Research Progress on Eclipse Phenomena of Spider Pulsars (Postprint)

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Abstract

The discovery of spider pulsars marks an important advancement in understanding the evolution of millisecond pulsars, and they are believed to be one of the sources of isolated millisecond pulsars. Spider pulsar systems display rich observational phenomena, with pulsar eclipsing being the most significant. Studies of eclipsing pulsars can aid in understanding the evolution of pulsar binaries, the formation of globular clusters, and the interstellar medium. This review summarizes the main progress in pulsar eclipsing research in recent years, including the characteristics of pulsar eclipses, statistics and examples of eclipsing pulsar systems, and discusses commonly employed eclipsing mechanisms. In the coming decade, with the deployment of radio telescopes featuring ultra-high sensitivity and ultra-fast survey speeds, such as the Square Kilometre Array (SKA), research on eclipsing pulsars is expected to break new ground and positively influence the development of eclipsing mechanism theories, helping to resolve some outstanding mysteries.

Full Text

Preamble

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The Research Progress of the Eclipsing Phenomenon of Spider Pulsars

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Abstract

The discovery of spider pulsars represents an important advance in understanding the evolution of millisecond pulsars, as these systems are considered potential progenitors of isolated millisecond pulsars. Spider pulsar systems exhibit rich observational phenomena, most notably the eclipsing of pulsar emission. Studies of eclipsing pulsars help illuminate the evolution of binary pulsar systems, the formation of globular clusters, and the properties of the interstellar medium. This review summarizes the major research progress on pulsar eclipsing over the past three decades, including the characteristics of pulsar eclipses, statistical properties and examples of eclipsing pulsar systems, and commonly invoked eclipsing mechanisms. Over the next decade, with the commissioning of ultra-sensitive, high-survey-speed radio telescopes such as the Square Kilometre Array (SKA), research on eclipsing pulsars is expected to open new frontiers, positively influence the development of eclipsing mechanism theories, and help resolve some outstanding mysteries.

Keywords: pulsar; eclipse; eclipsing mechanism; mass loss

1 Introduction

Spider pulsars refer to binary systems composed of a millisecond pulsar and a low-mass companion star in an advanced evolutionary stage. These binaries have relatively small separations, with most companion orbital periods shorter than one day, causing the companion to be continuously ablated by the pulsar wind. Spider pulsars are divided into two categories: "black widows" (BW) and "redbacks" (RB), distinguished solely by the companion mass m_c. Black widow pulsars have companion masses of $0.01 \sim 0.05 M_{\odot}$, while redback companions typically range from $0.1 \sim 0.5 M_{\odot}$ [?]. To date, over 90 such special binary systems have been discovered, with nearly half residing in globular clusters (GCs)—ancient stellar systems.

Observationally, most spider pulsars exhibit periodic eclipsing phenomena. When the expanded companion passes in front of the pulsar along the line of sight near the inferior conjunction of the binary orbit, it blocks the pulsar' s radiation, causing the radio signal to weaken or disappear entirely. The first eclipsing pulsar was discovered in a black widow system in 1988 [?]. After more than 30 years of observational statistics, eclipsing occurs in 50% of black widow pulsars and as many as 90% of redback systems (see statistics below). Because this periodic eclipsing occurs at specific orbital positions, it is termed "regular" eclipsing. Many well-studied regular eclipsing systems exist, such as B1957+20 [?] and J2051-0827 [?]. Another type is "irregular" eclipsing, where eclipses can occur at any orbital phase. To date, only four irregular eclipsing pulsars have been found: J1748-2446A [?], J0024-7204V [?], J1740-5340A [?], and J1748-2446P [?]. All are redback systems located in globular clusters.

Pulsar eclipsing phenomena typically appear in old binary systems, with nearly half of all eclipsing pulsar systems found in globular clusters, making them important for studies of stellar evolution and the interstellar medium. Very few eclipsing systems have been comprehensively studied, and current theories cannot fully explain all observed phenomena during various eclipsing processes. The next decade will be a period of rapid development for radio astronomy. The Square Kilometre Array (SKA), with its ultra-fast survey speed and digital multi-beam capability, is expected to discover $50 \sim 300$ eclipsing pulsar systems during SKA1 and SKA2 phases, potentially revealing more exotic eclipsing systems. Concurrently, several research avenues will be pursued: (1) studying eclipsing mechanisms by detecting flux variations before and after eclipses; and (2) measuring changes in dispersion measure (DM, in units of $\mathrm{pc} \cdot \mathrm{cm}^{-3}$) to determine the density and magnetic field structure of the eclipsing medium [?]. China' s Five-hundred-meter Aperture Spherical Telescope (FAST) can also conduct precise studies of DM and flux variations around eclipses, potentially discovering additional exotic eclipsing systems.

This review summarizes over 30 years of research progress on eclipsing spider pulsars at radio wavelengths. The structure is as follows: Section 2 describes the characteristics of pulsar eclipses, such as eclipse asymmetry and frequency dependence; Section 3 presents statistics on the 60 known eclipsing spider pulsars and provides examples of important eclipsing systems; Section 4 outlines current eclipsing models; and finally, we provide a summary and outlook.

2.1 Basic Picture of Eclipses

All eclipsing pulsars reside in binary systems, with the basic geometry shown in Figure 1 [Figure 1: see original paper] [?]. Similar to stellar eclipses, pulsar eclipses arise from obscuration of the pulsed radiation by material along the line of sight, primarily caused by the companion star. Consequently, pulsar eclipses typically occur near the inferior conjunction of the binary orbit (orbital phase $\phi = 0.25$). During the eclipse process, because the gravitational binding of material in the companion' s outer envelope gradually weakens, the eclipsing region usually exceeds the companion' s Roche lobe. Additionally, the eclipsing region is asymmetric: the "ingress" region is typically smaller than the "egress" region, indicating that the medium around the companion is not circularly distributed but likely possesses a comet-like "tail" structure. Finally, the eclipsing region at low frequencies (below 1 GHz) is generally larger than at high frequencies, which we describe in detail in the next section.

2.2 Frequency Dependence of Eclipses

Pulsar eclipses exhibit strong frequency dependence (see Figure 1). By measuring eclipse durations at different frequencies, various eclipsing models can be tested and the properties of the eclipsing medium investigated. However, studying frequency dependence presents observational challenges. Because binary orbital periods are long, obtaining multi-frequency observations of sufficient duration requires substantial radio telescope resources, a demand that is often difficult to satisfy. In 1994, Thompson et al. [?] studied the relationship between eclipse duration and observing frequency for two pulsars (B1957+20 and J1748-2446A) to validate eclipsing models (detailed in Section 4), but few eclipsing systems have been studied so carefully.

The definition of eclipse duration is not uniform across studies. In 2018, Polzin et al. [?] used a Fermi-Dirac function to fit the flux variation curve of pulsar J1810+1744, enabling quantitative study of the eclipsing region, as shown in Figure 2 [Figure 2: see original paper]. The Fermi-Dirac function is expressed as:

$$f(\phi) = \frac{1}{\exp((\phi + p_1)/p_2) + 1}$$

where f is the normalized pulsar flux, ϕ is the binary orbital phase, and p_1 and p_2 are fitting parameters. The parameter p_1 is defined as the orbital phase at eclipse ingress or egress, representing the position where the flux is half its stable value. The eclipse region range can thus be defined as:

$$\Delta\phi = p_{1;\mathrm{eg}} - p_{1;\mathrm{in}}$$

where $p_{1;\mathrm{in}}$ and $p_{1;\mathrm{eg}}$ are the orbital phases at eclipse ingress and egress, respectively. The eclipse radius is defined as:

$$R_E = x \sin(\pi\Delta\phi)$$

where x is the projected semi-major axis of the orbit (in light-seconds), equivalent to 3.0×10^8 m; R_E is typically converted to centimeters.

Generally, the eclipse range $\Delta\phi$ decreases with increasing frequency, and eclipses may cease altogether at high frequencies. For example, J1810+1744 has $\Delta\phi \approx 0.13$ at 149 MHz and $\Delta\phi \approx 0.09$ at 345 MHz (assuming a binary orbital inclination of 90°) [?]. For J1748-2446A in Terzan 5, observations with the Green Bank Telescope (GBT) at 800 MHz, 1330 MHz, and 1660 MHz revealed a relationship of $\Delta\phi \approx \nu^{-0.63\pm0.18}$ [?]. However, in some eclipsing systems, no clear correlation between eclipse range and observing frequency is found. For instance, in J2051-0827, eclipses only occur below 1 GHz, with no significant variation in eclipse range at 325 MHz, 430 MHz, and 660 MHz [?].

2.3 Relationship Between Eclipse Delay and Dispersion

Before and after an eclipse, the pulsar arrival time exhibits additional low-frequency delay, manifesting as extra dispersion measure variations at the edges of the eclipsing region (see Figure 3 [Figure 3: see original paper]). By measuring this excess delay, the density distribution of the eclipsing medium can be further investigated. The relationship between eclipse delay and excess dispersion is [?]:

$$\mathrm{DM}_{\mathrm{ex}} = 2.4 \times 10^{-10} \times t_{\mathrm{ex}} f^2$$

where $\mathrm{DM}_{\mathrm{ex}}$ is the excess dispersion value, t_{ex} is the observed excess delay time (in μs), and f is the observing frequency (in MHz). The relationship between excess dispersion and electron column density N_e is [?]:

$$N_e = 3 \times 10^{18} \times \mathrm{DM}_{\mathrm{ex}}$$

where N_e has units of cm^{-2}. Typically, the signal delay around eclipses is on the order of milliseconds. For example, J1748-2021D shows a delay of 0.5 ms at 1950 MHz [?], while J2055+3829 has a maximum delay of approximately 0.05 ms (at 1.4 GHz), with a maximum electron column density in the eclipsing medium of about 10^{17} cm^{-2} [?].

2.4 Short Eclipses

In some spider systems with eclipses, besides the "primary eclipse" at inferior conjunction, short eclipses occur at other orbital phases, typically lasting from seconds to several hours. For example, J1048+2339 exhibits short eclipses near superior conjunction ($\phi \approx 0.75$), with dynamically varying eclipse region sizes on timescales of hours to days [?]. J2051-0827 shows clear short eclipses at both 149 MHz and 345 MHz. Interestingly, these short eclipses were only detected during a two-week period in February 2015 and not during other observing sessions. After excluding diffractive interstellar scintillation and ionospheric effects, the specific origin of short eclipses remains to be further investigated [?]. J1544+4937 has short eclipses lasting nearly 180 s, possibly caused by fragmented plasma clumps around the companion [?]. J1717+4308A has a longest eclipse region reaching 40% of the orbital period, along with short eclipses occupying 6%–12% of the orbital period [?].

2.5 Regular vs. Irregular Eclipses

Currently discovered eclipsing systems can be divided into two main categories based on the orbital phase at which eclipses occur: regular and irregular eclipses. Regular eclipses refer to those occurring near inferior conjunction (as shown in Figure 4 [Figure 4: see original paper]a, where the blue vertical line indicates inferior conjunction), with most sources showing slight variations in eclipse duration. The majority of known eclipsing systems belong to this category, such as B1957+20 [?] and J2051-0827 [?]. Irregular eclipses occur not only near inferior conjunction but also at any other orbital phase (as shown in Figure 4b). The four known irregular eclipsing systems are J1748-2446A [?], J0024-7204V [?], J1740-5340A [?], and J1748-2446P [?], all of which are redback systems in globular clusters. We will discuss them further in Section 3.2.

3.1 Known Eclipsing Spider Pulsar Systems

Sixty eclipsing spider pulsar systems have been discovered to date. We have compiled their pulsar names, spin periods, dispersion measures, binary orbital periods, minimum companion masses, and system types in Table 1 . Among these, 29 eclipsing spider systems were discovered in globular clusters (11 black widows and 18 redbacks), while 31 were found in the field (18 black widows and 13 redbacks). Their sky distribution is shown in Figure 5 [Figure 5: see original paper]. Similar to the spatial distribution of millisecond pulsars, these eclipsing systems are relatively uniformly distributed across the sky without strong concentration toward the Galactic plane. Using the data in Table 1, we plot the pulsar spin periods, binary orbital periods, and minimum companion masses in Figure 6 [Figure 6: see original paper]. Statistically, most known eclipsing spider pulsars have spin periods shorter than 30 ms and orbital periods shorter than 1 day. For black widow systems, the fastest-spinning is B1957+20B (1.61 ms) and the slowest is J1953+1846A (4.88 ms); the largest orbital period is J1311-3430 (0.382 d) and the smallest is J1957+20 (0.065 d). For redback systems, the fastest-spinning is J1748-2446ad (1.39 ms) and the slowest is B1718-19(A) (1004.04 ms)—also the fastest and slowest among all eclipsing spider pulsars. The largest orbital period is J1748-2446A (1.977 d) and the smallest is J1740-5340B (0.076 d). Figure 6 also shows that redback systems have larger peak values in both spin period and orbital period distributions compared to black widows, reflecting different evolutionary histories for the two types of systems.

3.2 Special Eclipsing Spider Pulsar Systems

Among the 60 spider pulsars listed above, several have been the focus of intensive study. Most are ordinary regular eclipsing pulsars, but we highlight two early-discovered, well-studied examples (B1957+20 [?] and J2051-0827 [?]). More exotic systems constitute a smaller fraction, about 10%-20%. Some spider pulsars exhibit short or irregular eclipses, including J1748-2446A [?], J0024-7204V [?], J1740-5340A [?], and J1748-2446P [?], challenging theoretical explanations of eclipsing mechanisms. Additionally, some redback systems have been identified as transitional millisecond pulsars (tMSPs) [?]. These systems can switch between states: (1) an accretion disk state with no radio emission; (2) an observable radio pulsar state with no accretion; and (3) a state resembling low-mass X-ray binaries (LMXBs) where the pulsar accretes matter from its companion. The discovery of tMSPs provides strong evidence for the origin of millisecond pulsars from LMXB systems. The three known tMSPs—J1023+0038, J1227-4853, and J1824-2452I—all happen to exhibit eclipses, likely because the companion has evolved to fill its Roche lobe, becoming larger and surrounded by more diffuse interstellar medium. Among the three tMSPs, only the first two have detailed radio eclipse observations.

B1957+20 was the first eclipsing pulsar system, discovered by Fruchter et al. [?] using the Arecibo radio telescope. It has a spin period of 1.6 ms, an orbital period of 9.17 h, and approximately 10% of its orbital phase is occulted, with clear pulse arrival time delays around eclipses. Optical observations indicate that the companion surface is strongly eroded by the pulsar wind. The companion radius is about $0.12R_{\odot}$, smaller than the system' s Roche radius $R_L \approx 0.29R_{\odot}$. X-ray observations further reveal that high-energy radiation originates from interactions between the pulsar wind and the companion' s surrounding medium [?].

J2051-0827 is a black widow pulsar discovered by Stappers et al. [?] in 1996. It has a spin period of 4.5 ms, a binary orbital period of 2.38 h, and a minimum companion mass of about $0.03M_{\odot}$. The eclipse region covers about 10% of the orbital phase (at an observing frequency of 436 MHz). At frequencies of 436–660 MHz, the relationship between eclipse range and observing frequency is $\Delta t \propto \nu^{-0.15}$. Stappers et al. [?] detected the companion optically with magnitude 22.3–23.2. The companion radius $R_{\rm opt} \approx 0.067$–$0.18R_{\odot}$, while the Roche radius is $R_L \approx 0.13R_{\odot}$, suggesting the companion may fill its Roche lobe.

J1748-2446A is the second discovered eclipsing pulsar system and the first irregular eclipsing system. Located in the globular cluster Terzan 5, it has a spin period of 11.56 ms [?]. Its eclipse ranges from one-third to nearly the entire orbital period, with delays of 0.3 ms around eclipses. Sometimes, pulsed signals can be observed near inferior conjunction, with longer eclipses at lower frequencies. Short eclipses also occur at other orbital phases. The irregular eclipses may result from the pulsar ablating the companion and producing a complex, dynamically variable wind [?], as illustrated in Figure 4b. Tavani and Brookshaw [?] developed a dynamical model for this system to simulate the distribution of material around the companion, finding good agreement with observed eclipse phenomena.

J0024-7204V exhibits irregular eclipses occurring at multiple orbital phases, with about 50% of the region near inferior conjunction always invisible. The system also shows short eclipses with pulse delays up to 0.5 ms. Because pulsed signals were not observed for several years, it was considered a candidate transitional MSP. However, X-ray and optical observations indicate that it did not evolve into an accreting transitional MSP during the radio-quiet period [?].

J1740-5340A, located in globular cluster NGC 6397, has a spin period of 3.65 ms and an orbital period of 1.35 d. Its eclipse covers 30%–50% of the orbital period, with maximum delays up to 3 ms. Amico et al. [?] proposed that the system' s orbital inclination may be less than 20° and the companion might be a specially evolved star reaching the "turnoff" mass in globular clusters (about $0.8M_{\odot}$). In this scenario, the companion could produce a sufficiently dense and complex wind to create irregular eclipses.

J1748-2446P, in globular cluster Terzan 5, has a spin period of 1.72 ms and an orbital period of 0.362 d. Its eclipses are also irregular, with eclipsing regions reaching several times the solar radius. Ransom et al. [?] suggested that the irregular eclipses may arise from a similar cause as J1740-5340A—namely, a specially evolved companion capable of producing a complex wind, possibly having undergone at least one companion exchange event.

J1023+0038 has a spin period of 1.68 ms and an orbital period of 0.198 d, with a magnetic field strength of about 10^4 T. It shows variable-length primary eclipses near inferior conjunction. At 150 MHz and 350 MHz, the pulsar signal experiences several-second short eclipses outside the primary eclipse, but this phenomenon does not occur above 1 GHz [**?**].

J1227-4853 has a spin period of 1.69 ms and an orbital period of 0.287 d. At observing frequencies of 607 MHz and 1.4 GHz, eclipse ranges occupy 40% and 30% of the orbital period, respectively [**?**, **?**]. Kudale et al. [**?**] observed this system with the Giant Metrewave Radio Telescope (GMRT) at 607 MHz and found that the eclipses may be caused by cyclotron absorption. Additionally, the system shows significant pulse delays near superior conjunction, accompanied by reduced pulse flux.

3.3 Mass Functions of Eclipsing and Non-Eclipsing Systems

The mass function $f(m_p, m_c, i)$ of a binary system characterizes the relationship between binary masses (where m_p is the pulsar mass and m_c is the companion mass) and the orbital inclination i, and can be obtained directly from pulsar timing observations:

$$f(m_p, m_c, i) = \frac{(m_c \sin i)^3}{(m_p + m_c)^2} = \frac{4\pi^2 x^3}{G P_b^2}$$

where x is the projected semi-major axis of the binary orbit, P_b is the orbital period, and G is the gravitational constant. Assuming a constant pulsar mass of $1.4M_\odot$, the companion mass m_c and binary inclination i are strongly correlated and difficult to determine precisely individually.

Guillemot et al. [**?**] statistically compared the mass function distributions of eclipsing and non-eclipsing black widow pulsar systems inside and outside globular clusters, finding that eclipsing black widow systems have higher mass functions, with no significant difference between cluster and field populations. Assuming constant pulsar mass, the orbital inclination i has the greatest influence on the mass function for a given companion type. It is easy to understand that larger inclinations make the companion and its surrounding medium more likely to block the pulsar signal, causing eclipses. By extension, eclipsing redback systems should also have larger mass functions than non-eclipsing redbacks.

Based on our updated sample, we further statistically analyzed the mass functions of redback and black widow eclipsing systems, as well as cluster and field eclipsing systems, using 50 pulsars from Table 1 (excluding 10 sources lacking mass function data). The results are shown in Figure 7 [Figure 7: see original paper]. The mass function distributions of eclipsing redbacks and black widows show a clear separation, caused by their distinctly different companion mass ranges, though the slope differences are modest. For cluster versus field eclipsing systems, the mass function distributions show no significant difference.

4 Eclipse Models

Following the discovery of the first eclipsing pulsar, Kluzniak et al. [?] proposed various models to explain the phenomenon, which Thompson et al. [?] later summarized in detail and applied to B1957+20 and J1748-2446A. Below we briefly introduce these models; all formulas are derived from [?]. The main eclipsing mechanisms include refraction, free-free absorption, induced Compton scattering, and cyclotron/synchrotron absorption. Since eclipsing regions typically exceed the companion' s Roche lobe, the companion' s occultation alone cannot account for the eclipse. These models therefore assume that part of the obscuration results from interactions between the pulsar signal and plasma around the companion, particularly during eclipse ingress and egress. Based on current observational data, none of these models can satisfactorily explain all eclipsing phenomena, and the theories remain incomplete.

4.1 Refraction Model

This model assumes the eclipsing medium consists of sufficiently dense, ionized plasma with a density distribution that follows a power law with distance from the companion, and that the refractive index in this region can become large enough to deflect the pulsar beam away from the line of sight, as illustrated in Figure 8 [Figure 8: see original paper].

Assuming refraction occurs when the plasma frequency approaches the radio observing frequency, the radio deflection frequency is expressed as:

$$\nu_p = \left(\frac{e^2 n_e(b)}{2\pi m_e} \right)^{1/2} \approx \frac{\nu_{\text{obs}}}{2\beta + 1} \beta^2 a \cos\psi f; c$$

where ν_p is the plasma frequency, ν_{obs} is the observing frequency (both in MHz), n_e is the free electron density (in cm^{-3}), b is the impact parameter, m_e is the electron mass, and the relationship between observing frequency ν and eclipse radius b_c is:

$$b_c \approx \nu^{(\beta+1)}$$

where β is a fitting parameter. The refraction model applies when the pulsar beam deflection angle is small, producing eclipse time delays of $10 \sim 100$ ms. When applied to B1957+20, the theoretically predicted frequency dependence of eclipse duration and pulse delay times are inconsistent with observations. For J1748-2446A, the plasma density around the companion is too low to produce significant refraction of the pulsar beam.

4.2 Free-Free Absorption

Assuming the eclipsing medium is highly concentrated and relatively cold, and sufficiently dense, radio photons passing through the region can be absorbed by plasma through free-free absorption. The free-free optical depth is:

$$\tau_{ff} \simeq 3.1 \times 10^{-8} T_{e,7}^{-3/2} \nu_9^{-2} L_{11}^{-1} \ln(1.6 \times 10^5 T_{e,7}^{3/2} \nu_9^{-1}) N_{e,17}^2 f_{cl}$$

where $f_{cl} = \langle n_e^2 \rangle / \langle n_e \rangle^2$ is the clumping factor, T_e is the medium temperature (in units of 10^7 K), ν is the observing frequency (in units of 10^9 Hz), L is the absorption length (in units of 10^{11} cm), and N_e is the electron column density (in units of 10^{17} cm^2). Applying this model to B1957+20 and J1748-2446A requires either extremely low plasma temperatures or very large clumping factors to achieve sufficient optical depth, which contradicts actual conditions. Therefore, free-free absorption cannot explain these two systems.

4.3 Induced Compton Scattering

When pulsar radiation interacts with plasma around the companion, photons may scatter in different directions at different frequencies. When the plasma is sufficiently dense, the optical depth changes continuously, and Compton scattering occurs at some critical point with large scattering angles. The optical depth is defined as:

$$\tau_{\text{ind}} \simeq 4 \times 10^{-5} N_{e,17} S_0 \left| \frac{\alpha + 1}{\alpha + 3} \right| \frac{d_{\text{kpc}}^2}{a_{11}^2} M$$

where S_0 is the average flux density (in mJy), α is the pulsar spectral index, d_{kpc} is the pulsar distance (in kpc), a is the binary separation (in 10^{11} cm), and M is a parameter $M \approx (R_C/2r)^2$, where R_C is the curvature radius of the plasma cloud. When applied to B1957+20 and J1748-2446A, this model yields optical depths too small to produce eclipses. Thus, induced Compton scattering cannot reasonably explain these two eclipsing systems.

4.4 Cyclotron/Synchrotron Absorption

This model assumes a strong magnetic field in the eclipsing medium, originating from the pulsar wind or possibly a strong companion magnetic field. When the pulsar radio signal passes through this region, radio waves are absorbed at the cyclotron resonance frequency and its harmonics. In this model, higher harmonics have smaller optical depths, which can explain why eclipses occur at low frequencies but not at high frequencies. The characteristic magnetic field strength B_E at distance a from the companion is:

$$B_E \approx \left(\frac{2I_{\mathrm{PSR}}\dot{P}}{P^3 a^2 c} \right)^{1/2}$$

where I_{PSR} is the pulsar moment of inertia, P is the spin period, $\dot{P}$ is the period derivative, and a is the binary separation. The cyclotron frequency is $\nu_B = eB/2\pi m_e c$, and the magnetic field strength required for absorption at the m-th harmonic ($m = \nu/\nu_B$) is:

$$B = 350\, m^{-1} \nu_9$$

where ν_9 is the frequency in units of 10^9 Hz. When applied to J1748-2446A, the resulting characteristic magnetic field strength of the eclipsing medium is too small to satisfy eclipse conditions. Therefore, cyclotron absorption cannot reasonably explain its eclipses. When applied to B1957+20, the model may be viable at 318 MHz and 430 MHz. However, whether the eclipsing medium can satisfy the strong magnetic field requirements of this model needs further observational verification.

4.5 Mass Loss

By studying eclipse characteristics, properties of the companion and surrounding medium can be investigated, such as calculating the companion mass loss rate $\dot{M}_c$. Assuming $\dot{M}_c$ is constant and the eclipsing region is symmetric, it can be expressed as:

$$\dot{M}_c \simeq \pi R_E^2 m_p n_e V_W$$

where R_E is the eclipse radius, m_p is the particle mass in the plasma, n_e is the electron column density, and V_W is the outflow velocity of material ablated by the pulsar wind. Thompson et al. [?] used this method to calculate the companion mass loss rate for B1957+20, obtaining $\dot{M}_c \approx 3 \times 10^{-13} M_{\odot} \cdot \mathrm{yr}^{-1}$, suggesting that the companion cannot be evaporated within a cosmological timescale to become an isolated millisecond pulsar system. This theoretical model has limitations, such as the initial assumption of a constant mass loss rate, which may actually vary dynamically during the complex evolution of the binary. Later, Ginzburg and Quataert [?] used dynamical models to simulate the companion mass loss process, obtaining a companion lifetime of 3.4 Gyr for B1957+20, also concluding that black widow systems are unlikely to become isolated millisecond pulsars through evaporation, though this possibility cannot be completely excluded. More accurate conclusions on this issue require expanded sample studies.

5 Summary and Outlook

Spider pulsars are important for studying pulsar winds and the evolution of millisecond pulsars. Since 1988, nearly 100 spider pulsars have been discovered, of which 60 exhibit eclipses. Black widows and redbacks are two distinct types of spider systems, differing primarily in companion mass ranges of $0.01M_{\odot} \sim 0.05M_{\odot}$ and $0.1M_{\odot} \sim 0.5M_{\odot}$, respectively. Both types share similar eclipse characteristics, such as asymmetric eclipses where the ingress region is typically smaller than the egress region, suggesting a comet-like tail structure for the eclipsing medium. Eclipse durations are frequency-dependent, generally following a power-law relationship with observing frequency, making eclipses more likely and longer at low frequencies, though some individual cases show no clear frequency dependence. Significant variations in dispersion measure and flux occur around eclipses, and studying these DM variations helps us understand the density distribution and magnetic field structure of the eclipsing medium.

We have compiled properties of these 60 known eclipsing spider pulsars, including their spatial distribution, periodic properties, eclipse characteristics, and mass functions. The spatial distribution is relatively uniform, with balanced numbers inside and outside globular clusters. Black widow systems have smaller pulsar spin periods and binary orbital periods than some redback systems, reflecting different evolutionary paths. Short and irregular eclipses appear in some systems, such as the four known irregular eclipsing systems J1748-2446A, J0024-7204V, J1740-5340A, and J1748-2446P, whose origins remain mysterious and require further observation and study. Some systems are undergoing binary state transitions where the companion fills its Roche lobe, which we have also highlighted. Regarding mass functions, previous work concluded that eclipsing black widow systems have higher mass functions than non-eclipsing systems [**?**], primarily due to different binary inclinations. Our expanded statistics including redbacks show that the integrated mass functions of eclipsing black widow and redback systems are offset overall but have very similar slopes, with the main difference arising from companion mass. The mass function distributions of eclipsing systems inside and outside globular clusters are very similar, consistent with conclusions for black widow systems alone [**?**].

Regarding eclipsing mechanisms, besides companion occultation, the role of interstellar medium within the system is essential. Although multiple models have been proposed—including refraction, free-free absorption, induced Compton scattering, and cyclotron/synchrotron absorption—all have significant shortcomings in explaining observations. Furthermore, studying eclipsing pulsar systems allows estimation of companion lifetimes. For example, current theoretical models and simulations suggest that black widow systems may not be progenitors of isolated millisecond pulsars. However, the theory has room for improvement and requires further study with larger samples. In the era of multi-wavelength and multi-messenger astronomy, observations at radio, optical, X-ray, and gamma-ray bands are all advancing research on these systems. Notably, with FAST and the construction of SKA, more eclipsing spider pulsars will be observed with greater frequency coverage and timing precision, driving progress in this field. For instance, FAST' s high-precision timing can study variations in dispersion and delay around eclipses, enabling more precise investigation of the density and magnetic field structure of the eclipsing medium. During the SKA era, $50 \sim 300$ eclipsing pulsar systems are expected to be discovered [**?**], revealing more exotic spider systems. For example, the currently known fastest-spinning pulsar is the redback J1748-2446ad, suggesting that theoretically predicted sub-millisecond pulsars may exist in such systems and will eventually be found.

Ultimately, we anticipate breakthroughs in understanding spider pulsar eclipsing mechanisms to solve many poorly explained problems, such as the origin of irregular eclipses, whether black widow pulsars can become isolated millisecond pulsars, and the exact nature of interactions between pulsar winds and eclipsing media. With advances in observations and theory, we expect these questions to be addressed while new questions and phenomena emerge, expanding the research landscape for eclipsing pulsars.

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