# Constraining the Orbital Inclination and Companion Properties of Three Black Widow Pulsars Detected by FAST (Postprint)

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**Date:** 2024-01-09T00:00:00+00:00

## Abstract

Black widow pulsars (BWs) are millisecond pulsars that erode their companion stars. Material outflowing from the companion can block the pulsar's radio emission, causing eclipsing phenomena. In this work, we construct a radio eclipse model by calculating the bow shock geometry between the pulsar wind and companion wind, which shapes the morphology of the eclipsing medium but has not been detailed in previous studies. The model is further applied to interpret variations in flux density and dispersion measure for three black widow pulsars—PSR B1957+20, J2055+3829, and J2051−0827—detected by the Five-hundred-meter Aperture Spherical radio Telescope (FAST). We thereby constrain system parameters for these three BWs, including orbital inclination and true anomaly as seen by the observer, as well as the companion's mass loss rate and wind velocity. With these constraints, future acquisition of additional observational data should enable further determination of the companion's magnetic field and even the pulsar's mass.

## Full Text

## Preamble

**Research in Astronomy and Astrophysics**, 23:125024 (8pp), 2023 December

https://doi.org/10.1088/1674-4527/ad034b

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Received 2023 July 20; revised 2023 September 25; accepted 2023 October 9; published 2023 November 28

## Abstract

Black widows (BWs) are millisecond pulsars that ablate their companion stars. The outflowing material from the companion can block the pulsar's radio emission, resulting in eclipses. In this paper, we construct a model for radio eclipses by calculating the geometry of the bow shock between the winds of the pulsar and its companion, where the shock shapes the eclipsing medium—a detail that had not been described in previous works. We apply this model to explain the variations in flux density and dispersion measure of three BW pulsars (PSR B1957+20, J2055+3829, and J2051−0827) detected by the Five-hundred-meter Aperture Spherical radio Telescope (FAST). Consequently, we constrain the parameters of these three BW systems, including the inclination angles and true anomalies of the observer, as well as the mass-loss rates and wind velocities of the companion stars. With these constraints, we anticipate that the magnetic fields of companion stars and even the masses of pulsars could be further determined once additional observations become available in the future.

**Key words:** (stars:) pulsars: individual (PSR B1957+20, PSR J2055+3829, PSR J2051-0827) – (stars:) binaries: eclipsing – stars: winds – outflows

## 1. Introduction

Millisecond pulsars (MSPs) are rapidly rotating neutron stars, many of which have been discovered in binary systems. It is widely believed that MSPs are spun up via angular momentum transfer from their companion stars through accretion processes (Bhattacharya 1996). Redbacks (RBs) and black widows (BWs), collectively known as spider pulsars, are subpopulations of MSPs that ablate their donors through powerful winds. The masses of RB companion stars typically range from (0.2–0.4) M , while BW companions have masses of (0.02–0.05) M (Roberts 2011; Polzin et al. 2019). Optical observations of RB and BW binaries have confirmed that the surfaces of their companion stars can be strongly irradiated by energetic pulsar winds (Khechinashvili et al. 2000). Furthermore, higher-energy observations have also discovered X-ray emission arising from the interaction of the pulsar wind with evaporated material (Kluzniak et al. 1988; Phinney 1988).

According to observations, the eclipse regions of spider pulsar binaries are typically larger than the Roche lobes of the companion stars, indicating that eclipses are not solely caused by stellar obscuration but likely result from absorption of the radio pulse signal by surrounding plasma, particularly during the beginning and ending stages of the eclipse. Since low-mass companion stars are surrounded by a diffuse evaporation halo, the radio emission from MSPs can in principle be eclipsed by this halo when it appears in the line of sight (LOS) near inferior conjunctions (Guillemot et al. 2019).

Such eclipses can occur as long as the binary's orbital inclination is sufficiently high. The first eclipsing BW discovered in radio observations was PSR B1957+20 (Fruchter et al. 1988). Approximately 10% of its orbital phase was found to be eclipsed, a range that cannot be covered by its companion's Roche lobe, indicating that ablated material must replenish the eclipse medium beyond the Roche lobe (Ray & Loeb 2017; Polzin et al. 2019). Therefore, studying MSP eclipses can help probe the properties of the evaporation material and, consequently, the companion stars themselves, while also providing constraints on the orbital parameters of the binaries.

The physical processes of eclipsing pulsars have been investigated thoroughly by Thompson et al. (1994), who confronted observational results for PSR B1957+20 and PSR J1748−2446A. Broderick et al. (2016) studied the correlation between eclipse duration and frequency for PSR J2215+5135, suggesting that the primary effect of the eclipsing medium is to absorb rather than scatter radio emission. Polzin et al. (2019) reported radio observations of PSR J2051−0827 in the frequency range of 110−4032 MHz and found that scattering and/or cyclotron absorption provides the most promising eclipse mechanism. Kudale et al. (2020) further suggested that absorption is primarily due to the cyclotron-synchrotron process, explaining the excess dispersion, scattering, and absorption of PSR J1227−4853. It is worth noting that cyclotron absorption requires a strong magnetic field in the eclipse medium.

In the last decade, many eclipsing pulsar binaries have been discovered, enabling more detailed studies of eclipse mechanisms (Bhattacharyya et al. 2013; Guillemot et al. 2019; Nieder et al. 2020). In particular, the Five-hundred-meter Aperture Spherical radio Telescope (FAST) has conducted extensive radio observations of several BW pulsars, including PSR B1957+20, PSR J2055+3829, and PSR J2051−0827, with long-term measurements of their flux density and dispersion measure (DM; Wang et al. 2023). Furthermore, rotation measure (RM) variation was found in PSR J2051−0827. At the current stage, it is necessary to combine these observational results with eclipse processes to constrain the physical properties of binary systems.

In the next section, we introduce an eclipse model that accounts for the shock interaction between the winds of the pulsar and companion star, as well as the resulting shock geometry. We then apply the model to fit the light curves and DM variations of the three FAST BWs in Section 3. The implications of the parameter constraints for the binary systems are discussed in Section 4, and conclusions are presented in Section 5.

## 2. The Model

The geometry of the eclipse medium is determined by the shock surface between the pulsar wind and stellar wind, as well as a magnetosphere (Romani & Sanchez 2016; Wadiasingh et al. 2017). Recently, Chen et al. (2021) investigated the shock interaction of a pulsar with an O/B star in high-mass gamma-ray binaries and estimated the radio emission windows of these pulsars. The primary difference between spider pulsar binaries and gamma-ray binaries is that in the latter case, the intense wind from the O/B star can nearly enclose the pulsar, whereas in spider binaries, the stellar wind can only blow a conical region. The geometry of the bow shock resulting from the interaction of the spider pulsar wind with the companion wind is depicted in Figure 1 [Figure 1: see original paper], determined by the mechanical balance between the two shocked wind regions.

The most crucial parameter is the momentum rate ratio between the winds:

$$\eta = \frac{L_{sd}/c}{\dot{M}_C v_w}$$

where $L_{sd}$ is the spin-down power of the pulsar, $c$ is the speed of light, $\dot{M}_C$ is the mass-loss rate of the companion star, and $v_w$ is the terminal speed of this wind.

Following Chen et al. (2021), when the observer's LOS intersects the bow shock, the pulsar's radio emission is suppressed as $F_\nu(\nu) = F_{\nu,0} \cdot e^{-\tau(\nu)}$, where the optical depth of the companion wind along the LOS is considered to be dominated by free–free absorption (FFA):

$$\tau(\nu) = \int_{l_{p,obs}} \alpha(\nu; T, n_e, n_i)\, dl$$

Here, $\alpha(\nu; T, n_e, n_i)$ is the FFA coefficient, which depends on the temperature ($T$) of the medium and the densities of electrons ($n_e$) and ions ($n_i$), and $l_{p,obs}$ is determined by the shape of the bow shock. We invoke the FFA process rather than cyclotron/synchrotron processes because the latter typically require strong magnetic fields. The magnetic field strength could in principle be measured by detecting variations in the RM of radio emission near eclipse boundaries (Polzin et al. 2019; Kudale et al. 2020). For the spider pulsar PSR B1957+20, Li et al. (2019) measured its RM values and found no evidence for large-scale magnetic fields over the egress plasma lensing region.

In addition to radio suppression, the companion wind provides an extra contribution to the DM of the pulsar radio emission, leading to a DM variation:

$$\Delta DM = \int_{l_{p,obs}} n_e \, dl$$

where $n_e$ is the electron number density, determined by the hydrogen abundance of the wind and the distance to the companion star's center. Specifically, we relate the electron number density to the ion density by $n_e = n_i \mu_i / \mu_e$, where the typical values of the mean ion molecular weight and electron weight are taken as $\mu_i \sim 1.29$ and $\mu_e \sim 1.18$, respectively (Zdziarski et al. 2010).

To complete these integrals, we express the companion wind number density (i.e., the ion density $n_i = n_w$) as a function of radius $r$ from the companion (Waters et al. 1988):

$$n_w(r) = n_{w,0} \left( \frac{r_\star}{r} \right)^2$$

where the base density $n_{w,0}$ at the stellar surface $r_\star$ is defined as:

$$n_{w,0} = \frac{\dot{M}_C}{4\pi r_\star^2 m_p v_w}$$

with $m_p$ being the proton mass and $v_w$ the wind velocity at the companion's surface. Here, the companion's mass loss is assumed to be isotropic, which is viable for regions not very close to the companion. Additionally, when the orbital inclination is high enough (i.e., $i_o > 90^\circ - \theta_\star$), the companion star can appear directly in the LOS and completely obstruct the radio emission, where $\theta_\star$ is the opening angle of the companion star with respect to the binary's centroid.

The temperature of the stellar wind gradually decreases through adiabatic cooling with increasing radial distance from the companion's surface. Consequently, the empirical temperature distribution can be expressed as a power law (Kochanek 1993):

$$T(r) = T_\star \left( \frac{r_\star}{r} \right)^\beta$$

where $T_\star$ is the effective temperature of the star at $r_\star$ and $\beta$ is an index that depends on the adiabatic index of the wind gas, ranging from (2/3–4/3). In our calculations, we adopt $\beta = 2/3$.

Strictly speaking, the stellar surface temperature is anisotropic due to irradiation by the pulsar, so $T_\star$ can only be treated as an effective temperature. Nevertheless, it should be noted that the temperature directly involved in the calculation is that of the wind material far from the stellar surface, where anisotropy is likely less significant than on the surface itself.

By confronting this model with radio observations of spider pulsars, we can constrain the binary orbit parameters (inclination angle $i_o$ and observer's true anomaly $f_o$) and companion star parameters ($\dot{M}_C$, $v_w$, and $A$).

## 3.1. PSR B1957+20

PSR B1957+20 is the first MSP discovered in a binary with a low-mass companion and is classified as a BW system. The binary orbit has a period of $P_{orb} \sim 9.2$ hr and eccentricity $e < 4.0 \times 10^{-5}$ (Arzoumanian et al. 1994). The pulsar has a spin period of 1.607 ms and a spin-down luminosity of $L_{sd} \sim 1.6 \times 10^{35}$ erg s$^{-1}$ (Fruchter et al. 1988). During the eclipse phase, the flux density of PSR B1957+20 decreases to nearly zero, preventing DM measurements. In the left panel of Figure 2 [Figure 2: see original paper], we present observational data centered at $\nu \sim 1.25$ GHz from 2022 September 2, covering the entire 14,340 s eclipsing period, with flux density normalized by pre- and post-eclipse emission (S. Q. Wang et al. 2023, in preparation). Solid lines represent model fits to the data, with goodness-of-fit evaluated using the MCMC method.

Observational constraints on the model parameters are shown in the right panel of Figure 2, with corresponding parameter values and $1\sigma$ errors listed in Table 1 . The results indicate that the orbit of PSR B1957+20 is viewed nearly edge-on, consistent with the $i_o \sim 85°$ result from Johnson et al. (2014) based on their MSP light curve simulation model. In comparison, Reynolds et al. (2007) derived a smaller inclination of $i_o = 65° \pm 2°$ from photometric data of the William Herschel Telescope and Hubble Space Telescope, while Kandel et al. (2021) constrained the inclination to $i_o \sim 75°.8 \pm 5°.9$ using X-ray emission from stellar wind interactions.

The companion's mass-loss rate is well constrained to $\dot{M}_C \sim 10^{-10.8} M_\odot$ yr$^{-1}$, consistent with the result ($\dot{M}_C \sim 10^{-10.7} M_\odot$ yr$^{-1}$) of Polzin et al. (2020), who analyzed 149 MHz observations assuming an inclination of 65° (Reynolds et al. 2007). This mass loss is caused by evaporation due to irradiation from the MSP, with a rate that can be estimated by:

$$\dot{M}_C \sim \frac{f L_{sd}}{a_{orb}^2} \left( \frac{R_\star}{G M_\star} \right)$$

where $a_{orb}$ is the binary orbital separation and $f$ is the evaporation efficiency. Using this relation, we obtain $f = 2.35 \times 10^{-3}$ for PSR B1957+20. Furthermore, the mass-loss rate may provide clues to determine the evolutionary stage of the companion star (Chen et al. 2013).

## 3.2. PSR J2051−0827

PSR J2051−0827 is the second eclipsing MSP discovered after PSR B1957+20. The pulsar is in a 2.38 hr orbit with eccentricity $3 \times 10^{-4}$, has a spin period of 4.508 ms, and a spin-down luminosity of $6 \times 10^{33}$ erg s$^{-1}$. Low-frequency radio observations ($\nu \lesssim 0.6$ GHz) show eclipse features covering 10% of the orbital period (Stappers 1996). FAST observations of PSR J2051−0827 centered at $\nu \sim 1.26$ GHz were conducted on 2022 January 14, lasting 8,940 s and covering the entire binary orbit (Wang et al. 2023). The observational data, displayed in the left panel of Figure 3 [Figure 3: see original paper], show that the pulsar's radio emission was not completely obscured during the eclipse.

Compared to PSR B1957+20, the data for PSR J2051−0827 exhibit much larger scatter, preventing good fits with a simple model. A possible explanation for these large fluctuations is that the stellar wind in this source is highly unstable and inhomogeneous. Nevertheless, through rough fitting of the PSR J2051−0827 data, we can constrain the inclination angle to $59^\circ.50 \pm 0^\circ.36$. In previous work, Dhillon et al. (2022) found this angle to be $55^\circ.9^{+4.1}_{-4.1}$ by fitting symmetrical HiPERCAM light curves with a direct-heating model, while Stappers et al. (2001) estimated it to be $\sim 40^\circ$ using asymmetric optical light curves that account for gravitational distortion and pulsar wind irradiation. The companion's mass-loss rate is constrained to $\dot{M}_C \sim 10^{-11.2} M_\odot$ yr$^{-1}$, close to the previous estimate by Polzin et al. (2019), which implies an evaporation efficiency of $3.33 \times 10^{-2}$.

## 3.3. PSR J2055+3829

PSR J2055+3829 was first discovered by the SPAN512 survey with the Nançay Radio Telescope. It has a spin period of 2.08 ms and spin-down luminosity $L_{sd} \sim 4.3 \times 10^{33}$ erg s$^{-1}$ (Guillemot et al. 2019). As another BW pulsar, PSR J2055+3829 is in a tight binary with a very low-mass companion. S. Q. Wang et al. (2023, in preparation) observed PSR J2055+3829 for 11,640 s at 1.25 GHz on 2021 August 30, finding a clear eclipse lasting $1467 \pm 12$ s, about 13% of the orbital period. The observational data are shown in the left panel of Figure 4 [Figure 4: see original paper], along with model curves.

The fitting results indicate a moderate inclination angle of $i_o \sim 47^\circ.5 \pm 0^\circ.4$, between the edge-on orbit ($i_o \sim 90^\circ$) assumed by Guillemot et al. (2019) and the inclination of 26° estimated from the mass function with an upper limit on the companion mass. The companion wind's mass-loss rate and velocity are constrained to $\dot{M}_C \sim 10^{-11.3} M_\odot$ yr$^{-1}$ and $1.03 \times 10^8$ cm s$^{-1}$, respectively, indicating an evaporation efficiency of $f = 4.34 \times 10^{-2}$.

## 4.1. RM Measurements and Magnetic Fields

For PSR J2051−0827, Polzin et al. (2019) utilized linearly and circularly polarized flux to investigate possible magnetic fields through measurements of RM, Faraday delay, and depolarization, constraining the average magnetic field parallel to the LOS to $10^{-4}$ G $\lesssim B_{\parallel} \lesssim 10^{2}$ G. More recently, Wang et al. (2023) detected a regular decrease in the RM of PSR J2051−0827 during eclipse egress, with the RM gradually returning to normal as the LOS moves away from the eclipse medium, as shown by the data points in Figure 5 [Figure 5: see original paper]. This measurement provides direct evidence for magnetic fields in the eclipse medium.

Based on our constraints for orbital and companion wind properties, we can in principle predict the RM variation of spider pulsars by adopting a specific description of the magnetic field in the stellar wind ($B_w$). Typically, we can express the magnetic field as a combination of radial and toroidal components (Bosch-Ramon & Khangulyan 2011):

$$RM_{bow} = \int_{l_{p,obs}} n_e B_{w,\parallel}\, dl$$

where

$$B_w(r) = B_\star \left(\frac{r_\star}{r}\right)^2 \left[\cos\psi \hat{r} + \sin\psi \hat{\phi}\right]$$

with $\psi = \arctan\left(\frac{v_{w,f}}{v_w}\right)$, $B_\star$ is the magnetic field strength at $r_\star$, and the companion's surface rotation velocity is assumed to be $v_{w,f} \sim 0.1 v_w (r_\star/r)$. It should be noted that the symmetric axis of this magnetic field may not be parallel to the binary's angular momentum but could have an inclination angle $\psi_m$ relative to the orbital plane normal, which would also influence the RM variation. Here, the binary is assumed to be tidally locked.

Using these formulae, we plot theoretical RM variation curves in Figure 5 for different magnetic field strengths and inclinations, with orbital and wind parameters from Table 1 for PSR J2051−0827. However, comparing these curves with observational data reveals that the model cannot explain the measurements. A notable discrepancy is that the data are delayed by about 0.015% of the orbital period relative to the model prediction. This indicates that a more complicated magnetic field structure is needed, particularly around the bow shock (e.g., Phinney 1988). The magnetic field near the bow shock can be significantly compressed, and its distribution may not perfectly trace the shock geometry. The LOS could scan the bow shock tail for an extended period because the tail can be deflected by orbital motion. In this tail region, the magnetic field could be very strong, producing a significantly high RM contribution while the corresponding radio absorption and DM contribution remain negligible.

Additionally, the companion's orbital motion influences not only the shock tail but also causes the bow shock's symmetric axis to deflect from the binary connecting line. The deflection angle can be estimated by $\xi \sim \arctan(v_C/v_w)$, where $v_C$ is the companion's orbital velocity (Zabalza et al. 2013). For PSR J2051−0827, we obtain $\xi \sim 47^\circ.5$, which is much larger than in other BW binaries. Therefore, future modeling must consider these complications in the magnetic field configuration around the bow shock as more RM data become available.

## 4.2. The Companion Surface Temperature and Pulsar Masses

The companion star radius of PSR J2051−0827 has been measured to be $R_\star \sim 0.12R_\odot$ (Dhillon et al. 2022), allowing us to roughly derive its surface temperature as $T_\star \sim 4,000$ K from the obtained parameter value $A \sim 10^{10}$ K cm$^{2/3}$. This temperature is higher than the $T_\star = 4000$–$4700$ K estimated by Stappers et al. (1996b) from observed $R-I$ colors using cool M-type dwarf relations from Bessell.

For PSR J2055+3829, if we approximate the companion radius using the Roche lobe radius $R_L \sim 0.14R_\odot$, which is reasonable for an appropriate mass ratio between the pulsar and companion (Guillemot et al. 2019), we can estimate the companion's surface temperature to be $T_\star \sim 3,800$ K from the parameter value $A \sim 10^{10}$ K cm$^{2/3}$. However, for PSR B1957+20, combining the obtained parameter with the companion radius $r_\star \sim 0.25R_\odot$ (van Kerkwijk et al. 2011) yields an unrealistically low temperature of $T_\star \sim 2,000$ K, much lower than found by Reynolds et al. (2007). This suggests that $\beta = 2/3$ may not always be appropriate for Equation (6), or that a constant index is not strictly correct, especially for winds very close to the stellar surface. We emphasize again that the companion temperature should in fact be anisotropic due to pulsar wind irradiation, and the temperature obtained from fitting radio flux and DM is only an effective value that might be regarded as an average.

Determination of the companion surface temperature would in principle help calculate its emission luminosity and estimate the companion mass through an empirical mass–luminosity relationship. Meanwhile, determining the inclination angle of BW binaries enables us to fix the binary mass function:

$$f(M_p, M_C) = \frac{(M_C \sin i_o)^3}{(M_p + M_C)^2} = \frac{P_{orb} K_p^3}{2\pi G}$$

where $M_p$ and $M_C$ are the pulsar and companion masses, respectively. The $M_p - M_C$ relationships for the three FAST BW binaries are displayed in Figure 6 [Figure 6: see original paper]. If the companion mass can indeed be obtained from temperature measurements, we expect that the pulsar masses can finally be constrained.

## 5. Summary and Conclusion

Studies of pulsar eclipse processes in BW systems can provide deeper understanding of binary orbits and their companions. We propose that radio emission from the pulsar is absorbed by the companion's outflows. The interaction between the pulsar wind and stellar wind forms a bow shock, and the stellar outflows on the shock-wrapped companion side cause radio eclipses when the star moves near inferior conjunctions, provided the binary has relatively high orbital inclination.

We have established an eclipse model for this wind interaction scenario and fitted the radio flux density and DM variations of three BW pulsars detected by FAST: PSR B1957+20, PSR J2055+3829, and PSR J2051−0827. We constrained orbital parameters and companion wind properties under this eclipse model. For PSR B1957+20, we found an inclination $i_o \sim 84^\circ.6 \pm 0^\circ.1$ and observer true anomaly $f_o \sim 90^\circ.0 \pm 0^\circ.1$. The companion's mass-loss rate is $\dot{M}_C \sim 10^{-10.8} M_\odot$ yr$^{-1}$ and wind velocity $v_w \sim 2.05 \times 10^8$ cm s$^{-1}$. For PSR J2051−0827, we obtained orbital inclination $i_o \sim 59^\circ.5 \pm 0^\circ.4$ and observer true anomaly $f_o \sim 90^\circ.0 \pm 0^\circ.1$, with companion mass-loss rate $\dot{M}_C \sim 10^{-11.2} M_\odot$ yr$^{-1}$ and wind velocity $v_w \sim 0.54 \times 10^8$ cm s$^{-1}$. Similarly, for PSR J2055+3829, we constrained the orbital inclination to $i_o \sim 47^\circ.5 \pm 0^\circ.4$ and observer true anomaly $f_o \sim 90^\circ.0 \pm 0^\circ.1$, with companion mass-loss rate $\dot{M}_C \sim 10^{-11.3} M_\odot$ yr$^{-1}$ and wind velocity $v_w \sim 1.03 \times 10^8$ cm s$^{-1}$. These fitting results demonstrate that our eclipse model can constrain both orbital parameters and companion wind properties in BW binary systems.

However, our eclipse model requires further refinement, as evidenced by the magnetic field signatures detected in RM variations during late eclipse stages. We suggest that these signatures are not dominated by the companion star's magnetic field but by interactions between the pulsar wind's magnetic field and the bow shock, which requires a more accurate description of the magnetic field around the bow shock. Furthermore, if the companion's mass and radius can be obtained directly from optical observations, we can also estimate the pulsar mass in BW systems through eclipse modeling.

## Acknowledgments

We thank the referee for useful comments on the manuscript. This work is supported by the National SKA program of China (2020SKA0120300), the National Key R&D Program of China (2021YFA0718500), the National Natural Science Foundation of China (grant Nos. 11833003 and 12033001), the China Postdoctoral Science Foundation (No. 2023T160410), and the Opening Foundation of Xinjiang Key Laboratory (No. 2021D04016).

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