

Hydrodynamic Interaction between the Be Star and the Pulsar in the TeV Binary PSR B1259–63/LS 2883

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Abstract

We have been studying the interaction between the Be star and the pulsar in the TeV binary PSR B1259–63/LS 2883, using 3-D SPH simulations of the tidal and wind interactions in this Be–pulsar system. We first ran a simulation without pulsar wind nor Be wind, while taking into account only the gravitational effect of the pulsar on the Be disk. In this simulation, the gas particles are ejected at a constant rate from the equatorial surface of the Be star, which is tilted in a direction consistent with multi-waveband observations. We ran the simulation until the Be disk was fully developed and started to repeat a regular tidal interaction with the pulsar. Then, we turned on the pulsar wind and the Be wind. We ran two simulations with different wind mass-loss rates for the Be star, one for a B2 V type and the other for a significantly earlier spectral type. Although the global shape of the interaction surface between the pulsar wind and the Be wind agrees with the analytical solution, the effect of the pulsar wind on the Be disk is profound. The pulsar wind strips off an outer part of the Be disk, truncating the disk at a radius significantly smaller than the pulsar orbit. Our results, therefore, rule out the idea that the pulsar passes through the Be disk around periastron, which has been assumed in previous studies. It also turns out that the location of the contact discontinuity can be significantly different between phases when the pulsar wind directly hits the Be disk and those when the pulsar wind collides with the Be wind. It is thus important to adequately take into account the circumstellar environment of the Be star, in order to construct a satisfactory model for this prototypical TeV binary.

Key words: gamma rays: theory — stars: emission-line, Be — stars: individual (PSR B1259–63, LS 2883) — stars: winds, outflows

1. Introduction

PSR B1259–63/LS 2883 is a massive binary system consisting of a 48-ms radio pulsar and a Be star with a circumstellar disk (Johnston et al. 1992). The system is one of only three binaries from which periodic TeV gamma-ray emission has been detected (the others are LS I +61–303 and LS 5039; e.g., Paredes 2008). Among these TeV gamma-ray binaries, PSR B1259–63/LS 2883 has several distinctive properties. First, the compact star of this system is identified as a radio pulsar, namely a neutron star, while the nature of the compact object of the other two sources is still under debate. Second, the orbital period (3.4 yr) is very long compared to the other systems (3.9 d for LS 5039 and 26.5 d for LS I +61 303), and the eccentricity is so large that the binary separation at

periastron is less than a tenth of that at apastron (Johnston et al. 1994). Third, nonthermal emission is detected in X-ray and radio wave bands as well, and light curves of all bands including TeV gamma-rays exhibit multiple-peaked features, in most cases one before periastron passage and another after it, although the curves differ orbit to orbit (Chernyakova et al. 2009; Aharonian et al. 2009).

Considering the passage of the neutron star through a misaligned Be disk, shock acceleration in the disk–pulsar interaction region has been proposed as the mechanism for double-peaked light curves. Modeling of gamma-ray emission was first discussed by Tavani et al. (1994) for MeV energies following the CGRO observation. They considered shock acceleration in the interaction region, and showed that the double-peaked feature appeared in X-ray and MeV gamma-ray

ranges. Much theoretical work for high-energy emissions followed (e.g., Tavani & Arons 1997; Ball & Kirk 2000; Murata et al. 2003) and the emission in TeV energy range has been discussed in Ball and Kirk (2000) in particular. Assuming a disk-like outflow around the Be star, Kawachi et al. (2004) proposed a double-peaked light curve in TeV range, which was followed by the TeV gamma-ray detection with a marginal pre-periastron peak and a clear post-periastron peak (Aharonian et al. 2005). As shown in the radio observations, the light curve varies from orbit to orbit and the TeV double-peak was not clearly seen in the next 2007 periastron passage. Aharonian et al. (2009) suggested that the detection of the TeV emission 50 days prior to the periastron passage is with disfavor that the pulsar–disk interaction is the primary TeV emission mechanism.

It can be pointed out that all of the previous theoretical studies have either neglected the recent progress in Be star research, and adopted an out-of-dated view of the Be disk, or neglected even the presence of the Be disk. Given that the gas pressure in the Be disk is much higher than the ram pressure of the Be wind, it is important to take into account the interaction between the pulsar wind and the Be disk adequately. In this series of papers, we will study the high-energy emission from PSR B1259–63/LS 2883, for the first time based on 3-D numerical simulations with the latest model of the Be disk. As a first step, this paper explores the hydrodynamic interaction between the pulsar wind and the circumstellar environment of the Be star.

The structure of the paper is as follows. In section 2, we first describe the Be disk model and the numerical method. We then discuss the viscous evolution of the Be disk under the tidal interaction with the pulsar, based on simulations where only the tidal interaction is taken into account. In section 3, we show the results from simulations that also take account of both the pulsar wind and the Be wind, and examine the effects of the pulsar wind on the circumstellar environment of the Be star. In section 4, we discuss the implications for multi-wavelength observations, and summarize the conclusions.

2. Tidal Effect of the Pulsar on the Be Disk

2.1. Viscous Decretion Disk Model for Be Stars

In this subsection, we briefly summarize key observational features of Be stars and describe an up-to-date model of the Be disk that is widely accepted in the Be star community [see Porter & Rivinius (2003) for more detailed descriptions of Be stars and their circumstellar disks].

A Be star has a two-component extended atmosphere: a polar wind region and an equatorial disk region. The former consists of a low-density fast flow ($\sim 10^3 \text{ km s}^{-1}$) emitting UV radiation. The wind structure is well-explained by the line-driven wind model (Castor et al. 1975; Friend & Abbott 1986). On the other hand, the equatorial disk consists of a high-density plasma, from which the optical emission lines and the IR excess arise. The relationship between the disk size resolved with the optical interferometers (Quirrenbach et al. 1994, 1997) and the separation of the two peaks of the $H\alpha$ line profile is in agreement with that expected for a Keplerian disk. The outflow in the Be disk is very subsonic. Hanuschik (1994, 2000) and Waters and Marlborough (1994) showed that the radial velocity

of the disk is smaller than a few km s^{-1} , at least within ~ 10 stellar radii. Thus, it is unlikely that the Be disk is formed by channeling/focusing of the polar wind. Indeed, it is established that the Be disk cannot be modeled as a low-velocity wind.

One model that can reproduce all key features of the Be disk, and is thus widely accepted, is the viscous decretion disk model proposed by Lee et al. (1991) and developed by Porter (1999) and others (Okazaki 2001, 2007; Carciofi & Bjorkman 2006; Carciofi 2010). The model assumes that the star can eject material with the Keplerian velocity at the stellar equatorial surface. The ejected material then drifts outward by viscous diffusion, and forms a geometrically thin Keplerian disk. Recent Monte Carlo radiative transfer simulations show that such a disk has a temperature approximately constant at $\sim 60\%$ of the stellar effective temperature, except in an inner optically-thick region where the disk is significantly cooler (Carciofi & Bjorkman 2006). It should be noted that the viscous decretion disk model also provides a firm basis for the study of tidal interactions between the Be disk and the neutron star in Be/X-ray binaries (Negueruela & Okazaki 2001; Okazaki & Negueruela 2001).

2.2. Numerical Model

A simulation presented below was performed with a three-dimensional Smoothed Particle Hydrodynamics (SPH) code. The code is basically the same as that used by Okazaki et al. (2002) (see also Bate & Bonnell 1995). Using a variable smoothing length, the SPH equations with a standard cubic-spline kernel are integrated with an individual time step for each particle. In our code, the Be disk is modeled by an ensemble of gas particles with negligible self-gravity. For simplicity, the gas particles are assumed to be isothermal at $0.6 T_{\text{eff}}$ with T_{eff} being the effective temperature of the Be star. On the other hand, the Be star and the neutron star are represented by sink particles with the appropriate gravitational mass. Gas particles that fall within a specified accretion radius are accreted by the sink particle.

In simulations shown in this section, the numerical viscosity is adjusted so as to keep the Shakura–Sunyaev viscosity parameter, $\alpha_{\text{SS}} = 0.1$, using the approximate relation $\alpha_{\text{SS}} = 0.1 \alpha_{\text{SPH}} h/H$ and $\beta_{\text{SPH}} = 0$ (Okazaki et al. 2002), where α_{SPH} and β_{SPH} are the artificial viscosity parameters,¹ and h and H are the smoothing length of individual particles and the scale-height of the Be decretion disk, respectively. No effect of pulsar wind or Be wind is taken into account in these simulations.

We set the binary orbit in the x – y plane with the major axis along the x -axis. At $t = 0$, the pulsar is at the apastron (phase = 0.5). It orbits about the Be star with the orbital period $P_{\text{orb}} = 1236.79 \text{ d}$ and the eccentricity $e = 0.87$. It has long been expected that the Be disk is inclined from the orbital plane, because the pulsed radio emission disappears for about five weeks, centered on the epoch of periastron, e.g., $\sim 18 \text{ d}$ prior to the 2004 periastron through $\sim 16 \text{ d}$ after it (Johnston

¹ The artificial viscosity commonly used in SPH consists of two terms: a term that is linear in the velocity differences between particles, which produces a shear and bulk viscosity, and a term that is quadratic in the velocity differences, which is needed to eliminate particle interpenetration in high Mach number shocks. The parameters α_{SPH} and β_{SPH} control the linear and quadratic terms, respectively.

Table 1. Model parameters.

Be star parameters	
Mass of the Be star	$M_* = 10 M_\odot^\dagger$
Radius of the Be star	$R_* = 6 R_\odot^\dagger$
Effective temperature	$T_{\text{eff}} = 22800 \text{ K}^\ddagger$
Critical velocity	$V_{\text{crit}}(R_*) = 563.9 \text{ km s}^{-1}$
Wind velocity	$V_{\text{wind}} = 10^3 \text{ km s}^{-1}$
Wind mass-loss rate	$\dot{M}_{\text{wind}} = \begin{cases} 10^{-9} M_\odot \text{ yr}^{-1} & \text{("weak" case)} \\ 10^{-8} M_\odot \text{ yr}^{-1} & \text{("strong" case)} \end{cases}$
Mass injection rate to the disk	$\dot{M}_{\text{disk}} = 3.5 \times 10^{-9} M_\odot \text{ yr}^{-1} \S$
Be disk parameters	
Disk temperature	$T_{\text{d}} = 13680 \text{ K}^\parallel$
Disk thickness	$H(R_*)/R_* = 0.024$
Sound speed	$c_s = 13.8 \text{ km s}^{-1}$
Initial tilt angles	Misalignment by 45° from the binary orbital axis, with the polar axis projection of 19° from apastron [#] (see figure 1)
Pulsar and orbital parameters	
Pulsar wind power	$\dot{E}_{\text{PSR}} = 8.2 \times 10^{35} \text{ erg s}^{-1}^\dagger$
Orbital period	$P_{\text{orb}} = 1236.79 \text{ d} (= 3.386 \text{ yr})^{\dagger\dagger}$
Orbital eccentricity	$e = 0.87^\dagger$
Mass ratio	$q = 0.14 (M_{\text{PSR}} = 1.4 M_\odot)^\dagger$
Semimajor axis	$a = 181.82 R_* = 7.59 \cdot 10^{13} \text{ cm}^\dagger$

[†] Johnston et al. (1994).

[‡] The effective temperature of a B2 V star (Drilling & Landolt 2000).

[§] Mass ejection rate that gives the typical disk base density of $10^{-11} \text{ g cm}^{-3}$.

^{||} Assumed to be isothermal at $0.6 T_{\text{eff}}$ (Carciofi & Bjorkman 2006).

[#] Chernyakova et al. (2006).

^{††} Taken from Johnston et al. (1994). Recent timing analyses give $P_{\text{orb}} = 1236.72 \text{ d}$ (Wang et al. 2004).

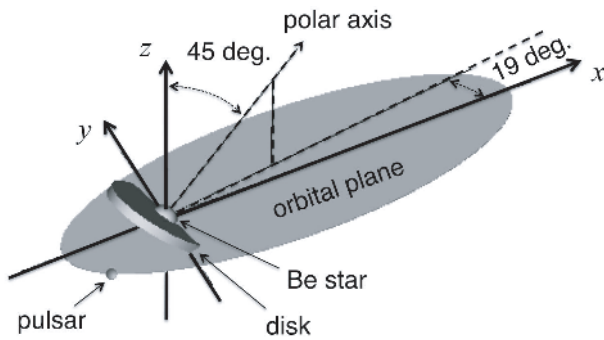


Fig. 1. Model configuration of the VHE gamma-ray binary PSR B1259–63/LS 2883. The binary orbit is in the x – y plane. The polar axis of Be star is tilted by 45° to the z -axis and has 19° of azimuth of tilt to the x -axis.

et al. 2005). We set the tilt angle between the binary orbital axis and the Be star’s polar axis to 45° as a parameter and the azimuth of tilt, i.e., the azimuthal angle of the Be star’s polar axis from the x -axis (the direction of apastron) to 19° , as suggested in Chernyakova et al. (2006) (see figure 1). In order to emulate the mass ejection from a Be star, we inject gas particles just outside the stellar equatorial surface at the rate of $3.5 \times 10^{-9} M_\odot \text{ yr}^{-1}$, which gives rise to a typical disk base

density of $10^{-11} \text{ g cm}^{-3}$. Once injected, gas particles interact with each other. As a result, most injected particles fall onto the Be star by losing angular momentum, but a small fraction of particles drift outwards, obtaining the angular momentum from the other particles, and form a disk.

Table 1 summarizes the parameters adopted in the following simulations. Note that not all parameters in table 1 are independent. For instance, all Be disk parameters, except for the tilt angles, are derived from other parameters.

2.3. Long-Term Evolution of the Be Disk under No Influence of the Pulsar Wind

Figure 2 shows the evolution of surface density from $t = 0$ to $12 P_{\text{orb}}$ (left panel) and the disk structure at $t = 12 P_{\text{orb}}$ (right panel). In figure 2, the volume density is integrated vertically and averaged azimuthally, while the velocity components are averaged vertically and azimuthally. Figure 2 left exhibits how a decretion disk forms if there is no influence of the pulsar wind. The disk density gradually increases with time and approaches an asymptotic distribution. The timescale of the disk growth is the viscous timescale, which is given by $[\alpha_{\text{SS}}(H/r)^2 \Omega_{\text{K}}]^{-1}$, where $\Omega_{\text{K}} = (GM_*/r^3)^{1/2}$ is the Keplerian angular frequency. For parameters summarized in table 1, this timescale is $\sim 12(\alpha/0.1)^{-1}(r/10R_*)^{1/2} \text{ yr}$. Thus, at $t \sim 12 P_{\text{orb}} \sim 40 \text{ yr}$, the disk is already fully developed,

as can be seen in figure 2 left.

We also note from figure 2 left that the disk extends beyond the periastron separation ($r \sim 24 R_*$) with no break in the radial density distribution. This suggests that the Be disk in long-period, highly-eccentric systems, like PSR B1259–63, is not truncated solely by the tidal torques of the neutron star, unlike disks in other Be–neutron star binaries with shorter orbital periods and lower eccentricities. In such systems, the neutron star passes through, and thus strongly disturbs, the Be disk around every periastron passage, as we will see in subsection 2.4.

As discussed in subsection 2.1, the Be disk is Keplerian. Figure 2 right shows that the angular velocity (the dashed line) for $r \lesssim 100 R_*$ is indistinguishable from the Keplerian rotation

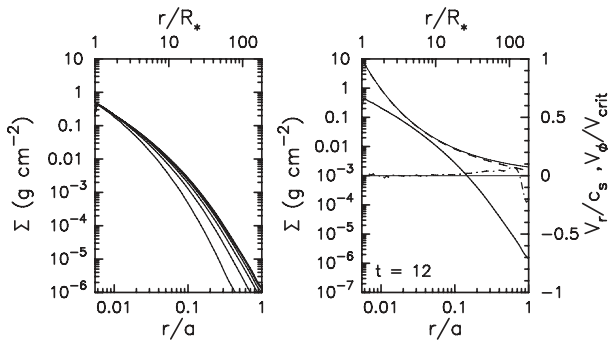


Fig. 2. Left: Surface density evolution from $t = 0$ to 12 in units of P_{orb} in a simulation where only the tidal interaction is taken into account. The interval of time between adjacent contours is 2 ($t = 2, 4, \dots, 12$ from bottom). Right: Disk structure at $t = 12$. The thick solid, dashed, and dash-dotted lines denote the surface density, the azimuthal velocity normalized by the stellar critical velocity, and the radial Mach number, respectively. For comparison, the Keplerian rotation distribution is shown by the thin solid line. In both panels, the density is integrated vertically and averaged azimuthally, while the velocity components are averaged vertically and azimuthally.

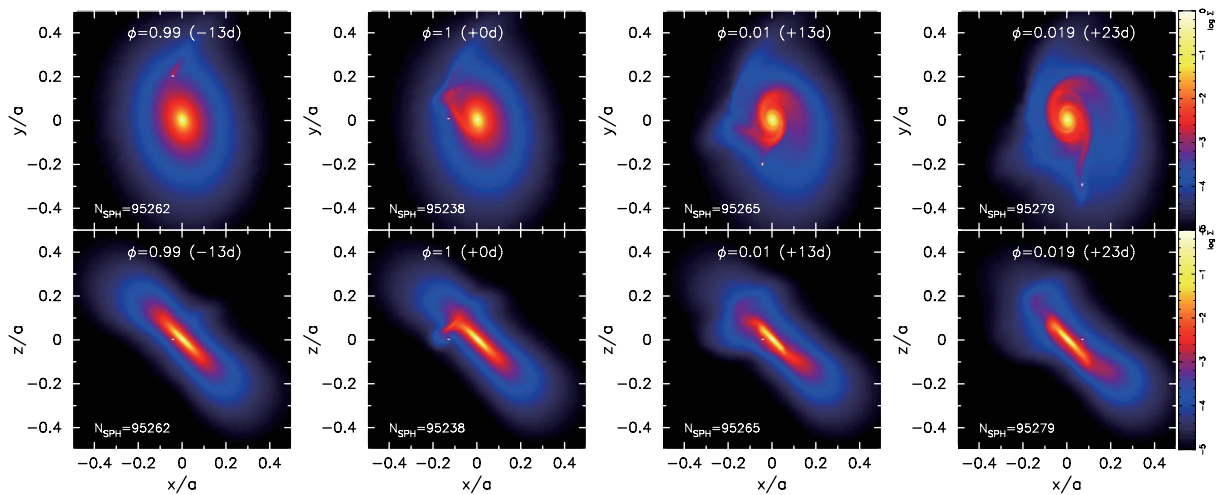


Fig. 3. Snapshots over one month around periastron passage for $\rho_0 = 10^{-11} \text{ g cm}^{-3}$, where ρ_0 is the base density of the Be disk. The upper panels show the column density along the z -axis (binary orbital axis) in cgs units, while the lower panels the column density along the y -axis (minor axis of the binary orbit). Annotated in each panel are the phase and time measured from periastron passage and the number of SPH particles.

(the thin solid line). The radial velocity, V_r , is very subsonic. It increases with radius, but even at $100 R_*$, V_r is still on the order of $\sim 0.1 c_s \sim 1 \text{ km s}^{-1}$, where c_s is the isothermal sound speed in the Be disk. These are typical features of viscous accretion disks around Be stars (e.g., Lee et al. 1991).

2.4. Tidal Interaction around Periastron Passage

Figure 3 provides snapshots over one month from 13 d before periastron passage ($\phi = 0.99$) to 23 d after it ($\phi = 0.02$). The upper and lower panels show, respectively, the column density in cgs units along the binary orbital axis (z -axis) and the minor axis of the binary orbit (y -axis). The first disk-passing event of the pulsar starts about 20 days prior to periastron passage, while the second event starts ~ 12 days after it. Each event lasts for ~ 2 weeks. As can be seen in the figure, the Be disk is strongly disturbed by these events. The disk is temporarily warped at each of these events via the tidal interaction with the pulsar. At the same time, the tidal interaction around periastron excites a two-armed spiral wave, via which angular momentum is removed from the disk (see, e.g., Artymowicz & Lubow 1994). This angular momentum transfer causes shrinking of the Be disk. Its radius gradually recovers afterward by viscous diffusion (Okazaki et al. 2002). Note that because of the cumulative effect of the tidal torques, the disturbance in the Be disk is larger after periastron passage, despite that the distance between the Be disk and pulsar is closest at the first disk-passing event.

3. Effects of the Pulsar Wind on the Circumstellar Environment of the Be Star

3.1. Numerical Setup

In order to see how the pulsar wind interacts with the Be disk and wind, we carried out simulations where both the pulsar and Be winds are now taken into account, using the data from the above-mentioned tidal simulation. In these new wind simulations, we turned on the pulsar and Be winds at a certain time,

after the Be disk was fully developed in the tidal simulation. We started the wind simulation at $t = 11.44 P_{\text{orb}}$, 74 days prior to periastron passage, much longer than the crossing time of the Be wind over the simulation volume, ~ 10 d. The relativistic pulsar wind crosses the simulation volume much faster. Although in the following we model the pulsar wind by a flow with the non-relativistic speed of 10^4 km s^{-1} , the crossing time for such a *slow* wind is only ~ 1 d. Therefore, the starting time does not matter as long as it is at least several tens of days before periastron passage.

In the tidal simulation, we emulated the Shakura–Sunyaev viscosity, while adopting variable α_{SPH} over space and time and fixing β_{SPH} to 0. In the wind simulation, however, this method would fail, allowing the particle interpenetration at strong shocks. Therefore, we adopted the standard values of the artificial viscosity parameters in the wind simulation, i.e., $\alpha_{\text{SPH}} = 1$ and $\beta_{\text{SPH}} = 2$. In the wind simulations, the energy equation is also different from the tidal simulation. In the latter, the gas was assumed to be isothermal, in order to emulate the temperature distribution in the Be disk. However, the purpose of the wind simulation is to study the structure of the wind–wind and wind–disk collisions. Therefore, in the wind simulation, we take account of optically thin radiative cooling. Numerical implementation of radiative cooling is done by adopting Townsend (2009)’s Exact Integration Scheme for radiative cooling, with the cooling function generated with CLOUDY 90.01 for an optically thin plasma with solar abundances (Ferland 1996).

With a large binary separation, the winds are likely to collide after the Be wind reaches a terminal speed. Thus, for simplicity, we assume that the winds coast without any net external forces, assuming in effect that gravitational forces are either negligible (i.e., for the pulsar wind) or are canceled by radiative driving terms (i.e., for the Be wind). The relativistic pulsar wind is emulated by a non-relativistic 10^4 km s^{-1} wind with the adjusted mass-loss rate so as to give the same momentum flux as a relativistic flow with the assumed energy, as in Romero et al. (2007).

In the following, for simplicity, we assume that all the spin down energy $\dot{E}_{\text{PSR}} = 8.2 \times 10^{35} \text{ erg s}^{-1}$ goes to the kinetic energy of a spherically symmetric pulsar wind. We also assume the Be wind to be spherically symmetric. Given a recent high-resolution spectroscopic study of LS 2883 suggesting a significantly earlier spectral type than the conventionally used spectral type B2 V (Negueruela et al. 2011), we take two different values of mass-loss rates, $10^{-9} M_{\odot} \text{ yr}^{-1}$ for the conventional spectral type B2 V and $10^{-8} M_{\odot} \text{ yr}^{-1}$ for an earlier spectral type. The mass injection rate to the Be disk is fixed to $3.5 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$.

3.2. Interaction between the Pulsar Wind and the Be Disk and Wind

Once winds are turned on, the faster pulsar wind soon fills up the whole simulation volume of $r \leq a$. Then, the slower Be wind pushes the pulsar wind back to the radii where the ram pressures of both winds are balanced. Without the Be disk, the shape of the interaction surface would be determined by the wind–wind collision. A key parameter would, then, be the ratio of wind momentum fluxes, given by

$$\eta = \frac{\dot{E}_{\text{PSR}}}{\dot{M}_{\text{wind}} V_{\text{wind}} c}, \quad (1)$$

where V_{wind} and \dot{M}_{wind} are the velocity and mass loss rate of the Be wind, respectively, and \dot{E}_{PSR} is the power of the pulsar wind. Taking $\dot{E}_{\text{PSR}} = 8.2 \times 10^{35} \text{ erg s}^{-1}$ for the spherically symmetric pulsar wind and $V_{\text{wind}} = 10^3 \text{ km s}^{-1}$ as the velocity of the Be wind, we have $\eta \sim 4.3$ for the “weak” wind case ($\dot{M}_{\text{wind}} = 10^{-9} M_{\odot} \text{ yr}^{-1}$) and $\eta \sim 0.43$ for the “strong” wind case ($\dot{M}_{\text{wind}} = 10^{-8} M_{\odot} \text{ yr}^{-1}$). Note that the pulsar wind dominates the Be wind in the former case, while the Be wind is about twice stronger than the pulsar wind in the latter case. Thus, having an accurate spectral type of the Be star is important to construct any satisfactory model for this VHE gamma-ray binary.

In a simple 2D model that ignores orbital motion, the ram pressure balance then implies that, for a binary separation D , the interface should be located at a distance

$$d = \frac{D}{1 + \sqrt{\eta}} \sim \begin{cases} 0.60 D & (\text{strong wind}) \\ 0.33 D & (\text{weak wind}) \end{cases} \quad (2)$$

from the Be star (Stevens et al. 1992; Cantó et al. 1996). In adiabatic shocks, the interaction surface approaches a cone with the half opening angle,

$$\theta = 2 (\tan^{-1} \eta)^{1/4} \sim \begin{cases} 102^\circ & (\text{strong wind}) \\ 69^\circ & (\text{weak wind}) \end{cases} \quad (3)$$

(Gayley 2009), measured from the Be star. Thus, the shock is wrapped around the Be star in the weaker wind case, while it is around the pulsar in the stronger wind case.

In PSR B1259–63/LS 2883, the presence of the Be disk adds extra complications in the interaction with the pulsar wind. Figure 4 shows how the interaction occurs around periastron in the weak (upper figure) and strong (lower figure) wind simulations. In each figure, the upper and lower panels, respectively, present the column density along the z -axis (binary orbital axis) and along the y -axis (minor axis or the binary orbit). The change in the Be disk structure from that in the tidal simulation (figure 3) is drastic. The pulsar wind now strips off an outer part of the Be disk on the side facing the pulsar, truncating it at a radius where the gas pressure of the disk is roughly comparable to the ram pressure of the pulsar wind. Since the pulsar wind has a velocity component perpendicular to the line connecting the Be star and the pulsar, the material in the disk outside this truncation radius is pushed sideways, forming a warped filament in the prograde direction. This feature is more remarkable in the weak wind simulation than in the strong wind simulation, because, unlike in the latter simulation, the Be wind in the former simulation is too weak to shield the disk from the pulsar wind.

The interaction between the pulsar wind and the Be-star circumstellar environment is more clearly seen in figure 5, in particular in the upper panels, where the volume density in the binary orbital plane (upper panels) and along the disk mid-plane (lower panels) is shown at the same phases as in figures 3 and 4. Comparing figure 5a for the weak wind case with figure 5b for the strong wind case, we note that the effect of the pulsar wind on the Be disk depends on the relative strength of the Be wind. In the case of a weak Be wind, the Be disk

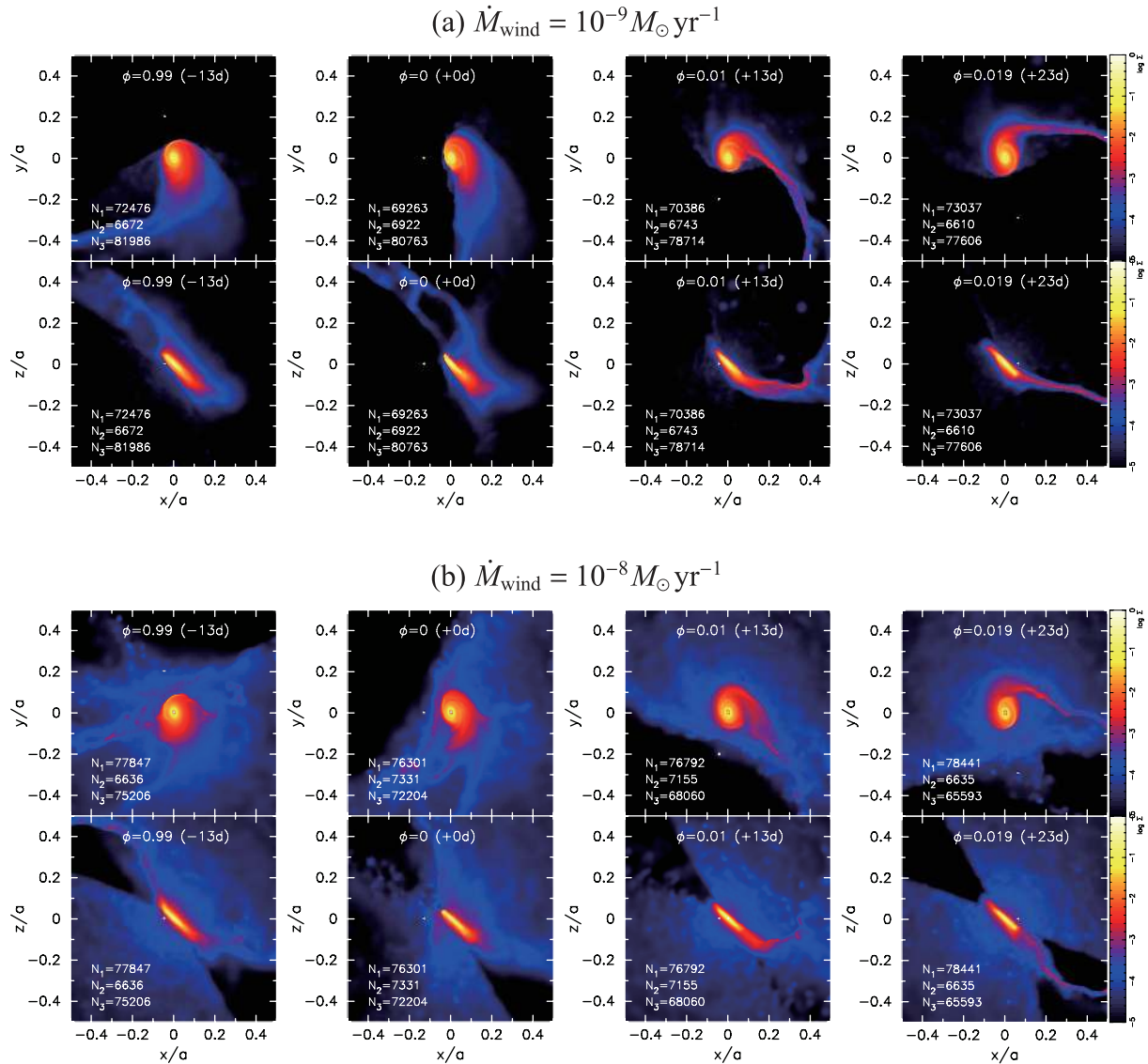


Fig. 4. Snapshots over one month around periastron passage from simulations in which both the pulsar wind and the Be wind are taken into account: (a) $\dot{M}_{\text{wind}} = 10^{-9} M_{\odot} \text{yr}^{-1}$ and (b) $\dot{M}_{\text{wind}} = 10^{-8} M_{\odot} \text{yr}^{-1}$, where \dot{M}_{wind} is the mass-loss rate through the Be wind. The mass-loss rate via the Be disk is $3.5 \times 10^{-9} M_{\odot} \text{yr}^{-1}$. In each panel, N_1 , N_2 , and N_3 annotated at the lower left corner are the numbers of particles in the Be wind, the pulsar wind, and the Be disk, respectively.

is not only truncated, but also strongly deformed by the pulsar wind's ram pressure around periastron. In contrast, little deformation is seen in the case of a strong Be wind, where the Be wind shields the Be disk from the pulsar wind.

In both simulations, the truncation of the Be disk is so efficient that the disk has a sharp density drop at the outer radius. At phases of closest encounter of the pulsar with the disk outer radius, the density at the outer radius is enhanced by shock by a factor of several, as can be seen in the lower panels of figure 5. This sharp truncation of the Be disk is likely a characteristic to be seen only in systems consisting of a Be star and an object with a strong wind. Although Be disks in binaries are, in general, tidally truncated, the density decrease beyond the disk outer radius is much more gradual in the tidal truncation. The density drop near the central star is due to ablation by the Be wind.

Despite these features related to the Be disk, the location and global shape of the interaction surface between the pulsar wind and the circumstellar environment of the Be star, i.e., the Be disk and wind, are consistent with that expected in the above analysis using a simple 2D model without the Be disk. We can see that in figure 5, where the density on the binary orbital plane is shown at the same phases as in figures 3 and 4, the apex location and conical shape of the interaction surface in the simulation, in general, agree with those given by equations (2) and (3).

4. Summary and Discussion

In this paper, we have numerically investigated the hydrodynamic interaction of the circumstellar environment of the Be star with the pulsar in the TeV binary PSR B1259–63/LS 2883.

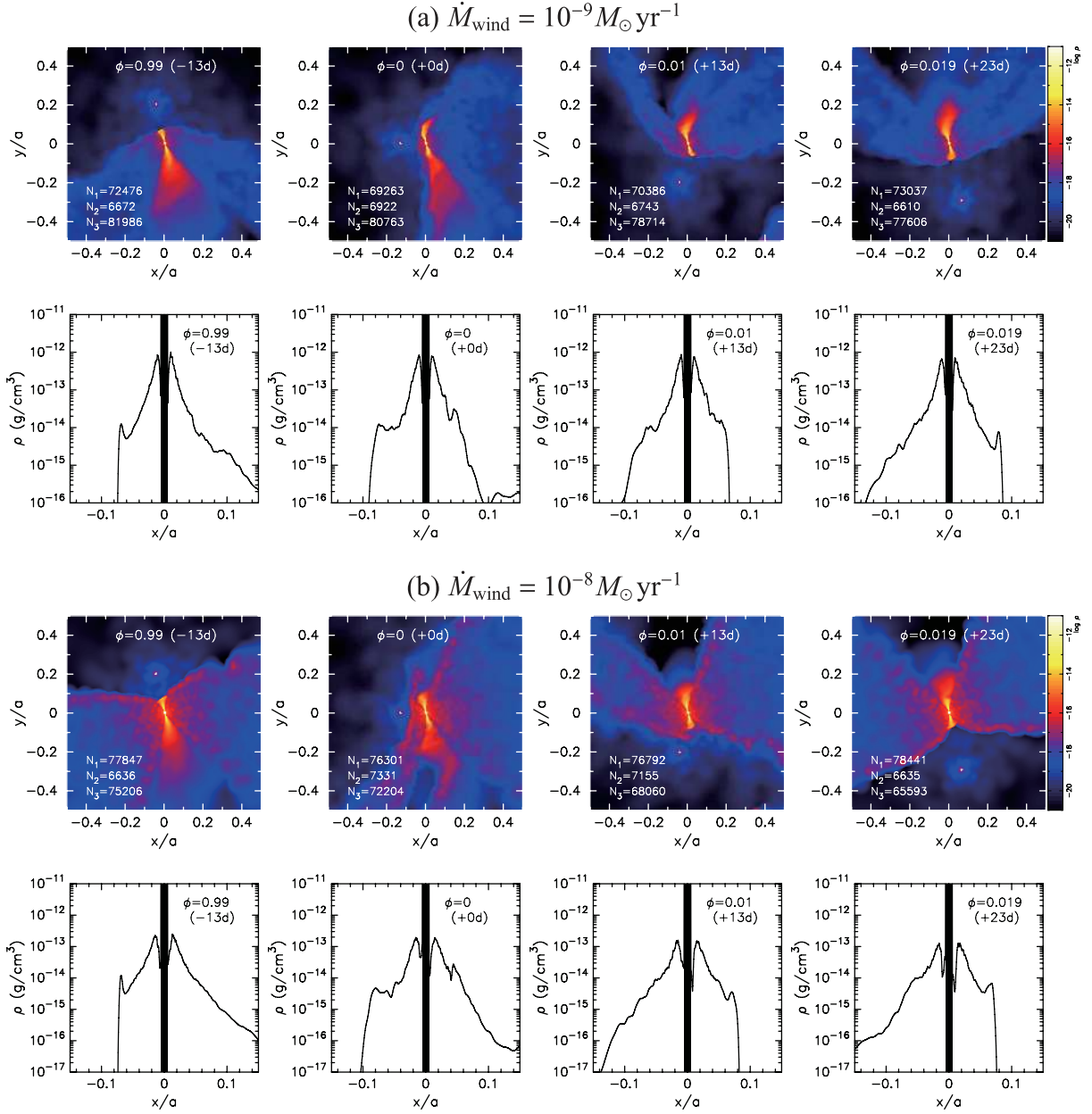


Fig. 5. Snapshots of the volume density in the orbital plane (upper panels) and along the disk mid-plane (lower panels): (a) $\dot{M}_{\text{wind}} = 10^{-9} M_{\odot} \text{yr}^{-1}$ and (b) $\dot{M}_{\text{wind}} = 10^{-8} M_{\odot} \text{yr}^{-1}$. In the lower panels of each figure, the $x > 0$ part corresponds to the $x > 0$ disk region (lower-right direction along the disk mid-plane) in the upper panels. Times of the plots are the same as in figures 3 and 4.

We broke the computation into two separate, but linked parts. The first part considers only the gravitational interaction with the pulsar, ignoring the effects of both the pulsar and Be star winds. One purpose of this part of simulation is to see how the Be disk evolves by the effect of viscosity and modulates by the tidal interaction with the pulsar. The other purpose is to set up the initial configuration for the second part of simulation, which takes account of both pulsar and Be winds.

From the first part, we confirmed the viscous decretion disk scenario that the material ejected from the stellar equatorial surface drifts outward due to the effect of viscosity, and forms a Keplerian disk. Note that the radial velocity caused

by viscous diffusion is very subsonic, so it takes more than a decade for this very wide system to have a fully developed Be disk. Without the pulsar wind, the Be disk is not truncated in such a highly eccentric system, unlike tidally truncated Be disks in binaries with lower eccentricities. Then, the pulsar passes through the disk twice an orbit, causing the tidal stream between the disk and the pulsar.

The second part focuses on the interaction between the pulsar wind and the circumstellar material of the Be star around periastron. It shows that once winds from the pulsar and the Be star are switched on, their effect soon becomes apparent in the structure of the Be disk. The pulsar truncates the Be disk on

the side facing the pulsar, sweeping up an outer part to a dense filament. The resulting structure of the disk is strongly asymmetric and phase dependent. The size of the truncated disk is so small that the pulsar never passes through the disk. Despite these features, the location and global shape of the interaction surface between the pulsar wind and the Be wind is well described by a simple 2D model.

We performed numerical simulations of Newtonian hydrodynamics without magnetic fields, although both the relativity and magnetic fields can play important roles on the dynamics of the system. A highly relativistic pulsar wind was emulated by a Newtonian wind by equating its momentum flux (thrust). Some studies of special-relativistic hydrodynamic simulations show that highly supersonic flows display extended cocoons with high pressure (Martí et al. 1997), which correspond to the shocked pulsar winds described in this study. The cocoons (or pulsar winds) have a smoother local structure in relativistic simulations than in non-relativistic simulations, because the inertia of a relativistic flow is smaller than that of a non-relativistic flow with the same thrust (Rosen et al. 1999). The global structure of the shocked pulsar wind, however, will not considerably be changed, since we have tuned the wind momentum flux in the simulation to be identical to that of relativistic wind of PSR B1259–63. The overall structure of the shock is basically determined by the balance of momentum fluxes of the flows. It is unlikely as well that the magnetic fields strongly affects the overall interaction feature, given that the kinetic energy is, in general, much greater than the magnetic field energy in pulsar winds near termination shocks (e.g., Kennel & Coroniti 1984). Introduction of magnetic fields into the simulation, however, may be needed to study the local structure in detail (McKinney 2006; Kommisarov et al. 2009; Nagataki 2009, 2011). Therefore, it will be important to extend our code to a relativistic regime (e.g., Monaghan & Price 2001; Ryu et al. 2006; Rosswog 2011) with magnetic fields (e.g., Price & Monaghan 2005) in the future so that we can self-consistently study these effects.

It is frequently discussed that particle acceleration occurs at the shock in the pulsar wind side and the accelerated, non-thermal electron–positron pairs emit radio to X-ray photons through synchrotron radiation while VHE (GeV–TeV) gamma-rays are produced by inverse-Compton scatterings of soft photons from the Be star (Tavani & Arons 1997; Sierpowska-Bartosik & Bednarek 2008; Takata & Taam 2009; Naito et al. 2010). It is also claimed that proton acceleration at the shock in the Be star side and VHE gamma-rays from pion decays that are produced through proton–proton interactions may be relevant to explain VHE gamma-rays (Kawachi et al. 2004; Chernyakova et al. 2006). From the point of view of the time-correlation among radio, X-rays, and VHE gamma-rays (Chernyakova et al. 2006), hadronic scenario may be favored. This is because the anti-correlation of fluxes between synchrotron emission and inverse-Compton scatterings is expected for the leptonic scenario, which seems to contradict the observations (Tavani & Arons 1997). To explain the observed correlation between X-ray and VHE emissions, therefore, Takata and Taam (2009) invoked the scenario that the observed emission in different orbital phases emanates from different magnetic field lines, giving rise to the pulsar wind

parameters changing with the orbital phase or that the power law index of the accelerated particles varies with the orbital phase. However, since these discussions depend on one-zone models adopted, the anti-correlation may not appear even for the leptonic scenario when we investigate a more realistic situation using the results from our simulations. For example, the previous leptonic models have assumed that the pulsar is confined by the shock (Tavani & Arons 1997; Takata & Taam 2009), whereas the result from the present simulations suggests that the shock geometry is sensitive to the mass loss rate from the Be star and to the orbital phase, as figure 5 shows. It is thus essential to calculate the high energy emission processes with a more realistic situation. We are planning to investigate it as our next step.

While a pulsar wind + stellar wind interaction model has also been proposed for other high-mass binaries with GeV–TeV gamma-ray emission (e.g., LS I +61 303 and LS 5039), PSR B1259–63 is so far the only such system with direct detection of pulsed radio emission. Johnston et al. (1996) showed that this radio emission disappears for a period of about 5 weeks centered on the periastron epoch of 1994 January 9. They attributed this as “most likely due to a combination of free–free absorption and severe pulse scattering in the Be-star disc.” But note that GHz radio emission is also expected to undergo strong free–free absorption by the much lower-density Be-star wind, since for typical wind parameters, the associated free–free optical depth can be of several *thousand* at orbital distances around an AU [see, e.g., equation (4) of Torres (2010)]. As such, the detection of radio pulses in PSR B1259–63 may actually be due to an observer perspective that is nearly aligned to the major axis of the binary orbit, such that during most of the orbit around apastron, the observed radio emission propagates mostly through the low-density shock cone surrounding the relativistic pair wind. In this scenario, the disappearance of radio emission near periastron could actually be attributed to the rapid rotation of the shock cone away from the viewer’s line of sight, causing strong free–free attenuation of the radio emission by the Be-star wind and its associated shock cone. A similar viewer perspective has been used to explain the several-week-long attenuation of X-ray emission in the colliding wind binary η Carinae (Okazaki et al. 2008). Our future work will further explore this shock-cone scenario as an alternative to the standard Be-disk attenuation model for the periastron disappearance of pulsar radio emission.

Observations of TeV binaries in high energy bands provide important information on the type of interaction and the emission mechanisms. For TeV binaries with Be stars, however, the high energy bands are not the sole window to probe these systems. As mentioned in section 2, the optical emission lines and infrared excess arise from the Be disk, while the Be wind emits UV radiation. Observations in these bands are thus suitable to study the effects of the pulsar wind on the circumstellar environment of the Be star. Particularly, spectroscopic and polarimetric observations in the optical and infrared can provide valuable information on the structure and dynamics of the disturbed Be disk, which gives clues for the interaction between the pulsar wind and the Be disk. UV observations, on the other hand, are adequate for

studying the strongly asymmetric Be wind around periastron (see figure 5 for the asymmetric structure of the Be wind). For a better understanding of TeV binaries with Be stars, including PSR B1259–63, multi-band observations are highly desirable.

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