Modeling the Wind of the Be Star SS 2883

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Observations of eclipses of the radio pulsar B1259-63 by the disk of its Be-star companion SS 2883 provide an excellent opportunity to study the winds of stars of this type. The eclipses lead to variations in the radio flux (due to variations in the free-free absorption), dispersion measure, rotation measure, and linear polarization of the pulsar. We have carried out numerical modeling of the parameters of the Be-star wind and compared the results with observations. The analysis assumes that the Be-star wind has two components: a disk wind in the equatorial plane of the Be star with a power-law fall-off in the electron density \( n_e \) with distance from the center of the star \( \rho (n_e \sim \rho^{-\beta_0}) \), and a spherical wind above the poles. The parameters for a disk model of the wind are estimated. The disk is thin (opening angle 7.5°) and dense (electron density at the stellar surface \( n_{0e} \sim 10^{12} / \text{cm}^3 \), \( \beta_0 = 2.55 \)). The spherical wind is weak (\( n_{0e} \lesssim 10^9 / \text{cm}^3 \), \( \beta_0 = 2 \)).

1 Introduction

The first binary system consisting of a radio pulsar and a Be star was discovered more than ten years ago using the Parkes radio telescope [1, 2]. This is the B1259-63 system, in which the pulsar moves along a very elongated orbit (\( e \geq 0.87 \)) around its companion – the 10\(^{m} \) Be star SS 2883.

The first theoretical estimates of the number of such systems, carried out in 1983-1987 using the “Scenario Machine” [3]-[6], showed that approximately one in 700 observed radio pulsars should have an OB companion. The detection of the B1259-63 system not only confirmed the possibility of the evolutionary scenario obtained by the authors of [3]-[6], but also provided a powerful tool for studies of the associated stellar wind, as was also predicted in these studies. Currently, 1500 radio pulsars are known, of which at least two are in binary systems with OB companions (B1259-63 and J0045-7319), consistent with the above estimate.

In 1997-1998, possible evolutionary tracks for the B1259-63 and J0045-7319 systems were computed using the “Scenario Machine” [7]. These computations were based on an evolutionary scenario that predicts the existence of systems consisting of a radio pulsar and a massive optical component. The high eccentricity of the orbit is explained as an effect of the “kick” given by the anisotropic supernova explosion that gave rise to the pulsar. Possible magnitudes and the direction of the kick velocity in the B1259-63 system were also derived [8].

In 2003, the “Scenario Machine” was used to estimate the number of such systems in which the orbital plane of the pulsar and the equatorial plane of the Be star do not coincide [9]. For characteristic anisotropic kick velocities of 50-200 km/s, these two planes should be inclined relative to one another by several tens of degrees in more than half of these systems.

A Be star is a main-sequence star of spectral class B which has one or more Balmer emission lines in its spectrum, with these lines usually displaying two peaks. Struve proposed in 1931 that this spectral characteristic could be explained as radiation from a rotating disk associated with the Be star. These disks have now been observed in the optical, infrared, and radio. They are comprised of dense, slowly rotating material that is located in or near the equatorial plane of the Be star. In addition, Be stars produce winds with low density and high velocity.

Observations of the transit of PSR B1259-63 provide a unique opportunity for studying the characteristics of the disk of the Be star based on the observed variations of the radio flux, linear polarization, rotation measure, and pulse delay. This is possible because the disk of SS 2883 is inclined relative to the orbital plane of its companion, so that the pulsar is sometimes eclipsed by the disk.

Attempts were undertaken to construct a model

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for the Be-star wind and compare the calculated parameters with the observed dispersion measure, rotation measure, and pulse delay time. A disk model with an exponential fall-off of the electron density with distance from the Be star and with height above the plane of the disk was considered in [10].

A model with a power-law fall-off of the density in the disk is more physically justified, however [11]; with some parameters, this model was able to explain the observed variations in the dispersion measure near periastron. A model with a clumpy disk wind from the Be star has also been developed [12, 13] (in addition to, not replacing the power-law disk). Rapidly moving bubbles (velocities of $\approx 2000$ km/s) with electron densities that differ from the value in the surrounding region ($n_e \sim 10^6$/cm$^3$, and dimensions $< 10^{10}$cm at a distance of 20-50 stellar radii) give rise to appreciable fluctuations in the electron density along the line of sight, and thereby to fluctuations in the flux, dispersion measure, and rotation measure.

An attempt to establish the position of the orbital plane of PSR B1259-63 relative to the equatorial plane of SS 2883 was made using timing measurements for the pulsar [14, 15]. However, it proved impossible to construct a unique model for the system due to the noise level and the prolonged eclipses of the pulsating radio emission.

A disk model for the Be-star wind is also considered, for example, in [16, 17], where the ratio of the densities of the outflowing material in the equatorial plane and at the poles is derived. If the Be star rotates with a velocity $v$ that is 90% of the critical velocity $v_{\text{crit}}$, then $N = 150$; slower rotation lowers this value (when $v = 70\% \cdot v_{\text{crit}}$, $N \approx 15 - 20$). According to [18], the rotational velocity of SS 2883 is approximately 70% of the critical velocity.

We consider here the absorption of the radio emission in a model with a power-law disk wind in the equatorial plane and a spherical wind above the poles of the Be star (without including the effect of clumpiness). In contrast to previous studies, we compare the calculated and observed fluxes of pulsating radio emission. The derived parameters of the wind differ from those presented in [11]. The available rotation measure data are sufficient only to derive order of magnitude estimates of the magnetic field strength in the wind (in particular, in bubbles), as was done in [11]-[13]. Accordingly, we will consider further only the radio flux and dispersion measure.

2 Model Be-star wind

Figure 1 depicts a schematic model of a binary system consisting of a radio pulsar and a Be star. The X axis is directed along the line of sight away from the observer. $\omega$ is the longitude of the ascending node, $i$ is the orbital inclination (the angle between the plane of the sky YZ and the orbital plane of the pulsar), P indicates the pulsar and Be the Be star, $i_b$ is the angle between the XY plane and the plane of the Be-star disk, and $\Omega_b$ is the angle between the Y axis and the line corresponding to the intersection of the XY plane and the disk of the Be star.

![Fig. 1: Schematic model for a system consisting of a radio pulsar and a Be star.](image-url)
Fig. 2: Model Be-star wind. There is a disk wind with a power-law fall-off in the electron density in the equatorial plane and a spherical wind above the poles.

The electron density $n_e$ at a distance $\rho$ from the star is calculated using the formula

$$n_e = n_{0e} \left( \frac{\rho_0}{\rho} \right)^{\beta_0}. \quad (1)$$

Here, $n_{0e}$ is the electron density at the stellar surface (i.e., at a distance $\rho_0$ from its center). For the spherical wind, $\beta_0 = 2$; this is a free parameter for the disk wind, whose value is one of the parameters for which we are searching.

We also assumed that the temperature of the disk wind can be determined by the power-law relation

$$T = T_0 \left( \frac{\rho_0}{\rho} \right)^{\beta_1}. \quad (2)$$

Here, $T$ is the temperature of the plasma at a distance $\rho$ from the star and $T_0$ is the temperature at the stellar surface.

The optical depth to radio emission can be calculated using the formula [19]:

$$\tau = 0.34 \left( \frac{1 \text{GHz}}{\nu} \right)^{2.1} \left( \frac{10^4 K}{T} \right)^{1.35} \frac{EM}{10^6 \text{Pc} \cdot \text{cm}^{-6}}. \quad (3)$$

Here, $\nu$ is the frequency of the radio emission, $T$ the temperature of the wind [2], and EM the emission measure, which is defined to be

$$EM = \int n_e^2 dl. \quad (4)$$

The dispersion measure is given by the formula

$$DM = \int n_e dl. \quad (5)$$

Fig. 3: Dependence of the 1384 MHz radio flux of B1259-63 on the position of the pulsar relative to SS 2883; $v$ is the true anomaly. The hollow squares show the observational data with their errors. The solid curve denotes the calculated model.

The quantity $n_e$ in (4) and (5) is calculated using (1).

3 Results

We carried out theoretical calculations of the flux and dispersion measure of the radio emission of the B1259-63 pulsar as a function of its position relative to its companion – the Be star SS 2883. These calculated values were compared with the observations.

The observational data on the radio fluxes were taken from Table 2 of [13], and on the dispersion measures from Table 1 of [10], Table 2 of [11], and Table 3 of [13]. The longitude of the ascending node of the pulsar orbit in the B1259-63 system is $\omega = 138^\circ$ [2], the orbital inclination is $i = 36^\circ$, the characteristic radius of the star is $\rho_0 = 6R_\odot$ and the mass of the optical star is $M = 10M_\odot$ and the projection of the semi-major axis onto the line of sight is $a \sin i = 1295.98$ light seconds [2]. The interstellar contribution to the dispersion measure of the B1259-63 pulsar is 146.8 Pc/cm$^3$ [13].

The velocity of the Be-star wind at infinity is $V_\infty \approx 1000 – 1300$ km/s in the equatorial plane and, $\approx 2300$ km/s at the poles [17] (the characteristic wind velocity at infinity for SS 2883 is $\approx 1350 \pm 200$ km/s).
km/s [20]). The radial outflow velocity of the disk material at the Be-star surface is 5-10 km/s [21]. To check the resulting parameters of the stellar wind, we must compare the mass-loss rate in the model obtained with the characteristic values for Be stars. The rate at which matter flows from the star can be found from the expression

$$\dot{M} = \Omega \rho^2 n m_i V;$$

(6)

where $\rho$ is the distance from the star, $n$ the particle density of the wind at the distance $\rho$ which is calculated using [10], $m_i$ the mean mass of the ions in the wind, $V$ the wind velocity at the distance $\rho$, and $\Omega$ the solid angle into which the given type of wind (spherical or disk) flows.

The mass loss of Be stars was investigated in detail in [22]. A Be star with an initial mass of $10^M$ loses mass at the rate $\dot{M} = 3 \cdot 10^{-9} M_\odot$/year.

We carried out numerical computations in order to determine the best-fit orientation of the disk of the Be star SS 2883 relative to the orbital plane of PSR B1259-63, which is given by the parameters $\Omega_b$ and $i_b$ (Fig. 1). We also wished to determine the best-fit values of $\beta_0$ for the disk wind and the electron density at the stellar surface $n_0$ for both the disk and spherical winds ($\beta_0 = 2$ for the spherical wind). We constructed theoretical light curves for the pulsar at 1384, 2496, 4800, and 8400 MHz together with the dependence of the dispersion measure of the pulsar radio emission on the position of the pulsar relative to its companion.

The results of the numerical simulations are shown in [3-7] together with the observational data. The criterion used to evaluate the correctness of a model is the closeness of the computed curves to the observational data. In addition, the model should not contradict our understanding of the matter outflow rate in Be stars.

The computations yielded the following best-fit parameters for the disk model. The disk opening angle was $\varphi = 7.5^\circ$, the electron density in the disk at the stellar surface was $n_{0e} \approx 1 \cdot 10^{12}/cm^3$, and $\beta_0 = 2.55$. The spherical wind was weak ($n_{0e} \lesssim 10^9/cm^3$, $\beta_0 = 2$). The orientation of the SS 2883 disk relative to the orbital plane is described by the parameters $\Omega_b$ and $i_b$ (Fig. 1), which have the values $\Omega_b = 12^\circ$ and $i_b = 67^\circ$ in the best-fit model. The disappearance of the pulsating emission of B1259-63 near periastron is due to eclipses of the pulsar by the Be-star disk. The weak spherical wind does not make an appreciable contribution to either the decrease in the radio flux or the increase in the dispersion measure. The model mass-loss rate via the SS 2883 wind estimated using (6) is consistent with our current understanding of the mass-loss rates of Be stars: $\dot{M} \approx 3 \cdot 10^{-9} M_\odot$/yr, in good agreement with the results of [22].

Although we have assumed that the temperature of the wind may depend on the distance from the Be star [2], the best-fit model was obtained for a constant temperature, equal to $10^4 K$. Substituting (1) and (2) into (3) we can see that the behavior of

Fig. 4: Same as Fig. 3 for 2496 MHz.

Fig. 5: Same as Fig. 3 for 4800 MHz.
the light curve will not change if \(2 \beta_0 - 1.35 \beta_1 = 5.1\) if we suppose that \(\beta_1 \neq 0\) (so that consequently, \(\beta_0 \neq 2.55\)). However, the variations of \(\beta_0\) must not be in contradiction with the observed dispersion measures, and cannot be large.

Figure 3 clearly displays a secondary minimum of the light curve at values of the true anomaly \(v\) from 100\(^\circ\) to 120\(^\circ\). Our model for the wind is not able to fit this observational feature. The computations yielded a model with \(\Omega_b \approx -55\)\(^\circ\) that can fit this secondary minimum, whose presence is then explained by the absorption of the radio emission in the disk. However, in this case, the pulsar and observer are located on the same side of the disk at periastron, and we must introduce a strong spherical wind in order to fit the decrease in the radio flux. This led to an implausibly high mass-loss rate \(\dot{M} \approx 3 \cdot 10^{-7} M_\odot/yr\). In addition, a strong spherical wind would make an appreciable contribution to the dispersion measure, so that it would be necessary to appreciably lower the interstellar dispersion measure (from 146.8 pc/cm\(^3\) to 135-140 pc/cm\(^3\)). We, accordingly, rejected this second model.

The parameters of the best-fit model presented here differ substantially from the results of [11], where, in particular, it was found that \(\beta_0 = 4.2\) in the disk and that the mass-loss rate of the optical star is \(\dot{M} = 5 \cdot 10^{-8} M_\odot/yr\).

**4 Conclusion**

Our computations have yielded the following best fit parameters for the disk model used. The opening angle of the disk is \(\varphi = 7.5\)\(^\circ\), the electron density in the disk at the stellar surface is \(n_{e0} \approx 1 \cdot 10^{12}/\text{cm}^3\), \(\beta_0 = 2.55\). The spherical wind is weak (\(n_{e0} \lesssim 10^9/\text{cm}^3\), \(\beta_0 = 2\)) and cannot make a significant contribution to either the decrease in the radio flux or the increase in the dispersion measure near periastron. The orientation of the SS 2883 disk relative to the pulsars orbital plane is fit by the parameters \(\Omega_b = 12\)\(^\circ\) and \(i_b = 67\)\(^\circ\) (Fig. 1). The mass-loss rate in the SS 2883 wind estimated using \(\Omega\), is consistent with current thinking about the mass-loss rates of Be stars: \(\dot{M} \approx 3 \cdot 10^{-9} M_\odot/yr\), in good agreement with the results of [22]. The disappearance of the pulsating radio emission of B1259-63 near periastron is due to eclipsing of the pulsar by the dense disk of the Be star.

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