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The Shape of Pulsar Beams

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Abstract. Observations of mean or average pulse profiles and their polarization give us much information on the shape of pulsar beams. The observed polarization variations, profile symmetry and frequency dependence of profile shape strongly suggest that the emission beam is conical and emitted from the vicinity of a magnetic pole. Central and outer parts of the beam have somewhat different properties, but the evidence is that they are emitted by the same basic mechanism. Recent observations suggest that the highly polarized pulse components seen in young pulsars may be emitted at a large angle to the magnetic axis.

1. Introduction

It is generally accepted that pulsars are rotating neutron stars. The fundamental frequency of the observed pulse train is then interpreted as the rotation frequency of the neutron star. One of the characteristic properties of pulsars is that, when an observed pulse train is folded at this fundamental frequency to form a mean or average pulse profile, this profile is (in most cases) extremely stable. Mean pulse profiles for different pulsars have some common properties, but differ in detail. For example, the pulsed emission is generally confined to a small portion (< 10%) of the pulse period, but some pulsars have one dominant component or peak, whereas others have several. Furthermore, the phase of this mean profile is very predictable – in fact, all precision timing of pulsars is based on observations of mean pulse profiles. This long-term stability implies that the mean profile is a cut through a radiation beam whose shape and orientation are fixed by relatively permanent features of the neutron star and its environs.

Another characteristic property of pulsar emission is that it is generally very highly polarized, with linear polarization dominating over circular. The form and phase of the polarization variations within mean profiles are also very stable. It is widely assumed that the polarization is determined by magnetic fields in or above the emission region, which are anchored to the solid neutron-star crust. Rapid swings of polarization position angle through the pulse, first observed in the Vela pulsar by Radhakrishnan et al. (1969), imply that the emission beam originates near a symmetry axis or vector which is fixed with respect to the neutron star.

For most pulsars, this ‘rotating vector model’ accounts very successfully for the observed position-angle variations (e.g. Rankin 1983; Lyne & Manchester 1988), at least when the presence of orthogonal modes (e.g. Stinebring et al. 1984) is recognized.

Again based on observations of the Vela pulsar, Radhakrishnan & Cooke (1969) proposed that the vector concerned was the dipole axis of the pulsar magnetic field. This interpretation, often known as the ‘magnetic pole model’, is supported by several of the observed characteristics of pulsar emission. The success of the rotating vector model in accounting for observed position-angle variations is certainly consistent with the magnetic pole model, but does not require it. Any vector fixed to the neutron star will do!

2. The Magnetic Pole Model

The magnetic pole model for pulsar beaming is popular, since many of the observed pulse properties can be readily accommodated within it. It also has theoretical backing (Sturrock 1971; Ruderman and Sutherland 1975; Arons 1983), although other theoretical ideas have been put forward (e.g. Michel 1987). As mentioned above, observed position-angle variations are generally consistent with the magnetic pole model. Other observational results which support the model are as follows.

Especially in pulsars of shorter period, a second pulse component is often observed midway, or very close to midway, between the main pulses. This interpulse may be interpreted as coming from the opposite pole of a dipole field.

Many mean pulse profiles have approximate time-reversal symmetry, that is, they are nearly symmetrical about the midpoint of the profile. Other properties, for example fluctuation characteristics or spectral properties, are also often symmetrical about the pulse centre. Figure 1 shows a good example. This symmetry implies, or at least is consistent with, a circular cross-section for the emission beam. A ‘double’ pulse structure with relatively strong outer components, usually with steep outer edges, such as that shown in Fig. 1, is common. Hence we are led to the idea of an annular or ‘conal’ beam. Especially in shorter-period pulsars and at lower frequencies, the profile is often dominated by a central component – the ‘core’ component. Core components are generally prominent only in pulsars where the ‘impact parameter’, or minimum angle between the symmetry (magnetic) axis and the observer’s direction, is small.

For pulsars where the profile is dominated by conal emission, observations over a wide frequency range (e.g. Hankins et al. 1991; Phillips & Wolszczan 1992; Thorsett 1991) show that the component separation increases with decreasing frequency and, after removing the delays due to interstellar dispersion, the profile expands symmetrically about its central point. These observations are naturally explained in the magnetic pole model, with lower frequencies being emitted at greater distances from the neutron star surface where the opening angle of polar field lines is greater – the so-called ‘radius-to-frequency mapping’ (Cordes 1978).

Core components, that is, components located near the centre of the pulse profile have rather different properties to conal components (Rankin 1983; Lyne &

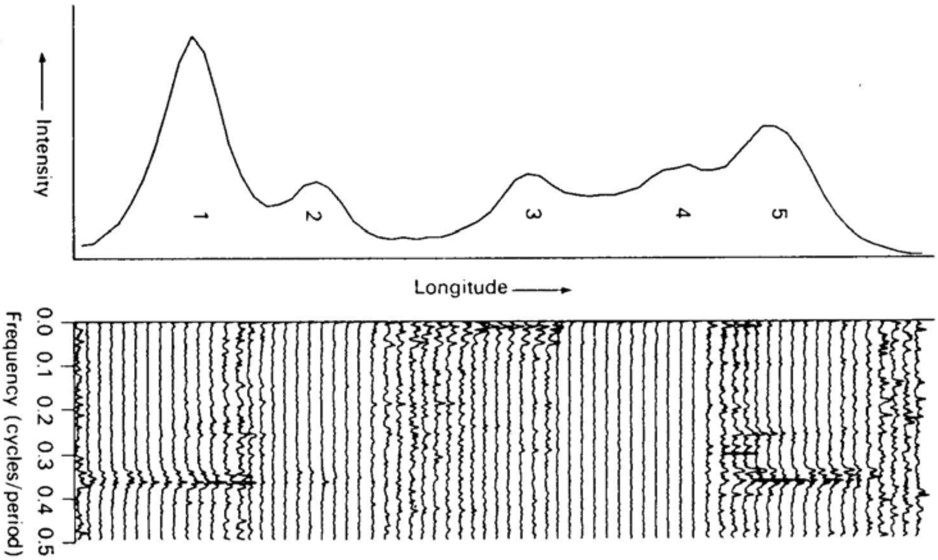

Figure 1: Mean pulse profile and phase-resolved pulse modulation spectra for PSR B1237+25 at 430 MHz (Backer 1973). Both the mean profile and the fluctuation characteristics are largely symmetric about the point midway between the outer edges of the profile.

Manchester 1988). For example, they generally have steeper spectra, especially in shorter-period pulsars. As illustrated in Fig. 1, fluctuation characteristics are often different. Drifting subpulses seem to be confined to the outer or conal parts of the emission beam. Rankin (1983, 1990) suggested that different emission processes are responsible for the core and conal parts of the beam and, in particular, that the core emission is generated close to the neutron-star surface from the entire polar cap. However, Lyne & Manchester argue that there is no fundamental difference between core and conal emission. Differences in properties result from differences in the location of the emission region with respect to the magnetic axis – core emission is generated close to the magnetic axis and conal emission from the outer parts of the open field-line bundle – and there is no need to invoke a different emission mechanism.

There are many similarities between the emission from the central and outer parts of pulse profiles. Despite varying pulse shapes and spectral indices, there is no great difference in the intensity of core and conal emission. If two emission mechanisms were involved, one might expect quite different emission intensities. Once allowance is made for orthogonal modes, polarization variations are normally continuous over the whole pulse profile; several examples are shown in Fig. 2. Orthogonal modes occur in both core and conal emission and variations in the

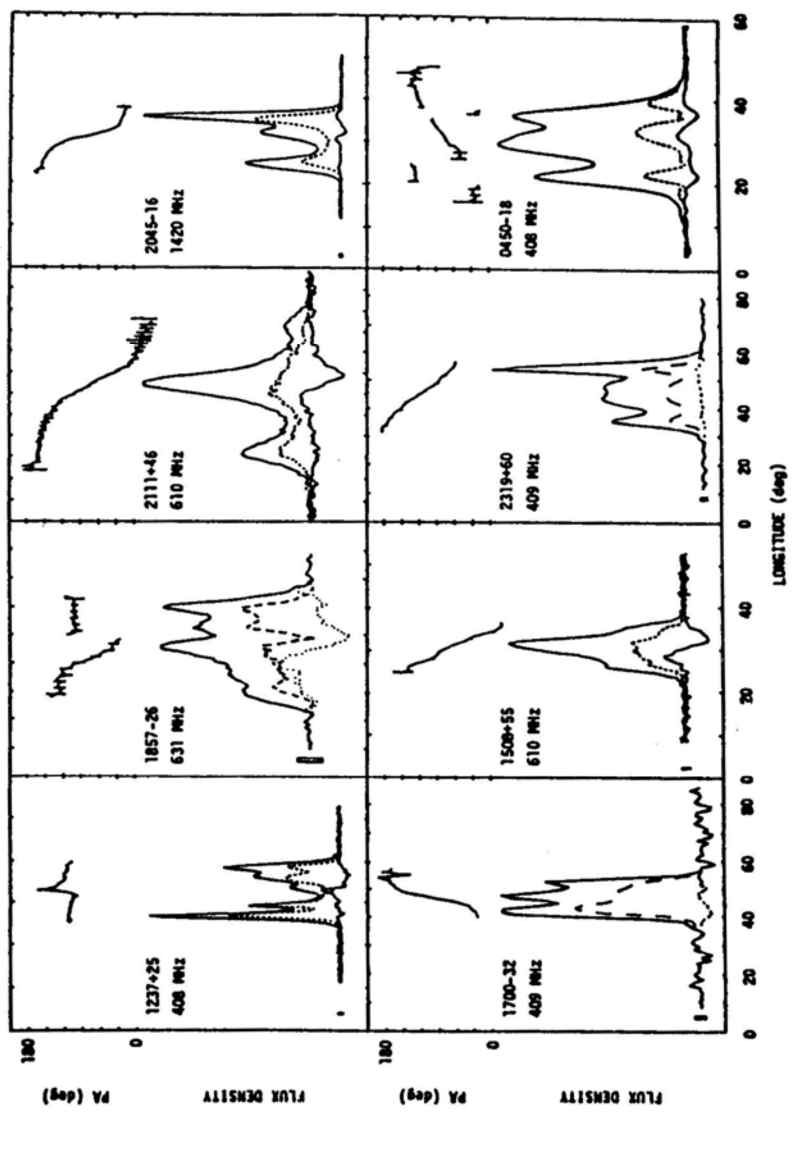

Figure 2: Mean pulse profiles and polarization parameters for pulsars showing both core and conal components (Lyne and Manchester 1988).

relative strength of the two modes occur smoothly across the profile. Subpulse widths are similar for core and conal emission (Taylor et al. 1975) and, although the sample is limited, micropulse properties seem similar for both core- and cone-dominated profiles (Cordes et al. 1990). Although spectral index differences are observed between core and conal components, these tend to be small or absent in longer-period pulsars, again suggesting that the same emission mechanism is involved.

For properties where there are clear differences between core and conal parts of the profile, these differences are related to location within the emission beam as a whole rather than to the actual core components. Figure 1 is a good illustration of this. The modulation patterns are symmetric about the mid-point of the profile (defined to be halfway between the outer edges) and are not related to the 'core' component which occurs at a significantly later phase. Spectral index differences are a function of radial distance from the beam axis, regardless of the presence or absence of components (Lyne & Manchester 1988). There is little spectral index variation across profiles for which the impact parameter is high, that is, where the observer sees emission from the outer parts of the cone. Furthermore, in wide double-pulse profiles in which there are no obvious core components, the central region often has a steeper spectrum than the outer regions.

Radio mean pulse profiles of pulsars are characterized by three components, two outer and one central. The relative strengths of these components vary with frequency and from pulsar to pulsar but they appear to be a common or generic feature of the emission beam. The central component often lags the centre of symmetry of the profile, defined to be midway between the outer edges of the outer components. Within this framework, each pulsar has its own character, often with lesser peaks apparently randomly distributed across the profile (Lyne & Manchester 1988). Rankin (1993) has suggested that a second pair of components, located inside the outer pair and corresponding to an 'inner cone', is also a characteristic feature. However, the evidence for this is weak. Inner components are not normally symmetrically located about the profile midpoint (e.g., Fig. 1). The characteristic separation of a few degrees of longitude between components simply reflects the fact that individual subpulses are a few degrees wide, and components more closely spaced than this are not resolved (or identified). Similarly, the observation that the number of components across profiles is usually five or less simply reflects the fact that the overall profile width is typically only a few times the subpulse width.

A model which represents the salient features of the radio pulse emission and beaming mechanism is illustrated in Fig. 3. Features which are common to all pulsars are represented by the window function, whereas the source function is unique to a given pulsar. The window function varies with radio frequency and pulsar period, and represents the basic or underlying form of the emission beam. The source function represents the emission pattern for a given pulsar and appears to be random in character. The window function is evidently determined by the dipole component of the pulsar magnetic field and the characteristics of the emission process, whereas the source function could, for example, be determined by the multipole structure of the magnetic field. Individual pulse observations suggest that the subpulse is a basic unit of emission. We therefore convolve the source function with a ‘subpulse beam’, taken to be a two-dimensional Gaussian of half-intensity width equal to one sixth of the conal diameter. The final beam pattern is given by the product of the window and convolved source functions. The observed pulse profile is represented by a cut across this beam pattern, with the vertical position of the cut determined by the relative latitude of the magnetic axis and the observer’s line of sight.

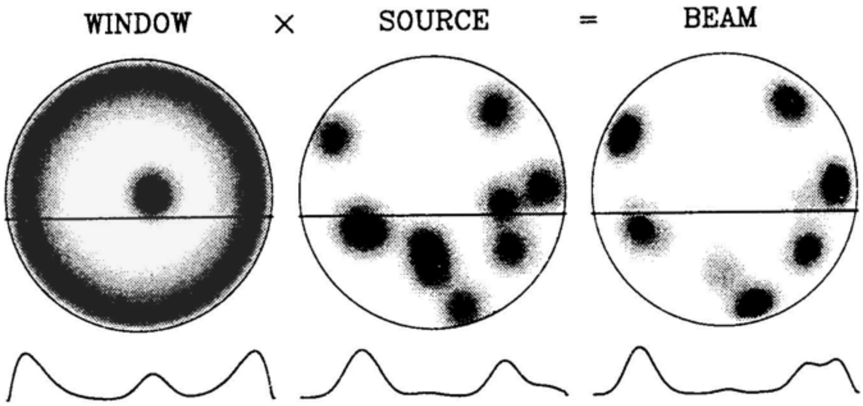

Figure 3: A model for the pulsar beam involving the product of a window function, common to all pulsars, and a source function, unique to each pulsar. Profiles under the beam patterns represent cuts through each pattern at the position of the horizontal lines.

It is well established that pulsars with shorter periods emit into a wider cone than longer-period pulsars, but the relationship between cone opening angle and period is somewhat uncertain. Lyne & Manchester (1988) found that the cone angular radius ρ is given by $\rho = 6.5° P^{-1/3}$, Rankin (1993) gives ρ $5.8° P^{-1/2}$, whereas Gould (1994) gives $\rho = 7.7° P^{-1/2}$. Observations of millisecond pulsars should help to tie down this relationship. The width of outer components of ‘double’ profiles (Fig. 4) and central components follow similar laws (Gould 1994). This suggests that the size of the bundle of emitting field lines relative to the size of the polar cap is independent of period. Fig. 4 also suggests that component width is independent of normalized impact parameter. This is consistent with the ‘patchy cone’ idea illustrated in Fig. 3, but not with complete cones; for complete cones, one would expect relatively wider components at higher impact parameters. Patchy cones are also implied by one-sided or partial conal profiles (Lyne & Manchester 1988; Qiao et al. 1994) and by secular variations in the mean pulse profile of PSR B1913+16 (Weisberg et al. 1989).

3. Interpulses

Interpulses are pulse components which lie close to midway between successive main pulses. As mentioned above, a natural interpretation is that interpulses originate from the other pole of a basically dipole magnetic field. This interpretation is supported by polarization data in several cases, e.g., PSR B1055–52 and PSR B1702–19 (Lyne & Manchester 1988) and PSR B1534+12 (Arzoumanian 1994). In many pulsars though, the separation of the main and interpulses is less than 180° of longitude. In some of these, for example, PSR B0950+08, polarization data suggest that the magnetic and rotation axes are nearly aligned and that all of the pulsed emission is from a single pole. A bridge of emission in the shorter gap between the main pulse and interpulse is a common feature of such profiles (Hankins & Fowler 1986).

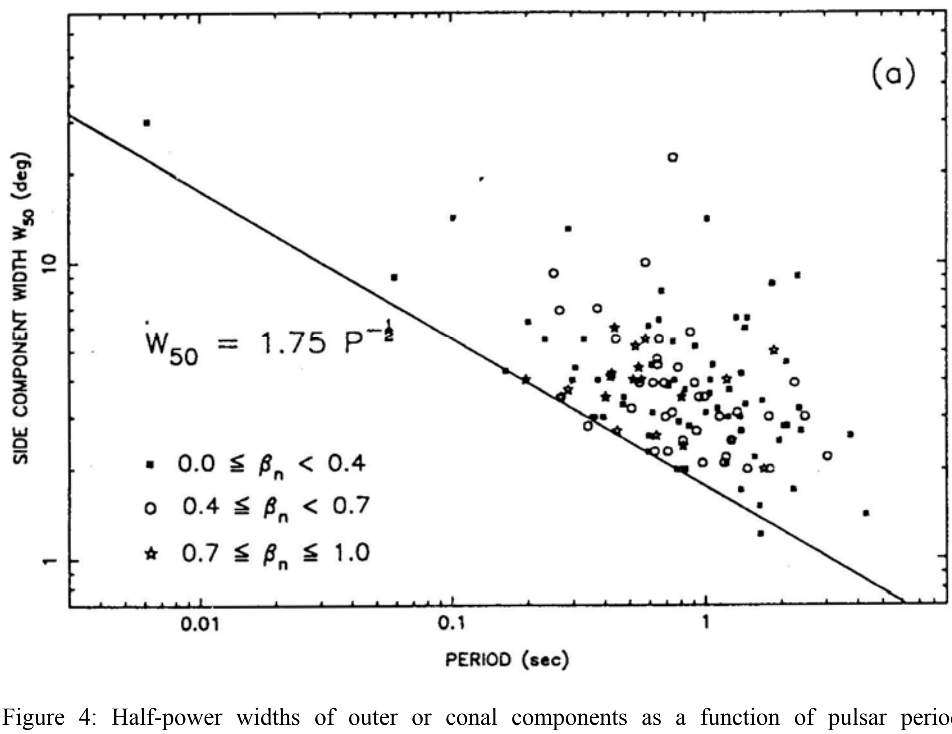

Figure 4: Half-power widths of outer or conal components as a function of pulsar period. Pulsars are divided into different classes depending on the 'normalized impact parameter', β_n , that is, the minimum angle between the observer's line of sight and the magnetic or symmetry axis normalized by the conal radius (from Gould 1994). If the observer's direction and the rotation axis are not orthogonal, the observed pulse width is greater than the emitted pulse width. The lower envelope of the points is therefore taken to represent the emitted pulse width.

Observed pulse profiles at optical, X-ray and γ-ray wavelengths for pulsars detected at these wavelengths also support a one-pole interpretation (Manchester and Lyne 1977). As shown in Fig. 5, the low-energy γ-ray pulse profile for the Crab pulsar has a strong bridge between the two components and looks very similar in appearance to radio 'double' pulse profiles. Romani & Yadigaroglu (1994) have recently modelled the Crab and other high-energy pulse profiles with a one-pole outer-gap model. They show that, when the full retarded potentials are used to describe the magnetic field structure, both the high-energy pulse shape and the optical polarization data for the Crab pulsar are well represented by the model. If this one-pole interpretation for the Crab pulsar is accepted, the phase relationships with the radio main pulse and interpulse (Fig. 5) imply that these also originate from the same outer-gap regions. However, the so-called 'precursor' pulse, which leads the main pulse, seems to be of a different character (e.g. Smith 1986).

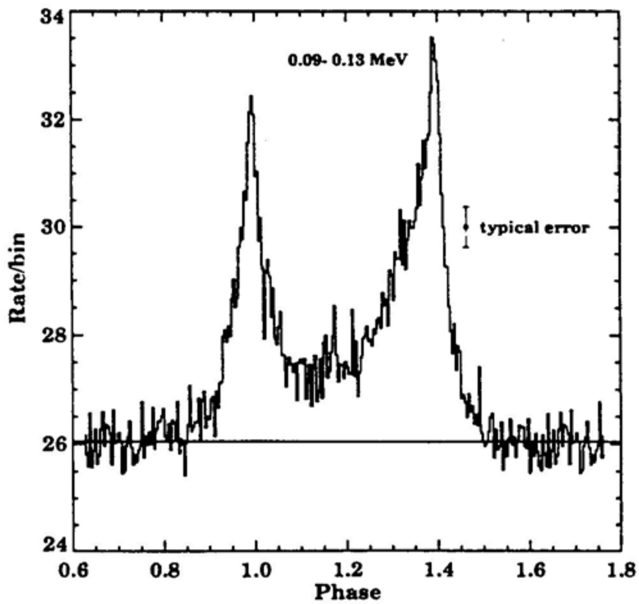

Figure 5: Low-energy γ-ray profile for the Crab pulsar from the OSSE experiment on the Compton Gamma Ray Observatory (Ulmer et al. 1994)

An extreme view would be that all pulsars emit from one pole only and that position-angle fits such as those for PSR B1534+12 are misleading us. Some observations seem to support such a view. An example is the remarkable mode-switching behaviour observed in PSR B1822-09 by Gil et al. (1994). The amplitude of the highly polarized precursor pulse, which leads the main pulse by about 15° of longitude, is anti-correlated with the amplitude of the interpulse, which is separated from the main pulse by 180° of longitude. Furthermore, the main pulse and interpulse amplitudes are correlated. These observations are difficult to understand on the standard two-pole model.

Recent observations of the eclipsing binary pulsar PSR B1259–63 have shown that the two pulse components are essentially 100% linearly polarized (Fig. 6).

In this respect they are similar to the precursor pulses of the Crab pulsar and PSR B1822–09 and to pulses from Vela and other young and short-period pulsars (Qiao et al. 1994). At 1520 MHz, the two components in PSR B1259–63 are separated by about 140°, but this separation is frequency dependent (Johnston et al. 1992). This strongly suggests that these two components emanate from a single pole. The wide separation of the components then implies that the emission is beamed at a correspondingly large angle to the magnetic axis. This has interesting implications for the Crab, Vela and other pulsars with these highly polarized components if they are emitted in the same way.

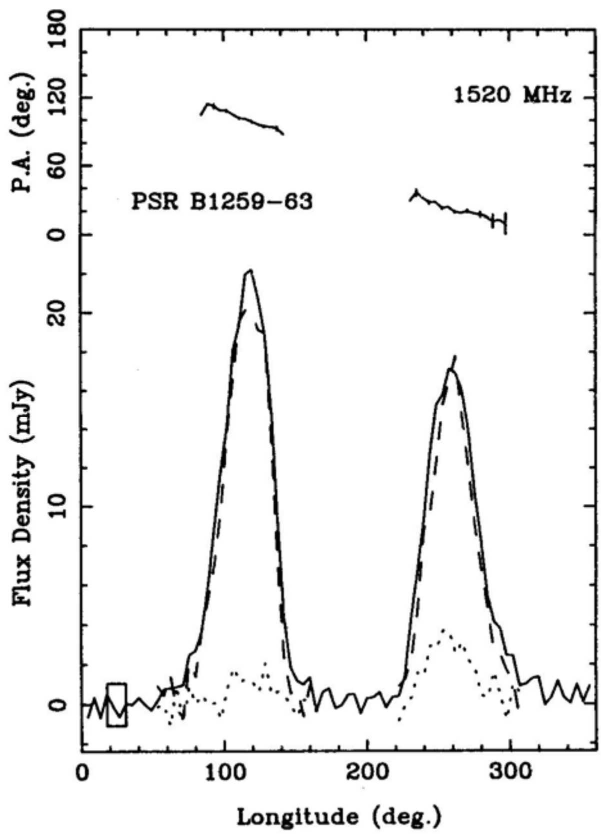

Figure 6: Mean pulse profile and polarization parameters for PSR B1259–63 at 1520 MHz (Manchester & Johnston, 1994). In the lower part of the figure the solid line represents the total intensity (Stokes parameter *I*), the dashed line the linearly polarized intensity and the dotted line the circularly polarized intensity (Stokes parameter *V*), The upper curve is the position angle of the linearly polarized part, plotted with $\pm 2\sigma$ error bars on every second point.

4. Conclusions

Observations of pulsar mean pulse profiles suggest that pulsar emission is in the form of a conical beam whose axis is the dipole axis of the neutron-star magnetic field. Although some properties such as radio-frequency spectral index and pulse-to-pulse fluctuations differ from central to outer parts of the observed pulse profile, it seems most likely that the same basic emission process is responsible for both parts of the profile. Observed pulse profiles can be represented by the product of a well-defined ‘window function’, which is determined by the dipole magnetic field structure and the characteristics of the emission process, and a random ‘source function’ which varies from pulsar to pulsar and may be determined by magnetic multipole structure.

High-energy pulse profiles suggest that, even in pulsars with interpulses, all of the observed emission originates. from a single pole on the star. This would make some observations, for example the correlated intensity fluctuations in the components of the PSR B1822–09 profile, easier to understand. Recent observations show that the two widely spaced components of PSR B1259–63 are highly linearly polarized and probably related to the similar highly polarized components observed mother young pulsars.

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