

as the pulse width (or spacing) corresponding to the hollow-cone radius ρ_{outer}. Power-law fits over six frequencies give

$$\rho_{\mathrm{outer}} = 35.1° f_{\mathrm{MHz}}^{-0.243}\ . \tag{5}$$

The amplitude difference between eq.(6) and eq.(2) can be explained if the amplitude of eq.(2) is taken as an upper limit instead of the true value as Wu *et al.* (1985) did. While we take the outer cone results as those of the outer edge of the hollow-cone, we take the inner cone data for the inner edge of the cone. The pulse width is taken between the peak positions

$$\Delta\phi = (|x_{\mathrm{L'}}| + x_{\mathrm{T'}})/2 \tag{6}$$

$$\rho_{\mathrm{inner}} = 0.66° f_{\mathrm{MHz}}^{0.21}\ . \tag{7}$$

We conclude that the hollow cone contributes four components in the total profile, corresponding to cuts through outer and inner conal emission zones (each twice, *cf.* figure 2).

Core emission and spectral indices

Core radiation has so far been recognized as an essential feature of pulsar emission (Backer 1976, Rankin 1983a, Lyne and Manchester 1988). To explain this phenomenon Wang *et al.* (1988) suggest a Cerenkov-instability mechanism, whereas Qiao (1988) discusses the inverse Compton effect. With the help of the amplitude data in table 1, we can calculate the spectral indices of the components (*cf.*

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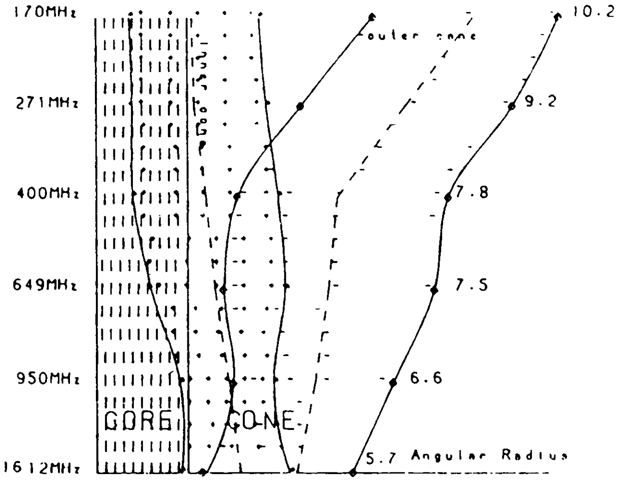

Figure 2 A comprehensive picture of the emission pattern of pulsar 1451−68. The data is from table 1. The boundary of each shaded region is defined by the half-power width of the component.

table 2). Compared with the calculations of Lyne and Manchester (1988), our method is improved in two ways: (1) We have diminished the effect of component merging, and we obtain α instead of the $\Delta\alpha$ computed by Lyne and Manchester (1988) for 23 pulsars. (2) The variation with angular radius is analyzed within one pulsar, without introducing ρ_n. The results are in agreement with Rankin (1983a) and Lyne and Manchester (1988). As the inner cone both has a small angular radius (and sometimes merges with the core) and behaves completely unlike the core, we expect a jump of the spectral indices between the core and the inner cone instead of a continuous transition as advocated by Lyne and Manchester (1988). This is easy to understand if we assume that the core and the cone have a completely different character.

Table 2 Spectral indices of the components of PSR 1451−68 between 271 and 1612 MHz.

Component	Spectral index
core	−1.58
cone (L_{outer})	−0.96
cone (T_{outer})	−1.42
cone (L_{inner})	−0.87
cone (T_{inner})	−0.85

We can also study the evolution of the core width. Within their errors the Δx_0 values are nearly the same. Certainly no clear case can be made for a low frequency broadening given that the lowest frequency values are probably the best determined. Therefore, the average value of $\Delta x_0 = 4.8° \pm 0.4$ or $\rho_{core} = 1.96°$. We can then ask if a constant core width obtains in a more general sense. Considering the results of Rankin (1983b, figure 2), there are essentially no frequency-dependent core-width changes in PSR 0329+54, PSR 1449−64 and PSR 1642−03. However, for PSR 1749−28 the core width changes as $f^{-0.31}$. If we look back at the original data, we see that the 170-MHz linear polarization profile of PSR 1749−28 has several peaks. Thus, if we had separated the profile, we might expect a much flatter dependence PSR 1749−28's core width. We are then on reasonably strong ground to suggest that the core has a constant width with frequency. It follows that the core emission height is frequency independent.

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