Observational Characteristics of the Radio Emission Beam of PSR J1906+0746 and Their Implications: Postprint

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Abstract

This study investigates the radiation characteristics of the main pulse and interpulse of PSR J1906+0746 using publicly available data. By performing Gaussian fitting on the average pulse profiles from various epochs, we obtained the corresponding 10% peak pulse widths and peak flux densities, and subsequently investigated their relationship with the impact angle. The results indicate that the primary visible component of the main pulse emission beam can be generated by a bundle of magnetic flux tubes with a defined range of magnetic longitude angles, whereas the interpulse originates from radiation along magnetic field lines encircling the magnetic axis. Existing fan-beam models can adequately explain the characteristics of the main pulse, but struggle to account for the radiation properties of the interpulse. The features of the interpulse necessitate improvements to the fan-beam model, where radiation from magnetic field lines surrounding the magnetic axis is assumed, and model parameters are reasonably selected to simulate the observed strip-shaped emission beam.

Full Text

Preamble

Observational Properties of Radio Emission Beams of PSR J1906+0746 and Their Implications

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Abstract: This paper investigates the emission characteristics of the main pulse and interpulse of PSR J1906+0746 using publicly available data. By fitting Gaussian components to the average pulse profiles from different epochs, we obtained the corresponding 10% peak pulse widths and peak flux densities, and subsequently studied their relationship with the impact angle. The results indicate that the main visible portion of the main-pulse emission beam can be produced by a magnetic flux tube with a defined range of magnetic longitude angles, whereas the interpulse emission originates from magnetic field lines encircling the magnetic axis. Existing fan beam models can satisfactorily explain the characteristics of the main pulse but struggle to account for the emission features of the interpulse. The interpulse characteristics require improvements to the fan beam model, specifically by assuming that radiation can be generated along magnetic field lines surrounding the magnetic axis and by selecting appropriate model parameters to simulate the observed strip-shaped emission beam.

Keywords: pulsars; radio emission; PSR J1906+0746; emission beam

1. Data Processing

The pulse profile data for this pulsar were downloaded from Zenodo, comprising 47 L-band average pulse profiles spanning from 2005 to 2018. The observations from 2005-2007 were obtained with the Nançay Radio Telescope, while those from 2008-2009 and 2012-2018 were from the Arecibo Radio Telescope; no observations exist for 2009-2012. Except for the Nançay data (covering MJD 53572 to MJD 54282), the flux densities from all other periods could reproduce the results from Desvignes et al. [9]. Consequently, we excluded the Nançay observations when analyzing flux characteristics. Since flux calibration is not required for measuring pulse widths, we utilized all available data for the width analysis.

In Desvignes et al. [9], the magnetic inclination angle was determined by fitting the Precessional Rotating Vector Model (PRVM) to the inflection points of the linear polarization position angle curves. The magnetic inclination angle for the pole associated with the main pulse was determined to be _MP = 99.41° ± 0.17°, with the inclination angle for the interpulse pole _IP being its supplement. Fixing these magnetic inclination angles, the impact angles for each observation were then derived by fitting the Rotating Vector Model (RVM) to the linear polarization position angle data for both the main pulse and interpulse. We directly adopted the impact angle results from Table S2 of the supplementary material in Desvignes et al. [9]. One special case required treatment: from MJD 56963 to 57553 (November 2014 to June 2016), the signal-to-noise ratio of the main pulse was too low to determine its impact angle. For this period, the main-pulse impact angle _MP was estimated from the interpulse impact angle _IP using the approximation _MP (_IP + _IP) − _MP.

Due to significant noise in many observations, we fitted the average pulse profiles of both main and interpulse components with several Gaussian components to obtain smooth profiles, from which we then measured the 50% peak width W_50 and 10% peak width W_10 (widths at 50% and 10% of peak height) and the peak flux density f_pk. Two exceptions were made: first, the main-pulse profile for MJD 57311 was excluded due to excessively low signal-to-noise ratio, which precluded reliable width and flux density measurements; second, the main pulse became undetectable after MJD 57553. Consequently, the final dataset comprised 34 effective measurements for main-pulse width and 25 for peak flux density, while the interpulse yielded 47 and 38 effective measurements for width and peak flux density, respectively.

The error in pulse width incorporates contributions from both the sampling interval and the Gaussian fitting measurement error, combined as the square root of the sum of their squares. All observations used 2048 sampling points, corresponding to a sampling interval error of 0.18°. Since all observations employed real-time dedispersion, errors from dispersion were negligible and thus ignored. The root-mean-square (rms) noise in flux density was typically around 0.1 mJy, which is significantly lower than the published L-band average flux errors [10]. Using the rms value as the error would likely underestimate the true uncertainty; therefore, we do not treat flux density errors in this analysis.

2.1 Relationship Between Pulse Width and Impact Angle

Figure 1 [Figure 1: see original paper] presents the variation of W_10 with | | for both the main pulse and interpulse. As shown in Figure 1(a), the main-pulse width exhibits a positive correlation with | |, qualitatively consistent with the predictions of the WPZ model. To test for quantitative agreement, we attempted to fit the data using the W- functional relationship from the WPZ model.

The WPZ model distinguishes between inner and outer regions of the emission beam. The inner region roughly extends from the magnetic axis to | | 2 _pc, i.e., the region where | | < 2 _pc, while | | > 2 _pc defines the outer region. Here, _pc is the half-opening angle of the polar cap region, defined as the angle between the tangent to magnetic field lines at the polar cap edge and the magnetic axis. Assuming a static magnetic dipole field, _pc 1.5R/R_e, where R is the neutron star radius (taken as 10 km) and R_e is the maximum distance from the stellar center along an open field line. For PSR J1906+0746 with P = 0.144 s, we calculated the minimum and maximum values of _pc for the outermost open field lines to be approximately 2.2° and 3.3°, respectively, using Equations (6) and (7) from Lee et al. [11] under the static dipole field assumption. The average value is about 2.75°, so we set the boundary between inner and outer beam regions at | | 5.5°, indicated by vertical dashed lines in Figure 1.

The WPZ model suggests that pulse profile width likely varies differently in the inner and outer regions. The inner region is more uncertain; with multiple flux tubes present, the pulse width might decrease outward from the magnetic axis. In the outer region, the geometric properties of dipolar flux tubes dominate, causing the pulse width W to increase with | | according to:

sin cos(+ C) = tan(+)(cos^2 + tan ^{2})^(1/2),

where C = tan ^{1}(sec / tan), and is the magnetic longitude angle of the magnetic field line defining the flux tube boundary. To define , we take the plane perpendicular to the plane containing the magnetic and rotation axes as the reference plane; the dihedral angle between the magnetic field line plane and this reference plane is the magnetic longitude angle. For the main-pulse pole, increases clockwise from the rotation direction when viewed downward, while for the interpulse pole it increases counterclockwise. This convention ensures that field lines with the same value at both poles have identical relative orientations with respect to the magnetic axis and rotation direction, facilitating comparison between the two emission beams.

Figure 1(a) shows that W_10 for the main pulse positively correlates with | |, with all values being negative and falling in the outer beam region. The red curve represents the best-fit obtained using Equation (2), yielding an optimal value of 19.5° ± 1.3°. From the perspective of the fan beam model, the main-pulse emission thus originates from a flux tube spanning a magnetic longitude range of approximately 39° ± 2°. The variation of W_50 with | | shows similar behavior.

It should be noted that Equation (2) assumes symmetry of the emission region about the plane containing the magnetic and rotation axes. However, the actual main-pulse emission beam is offset from this plane toward the rotation direction (see Figure 3 of Desvignes et al. [9] [Figure 3: see original paper]), making the above fit only a rough estimate. To better reveal the magnetic longitude distribution of the emission beam boundaries, we calculated the magnetic longitude angle for both left and right boundaries at the 10% intensity level for each main-pulse profile using:

= { + sign( ) cos ^{1}((cos - cos cos)/(sin sin)) (> /2) { -sign( ) cos ^{1}((cos - cos cos)/(sin sin)) (< /2)

where is the angle between the line of sight and the rotation axis, satisfying = + , and is the emission angle (angular distance from the magnetic axis) at phase relative to the profile reference center, calculated as:

$= \cos^{-1}(\cos \quad \cos \quad + \sin \quad \sin \quad \cos \quad).$

Here represents the phase difference relative to the central reference phase for each profile component, with sign( ) being the sign function; radiation with negative values reaches the observer earlier. In the rotating vector model, the phase of the inflection point of the linear polarization position angle (RVM) curve is considered to be the phase of the magnetic axis-rotation axis plane. Therefore, we adopted the RVM curve inflection phases for the main pulse and interpulse as their respective central reference phases (Φ_c,MP and Φ_c,IP), giving relative phases _MP/IP = Φ_MP/IP − Φ_c,MP/IP. The first expression in Equation (3) applies to the main pulse, the second to the interpulse.

Desvignes et al. [9] used the inflection points of the best-fit RVM curves to determine the central reference phases, setting them to 0° and 180° for profile alignment. The profiles shared on Zenodo have been phase-aligned, but the central phases are not at 0° and 180°, and the Zenodo technical documentation does not specify where the central reference phases are located. By comparing with the profiles in Desvignes et al. [9], we determined approximate central reference phases of 0.25 and 0.75 (in units of rotation period) for the main pulse and interpulse, respectively. Subtracting these values from the measured phases yielded the relative phases _MP and _IP, from which we calculated the magnetic longitude angles at each boundary.

Figure 2 Figure 2: see original paper shows the magnetic longitude angles of the 10% peak intensity boundaries for the main pulse as a function of impact angle. Both left and right boundaries oscillate around their respective mean values, with the resulting magnetic longitude width being $\Delta \; = 33° \pm 8°$ (Figure 2(b)), not substantially different from the result obtained via Equation (2).

To visualize the emission beam structure more intuitively, we projected the magnetic longitude range of the main pulse onto the celestial sphere, represented by blue line segments in Figure 3 [Figure 3: see original paper], with blue arrows indicating the temporal evolution direction of the impact angle. At the main-pulse pole, the emission beam lies primarily in the fourth quadrant. The two red dashed lines represent the average magnetic longitude angles of the left and right boundaries. As shown, the main-pulse emission beam can be well described by the beam bounded by these red lines.

It is important to note that using the 10% peak intensity boundaries of each profile to characterize the emission beam boundaries effectively normalizes each profile independently and creates a contour map at the 10% relative intensity level, which differs from the approach in Desvignes et al. [9] Figure 3 [Figure 3: see original paper], which used absolute flux for contour mapping. When flux density variations within the emission beam are large, absolute flux contour maps are less effective at revealing weak structures, whereas relative intensity contour maps offer advantages. Comparing the region below -15° in latitude in our figure with the corresponding portion of the main emission beam in Desvignes et al. [9] Figure 3 clearly demonstrates this difference.

In stark contrast to the main pulse, the interpulse shows a completely different correlation between pulse width and impact angle, as illustrated in Figure 1(b). In the inner beam region, W_10 exhibits a clear anti-correlation with | |. Since the WPZ model does not provide a relationship between width and impact angle for the inner region, we performed a simple linear fit, obtaining W_10 = −1.5° ± 0.4°| | + 26.3° ± 1.1°. Notably, the interpulse impact angle varies from approximately +13° to -6.2°, placing portions of the beam on both sides of the magnetic axis within the inner region. Interestingly, the relationship between W_10 and | | is essentially consistent for both portions (blue squares represent negative , black squares positive in Figure 1(b)). The variation of W_10 in the outer beam region is less regular, first decreasing then increasing with impact angle, likely due to irregular changes in the pulse profile shape.

Figure 2(c) shows the magnetic longitude angles of the 10% peak intensity boundaries for the interpulse as a function of impact angle. Unlike the main pulse, both boundaries show continuous variation rather than oscillation about mean values. Figure 2(d) reveals that as the impact angle changes from positive to negative values, the magnetic longitude width of the beam first increases gradually, reaching a maximum of 180° when the line of sight sweeps across the magnetic axis (= 0), then decreases. This indicates that the interpulse emission beam is not produced by a single flux tube of fixed magnetic longitude width, but rather originates from magnetic field lines encircling the polar axis. This can be visualized intuitively from the dark gray projected emission beam region in Figure 3. In terms of this characteristic magnetic longitude distribution, the interpulse emission beam resembles a conal beam model, but its latitudinal extent cannot be explained by conal beam models.

2.2 Relationship Between Flux Density and Impact Angle

Figure 4 shows the relationship between peak flux density and | |. As shown in Figure 4(a), the peak flux density in the outer region of the main-pulse beam decreases with increasing | |, qualitatively consistent with theoretical predictions from the WPZ model. In the WPZ model, the radiation intensity follows a power-law relationship with | |, so the observed peak flux density also follows a power law:

f_pk   A P^(q−4) P_−15^(−1/5) | |^(2q−6),

where P_−15 is the spin-down rate in units of 10^{1} s/s, and q is a parameter describing the relationship between coherent radiation power and emission altitude. This relationship depends on the specific radiation mechanism and how model parameters vary with altitude. WPZ adopted a phenomenological approach, assuming a power-law relationship where the exponent q reflects how rapidly the radiation power decays (or increases) with altitude. Using bisquare-weighted nonlinear regression, Equation (3) provides a good fit to the main-pulse observations. The red curve in Figure 4(a) represents the best fit, yielding an exponent q = −0.85 ± 0.93.

As shown in Figure 4(b), the interpulse peak flux density exhibits an overall positive correlation with | |. Theoretically, for individual flux tubes in the inner beam region, the WPZ model demonstrates that radiation intensity can increase with | |, but the situation becomes complex when multiple flux tubes are present. Thus, the WPZ model has the potential to explain the positive correlation in the inner region. However, the positive correlation observed in the outer beam region contradicts WPZ model predictions. The implications for model parameters are discussed in the following section. Finally, we attempted to fit the inner beam region with a power-law function, obtaining f__pk = 100.02±0.04 | |^(0.19±0.07); the best-fit curve is shown in Figure 4(b).

3.1 Difficulties with Existing Emission Beam Models

Since the emission beams at both poles of PSR J1906+0746 clearly do not conform to the core-double-cone beam model, we focus our discussion on fan beam models. The results above show that the WPZ fan beam model can explain some observational features but fails for others, which we summarize and discuss below.

(1) Observational facts that can be quantitatively explained by the WPZ model:

1. The positive correlation between main-pulse width and | | indicates that the visible portion of the emission beam is consistent with a fan beam produced by a flux tube spanning a magnetic longitude width of 33° ± 8°.
2. The anti-correlation between main-pulse peak flux density and | | matches the theoretical relationship of the WPZ model.

(2) Observational features difficult to explain with the WPZ model:

1. The variation of interpulse width with | | cannot be described by a fan beam from a single flux tube with a fixed magnetic longitude width. As shown in Figure 2(d), the magnetic longitude width of the emission beam changes continuously as the line of sight varies (accompanying ’ s transition from negative to positive values), first increasing then decreasing, reaching a maximum of 180° when crossing the magnetic pole. This suggests emission originates from magnetic field lines surrounding the magnetic axis, not from a flux tube with fixed width, contrary to the WPZ model’ s image of emission from discrete flux tubes (see Figure 7 of Wang et al. [5] [Figure 7: see original paper]).

2. The overall trend of increasing peak flux density with | | in the outer region of the interpulse beam is opposite to WPZ model predictions. If we still attempt to explain this using Equation (3) from the WPZ model, it would require q > 3, meaning coherent radiation power must increase significantly with altitude in the outer beam region—a physically questionable scenario. However, this positive correlation is unlikely to continue indefinitely; a turnover to decreasing flux at larger distances appears more reasonable.

We note that the two rightmost data points in Figure 5(b) [Figure 5: see original paper] indeed show decreasing peak flux density with increasing | |, but whether this trend continues awaits future observations.

3. The interpulse emission originates from around the magnetic axis, with the beam extending across it, posing a challenge for the WPZ model. Whether the main-pulse beam also possesses this cross-axis property lacks observational support, but the pulse observed in 1998 (see Desvignes et al. [9]) was relatively wide, located near the magnetic axis on the opposite side from the primary beam, suggesting that a cross-axis extension similar to the interpulse cannot be ruled out.

The difficulties of the WPZ model primarily stem from its assumption that the emission beam consists of sub-beams produced by single or several discrete flux tubes, each being an extended fan-shaped or strip-shaped structure converging at the magnetic axis (see Figures 5–8 of Wang et al. [5]), which cannot produce a coherent strip-shaped beam crossing the magnetic axis like the interpulse.

Other fan beam models, such as those by Dyks et al. [4,6] and Oswald et al. [12], do not explicitly provide relationships between beam width, flux, and impact angle, and typically assume the inner edge of the emission beam is at some distance from the magnetic axis, thus lacking consideration of emission near the axis.

3.2 Directions for Improving Fan Beam Models

The characteristics of the interpulse emission beam require a phenomenological model that combines features of both conal and fan beam models, satisfying the following elements:

1. The results in Figure 2(d) require that radiation can be generated along magnetic field lines at all magnetic longitudes, such as the ring of field lines around the magnetic axis within the polar cap region, or the entire polar cap area. This resembles assumptions commonly used in conal beam models.
2. The results of Desvignes et al. [9] indicate that 1.4 GHz radiation can be produced at vastly different emission altitudes, contradicting the conventional radius-to-frequency mapping assumption that different frequencies originate from different heights. A more reasonable assumption is that relativistic particle streams produce broadband radiation while flowing outward along field lines, making the emission beam at a single frequency sufficiently extended.
3. Under the above two assumptions, if the relationship between radiation intensity and altitude does not depend on magnetic longitude, a circular beam structure would inevitably result. However, the observed interpulse beam is extended in latitude and relatively compressed in longitude, requir-

ing that the radiation intensity-altitude relationship varies with magnetic longitude to explain this strip-shaped characteristic.

With these assumptions, it should be theoretically possible to construct a phenomenological model that reproduces the emission beam characteristics of PSR J1906+0746 by adjusting model parameters, providing valuable insights for developing more physically realistic emission models.

3.3 Physical Mechanisms for Radiation Near the Magnetic Axis

Explaining the radiation near the magnetic axis of PSR J1906+0746 is a crucial component of building emission models. Curvature radiation is frequently invoked to explain pulsar radio emission [13,14]. In a static magnetic dipole field, the curvature of field lines on the magnetic axis is zero, and the curvature of nearby open field lines is also very small, making efficient radio emission via curvature radiation impossible. However, in a rotating magnetic dipole field, the curvature of field lines increases, though whether this is sufficient to produce the observed radio frequencies and fluxes requires specific investigation.

The inverse Compton scattering (ICS) model [15,16] may offer advantages in this regard. In this model, low-frequency electromagnetic waves produced in the polar cap acceleration zone are scattered by secondary relativistic particles (through the inverse Compton scattering process) to generate higher-frequency radio waves. As long as the angle between the low-frequency wave vector and the secondary particle velocity is non-zero, scattering can occur. When secondary particle outflows exist near the magnetic axis, they can scatter low-frequency waves produced in other regions, satisfying the non-zero angle condition and potentially generating observable radio emission.

Both curvature radiation and ICS models require relativistic secondary particle outflows near the magnetic axis. Within the framework of inner acceleration zone models [13], this necessitates the existence of multipolar magnetic fields near the polar cap acceleration zone at the magnetic axis to provide sufficient field line curvature for cascade discharge processes to occur.

3.4 Differences Between the Two Polar Emission Beams

It is generally believed that the magnetic field structures at both poles of a pulsar should be identical, and that physical processes in regions with the same magnetic field structure should also be the same, implying identical emission beam structures at both poles. Figure 4 overlays the emission beams from both poles for comparison; the magnetic field structures are identical in the same quadrant. However, the main-pulse and interpulse emission beams differ dramatically, with substantially different magnetic longitude ranges even in regions traversed by the line of sight, the interpulse emission region being significantly wider. It should be noted that according to Desvignes et al. [9], the main pulse in 1998 was located near a latitude of ~5° in our Figure 3, with its profile center near longitude 0°, so the possibility cannot be excluded that the main-pulse beam also crosses the magnetic axis and originates from field lines encircling it. Even so, the difference in beam shape between the two poles remains striking. This point did not receive sufficient attention in Desvignes et al. [9], and PSR J1906+0746, as the first pulsar capable of revealing differences between the two polar emission beams, challenges conventional views.

The differences in beam shape between the two poles could arise from either different distributions of source field lines or different magnetic field structures at the two poles. Regarding the first possibility, one could use the emission geometry of a rotating magnetic dipole model to attempt to invert the source regions of emission at both poles from the observational data, examining possible differences in field line distributions and their plausibility. Regarding the second possibility, a few studies have proposed theoretical models with non-parallel magnetic dipoles [17,18], where the physical properties of the two poles may differ. In such models, the phases of the two magnetic poles deviate from 180°, and the linear polarization position angle curves deviate from the classic RVM, requiring model construction and fitting to polarization observational data to explore the parameter space and assess feasibility. The primary difference between these two models lies in the linear polarization position angle curve and the phase difference between the two magnetic poles, necessitating simultaneous fitting of the full-period linear polarization position angle data from both poles to attempt discrimination. If both models can explain the polarization observational features within reasonable parameter spaces, further consideration would be needed regarding their ability to explain differences in intensity distribution within the emission beams, though this would likely depend heavily on specific emission models.

4. Conclusions

This paper utilized open data for PSR J1906+0746 to study the emission characteristics of its main pulse and interpulse. The results show that the 10% peak intensity pulse width of the main pulse positively correlates with | |, while the peak flux density of the pulse profile anti-correlates with | |. The observational data can be reasonably fitted using the theoretical relationships of the WPZ fan beam model, suggesting that the main visible portion of the main-pulse emission beam can be explained as originating from a single flux tube. For the interpulse, the magnetic longitude angles derived from pulse width and data indicate that the emission originates from magnetic field lines surrounding the magnetic axis, making it difficult to describe the interpulse with an emission beam from a single flux tube with a fixed magnetic longitude range. Additionally, the peak flux density in the outer region of the interpulse beam increases with | |, contrary to WPZ model predictions. We argue that the characteristics of the interpulse emission beam of PSR J1906+0746 require a phenomenological model combining features of both conal and fan beam models, allowing radiation to be generated along magnetic field lines surrounding the magnetic axis and simulating the observed strip-shaped beam that continuously crosses the magnetic axis through appropriate selection of the dependence of radiation intensity on altitude and magnetic longitude. Furthermore, the observations reveal significant differences between the two polar emission beams, challenging the traditional view that the magnetospheric physical conditions and processes are identical at both poles.

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Note: Figure translations are in progress. See original paper for figures.