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Toward an Understanding of the Periastron Puzzle of PSR B1259$-$63 [*]

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Abstract Efforts are made to understand the timing behaviors (e.g., the jumps in the projected pulsar semimajor axis at the periastron passages) observed in the 13-year monitoring of PSR B1259–63. Planet-like objects are suggested to orbit around the Be star, which may gravitationally perturb the (probably low mass) pulsar when it passes through periastron. An accretion disk should exist outside the pulsar's light cylinder, which creates a spindown torque on the pulsar due to the propeller effect. The observed negative braking index and the discrepant timing residuals close to periastron could be related to the existence of a disk with a varying accretion rate. A speculation is presented that the accretion rate may increase on a long timescale in order to explain the negative braking index.

Key words: pulsars: individual: PSR B1259$-$63 — binaries: general — stars: neutron — stars: early-type

1 INTRODUCTION

Pulsars are clocks of great precision with which one can probe astrophysical processes. The pulsar clock technique has been very successful in the studies of dynamical systems (both general relativistic and Newtonian) and pulsar interiors (glitches).

Thirteen years of timing data have been obtained for the unique pulsar PSR B1259–63 which has a massive companion with a circumstellar disk (Wang et al. 2004). Unfortunately, as concluded by Wang et al. (2004), a plausible mechanism to account for the observed timing behavior still has not been forthcoming.

PSR B1259–63 was discovered in a survey of the Galactic plane by Johnston et al. (1992), but determining its timing properties has not been easy. Manchester et al. (1995) fitted the timing data by introducing $\Delta P/P \sim 10^{-9}$ at each periastron which they attributed to propeller torque spindown. Wex et al. (1998) presented a timing model with the inclusion of changing $\dot{\omega}$ and $\dot{x} = \mathrm{d}/\mathrm{d}t(a_p \sin i)$ terms, but still failed to accurately describe the 13-year dataset (Wang et al. 2004).

Wang et al. (2004) introduced *Jumps* in the projected semimajor axis $\Delta x = \Delta(a_p \sin i)$ at periastron. The rms residual in the orbit-jump model is only about half that in the ν-$\dot{\nu}$-jump model, even though there are four more free parameters in the latter than in the former.

PSR B1259–63 may accrete from a dense circumstellar environment at its periastron passage. Observations of the pulsar enable one to probe the circumstellar medium in such a case.

Recent studies show that propeller disks around such compact stars may play an important role in various astrophysical objects, including anomalous X-ray pulsars and soft γ-ray repeaters (AXP/SGRs, e.g., Chatterjee et al. 2000) and compact center objects (CCOs, Xu et al. 2003).

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Recently, evidence for a fossil disk around an anomalous X-ray pulsars, 4U 0142+61, has been proposed (Wang et al. 2006) after the detection of emission at two mid-infrared bands ($4.5\,\mu$m and $8.0\,\mu$m). [1] PSR B1259–63, as an ideal "laboratory", can be studied in great detail; it is the *only* known case of a pulsar's disk with material replenishment (from the wind-disc of the Be star).

2 THE X-JUMP SCENARIOS PROPOSED

The inclination of the system to our line of sight angle, $i = \sin^{-1}\{[f(M_p)(M_p+M_c)^2]^{1/3}/M_c\}$, is $\sim 35^{\rm o}$ ($i = 32^{\rm o} \sim 36^{\rm o}$ for $M_p/M_\odot = 0 \sim 1.4$) for the companion Be star with mass $M_c = 10M_\odot$ and mass function $f(M_p) = 1.53M_\odot$. The total orbital angular momentum L for a Keplerian orbit reads,

$$\begin{aligned} L &\simeq M_pM_c\sqrt{\tfrac{G(1-e^2)a_p}{M_p+M_c}} = M_p\sqrt{\tfrac{G(1-e^2)M_cx_p}{\sin i}} \\ &\sim 3\times10^{53}M_{p1}M_{c10}^{1/2}\ \mathrm{g\,cm^2\,s^{-1}}, \end{aligned} \tag{1}$$

for the PSR B1259$-$63 system when $M_p \ll M_c$ ($i \sim 35^{\rm o}$), where a_p is the semimajor axis and the projected pulsar semimajor axis $x_p = a_p\sin i$, $M_p = M_\odot M_{p1}$, $M_c = 10M_\odot M_{c10}$ ("p" and "c" denote the *p*ulsar and the *c*ompanion Be star, respectively).

The spin angular momentum S_c of the Be star can be approximated by

$$\begin{aligned} S_c &\sim 0.4M_cR_c^2\Omega_c \sim 0.4\sqrt{G}fM_c^{3/2}R_c^{1/2} \\ &\sim 8\times10^{52}f_{0.5}M_{c10}^{3/2}R_{c6}^{1/2}\ \mathrm{g\,cm^2/s}, \end{aligned} \tag{2}$$

where the Be star is rotating at f times the centrifugal breakup frequency $\Omega_k \simeq \sqrt{GM_c/R_c^3}$, $f = 0.5f_{0.5}$, the Be star radius $R_c = 6R_\odot R_{c6}$. It is evident that the magnitude of L and that of S_c are comparable. It would not be difficult to change $\boldsymbol{L}$ (while keeping $|\boldsymbol{L}|$ almost the same) via occasional spin-orbit coupling (i.e., transferring orbital to spin angular momentum, or vice versa).

As noted by Wang et al. (2004), it is not likely that the x-jumps are changes in semimajor axis a_p. Rather, if we assume a constant a_p, then a $\Delta x = \Delta(a_p\sin i)$ requires an inclination angle change per periastron passage,

$$\Delta i = (\Delta x_p/x_p)\tan i \sim 3^{\rm o}\times10^{-4}\Delta x_{p10}, \tag{3}$$

where $\Delta x_p = 10\mathrm{ms}\ c\ \Delta x_{p10}$, with c the speed of light. If $|\boldsymbol{L}|$ is the same, the orbital angular momentum change ΔL, which is nearly perpendicular to $\boldsymbol{L}$, is

$$\Delta L \simeq 5.4\times10^{-6}\Delta x_{p10}L \sim 10^{48}\Delta x_{10}M_{p1}M_{c10}^{1/2}\ \mathrm{g\,cm^2\,s^{-1}}, \tag{4}$$

which shows $\Delta L \ll L$.

No Δi can occur if the mass distribution is symmetric with respect to the orbital plane. Note that Δi should have only one sign as long as the asymmetric pattern of mass-distribution is nearly the same (e.g., the case in which an asymmetric pattern originates only from an angle between the spin axis of Be star and the orbit normal). One must therefore find mechanisms that can cause an asymmetric, time-variable mass distribution.

Planets around the Be star?

Neither observational nor theoretical conclusions of massive star formation and evolution are certain. Nevertheless, a general view for B-spectral class stars could be as follows: After gravitational collapse of a molecular cloud, a massive star may form inside the cloud, with a dense, dusty circumstellar disk and strong bipolar outflow. The star could then become a so-called young Herbig Be star if it is still embedded in a nebula (Fuente et al. 2003). It would then evolve to be a normal Be star (like SS 2883, the companion to PSR B1259–63, without a nebula). The outflow is weak (or there is a tenuous polar wind) and its

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[1] However, no emission is detected at $24\,\mu$m and $70\,\mu$m, at limits of 0.05 mJy and of 1.5 mJy, respectively (Bryden et al. 2006), for the famous pulsar-planetary system (PSR B1257+12). The observations of Wang et al. (2006) and Bryden et al. (2006) were expected in Xu (2005), where it was suggested that at least part of the millisecond pulsars are of supernova origin via accretion-induced collapses, and that quark planets could have been ejected from protoquark stars.

disk becomes less and less massive. Finally, the star becomes a B star when the disk disappears (like the companion of PSR J0045–7319).

One may speculate that planet-like objects (planets, proto-planets, or planetesimals) could form in the dusty disks of a Be star after the first supernova of the binary, with highly eccentric orbits. The number of such objects and thus the total mass decrease with time due to their being captured, disintegrated, or evaporated by their hot Be stars (or via the interaction with the disk-wind).

Evidence for planetesimals (with asteroidal size) falling onto a very young ($\sim 10^5$ years) Herbig Be star LkH$_\alpha$234 has recently been reported (Chakraborty, Ge & Mahadevan 2004). More than 100 extra-solar planets, with masses $\sim (1-10)M_{\rm Jupiter}$, have been discovered by radial-velocity surveys (Tremaine & Zakamska 2004). Alternatively, planets formed before the first supernova could have probably remained if the supernova occurs far way from its companion in a very highly eccentric orbit.

There might be many planet-like objects (planets, proto-planets, planetesimals, or even brown dwarfs) orbiting around the Be star; but the exact number could hardly obtained by observation or calculation. PSR B1259–63 would be perturbed by the gravity of one or more such planet-like bodies near its periastron if they orbit the Be star with much smaller semimajor axes than the pulsar's, a_p. However, if the pulsar is thought to have a conventional, normal mass $\sim 1.4M_\odot$, then the perturbation should be negligible. Nonetheless, pulsars could be quark stars having masses much smaller than $\sim M_\odot$ (Xu 2005a,b). Hence the perturbation might be strong enough for the observed x-jumps if PSR B1259–63 is a low-mass quark star.

The orbital angular momentum of a planet around the Be star is $L_{\rm planet} \sim 2\times10^{47} M_J a_{100}^{1/2}$ g cm^2 s^{-1}, where the planet mass is $M_J \times M_{\rm Jupiter}$ and its semimajor axis is $a_{100}\times 100R_\odot$. From Equation (4) one sees $\Delta L < L_{\rm planet}$ if $M_J \ll M_p < 0.2M_J a_{100}^{1/2}\Delta x_{10}^{-1} M_\odot$, and a significant x-jump of a low-mass quark star is possible through the gravitational perturbation of planet-like objects. An encounter of a planet and the pulsar per periastron passage would produce (1) a large exchange of angular momentum between the orbits (thus an x-jump) and (2) a large change in the orbital elements of the planet (thus a higher eccentricity of the planet). The migration inwards due to the interaction of the planets with the disk would increase the possibility of encounter and may decrease the eccentricity, but the pulsar might in turn "eject" the planet after the encounter.

It may be hard to believe that planets would exist around a Be star since it is conventionally thought that planets are formed by accretion over $\sim 10^7$ years. However, planet formation could be speeded up by the fragmentation of an unstable disk (Boss 2003).

Another possibility that can not be ruled out is that the planets could be strange planets (i.e., strange quark matter with planetary masses) which were born during the first supernova explosion. This kind of planet can not evaporate, and thus would exist for a long time.

Asymmetric mass distribution of the Be star?

Besides the suggestion above, two more scenarios are speculated for the x-jumps. The periastron separation between the pulsar and the Be star is $r_p \sim 24R_c \gg R_c$. If the Be star has stellar oscillations leading to multipoles of mass distribution, then the torque acting on the pulsar may result in an x-jump at each periastron passage. As no torque is related to the monopole term, the quadrupole term would be important for x-jumps. It is worth noting that the oscillations could be enhanced if they are excited resonantly (e.g., when the ratio of the orbital period to an oscillation period is an integer) by the orbiting pulsar (Witte & Savonije 1999). Chaotic orbital dynamics near the periastron could also be possible in this case (Mardling 1995), which would result in a random transfer of angular momenta between comparable values of L and S_c (Eq. (1-2)). Additional study of the structure and evolution of massive stars, especially their oscillation behaviors, might further elucidate the periastron puzzle in this scenario.

Asymmetric mass distribution of the disk of SS 2883?

The existence of a Be star disk is an obvious asymmetry with respect to the orbital plane, but this cannot cause sign-changed x-jumps if the disk is nearly homogeneous. However, if a density-wave pattern can be excited (e.g., by the pulsar or planets) in the disk, like the case of Saturn's ring structure affected by the satellite Mimas, then angular momentum may transfer between the orbiting pulsar and the disk at periastron passages, which might result in x-jumps, but it seems difficult to limit the duration of this effect (if it exists) only to the time when the pulsar passes near the Be star's disk.

3 PROPELLERS IN A RADIO PULSAR PHASE?

One strange feature of this system is that the braking index is about -37 after 13 years of timing of PSR B1259–63, while the indices are between 1.4 and 2.9 ($\lesssim 3$) for six pulsars, with great certainty (Xu & Qiao 2001; Livingstone et al. 2006). It is true that the data-fitting is improved significantly when x-jumps at periastron passages and a pulsar glitch near MJD 50691 are included, whereas a few residual points close to the periastron are still systematically discrepant. This could be due to errors in the DM correction (Wang et al. 2004). An alternative explanation presented below for the unusual braking index as well as the timing residuals is that the pulsar may capture SS 2883's circumstellar matter to form a pulsar disk which results in a torque that is antiparallel to the pulsar's spin (the viscosity timescale of accretion disk could be of the order of years).

By observing the un-pulsed radio emission at four different bands, Johnston et al. (2005) concluded that the pulsar passes through the dense circumstellar disk of the Be star just before and just after periastron. It seems intuitive that accretion would occur when the pulsar passes through the disk. Accretion of in-falling matter with negligible angular momentum was considered by Kochanek (1993) and Manchester et al. (1995), in which the pulsar loses its angular momentum in order for the in-falling matter to obtain enough angular momentum to escape. Besides spinning down the pulsar, the zero-angular-momentum accretion may also affect pulsar orbit parameters through frictional drag (Wex et al. 1998). However, if the material captured by the pulsar carries significant angular momentum, disk accretion around the pulsar occurs. To make this more precise, one should calculate the circularization radius to see if the accreted matter has sufficient angular momentum for disk formation.

Accretion disk formation around PSR B1259–63.

The cylindrical radius, $r_{\rm acc}$, within which a pulsar with mass M_p can gravitationally capture material with a relative velocity $v_{\rm rel}$, can be estimated as (e.g., Lipunov 1992)

$$r_{\rm acc} \simeq GM_p/v_{\rm rel}^2 \sim 1.3 \times 10^{12} M_{p1} v_{\rm rel100}^{-2}\ {\rm cm}, \tag{5}$$

where $v_{\rm rel100} = v_{\rm rel} \times 100\ {\rm km\ s^{-1}}$. Note that the radius of PSR B1259–63's light cylinder is only $r_{\rm lc} = cP/(2\pi) = 2.3 \times 10^8$ cm. If the accreted material is from the Be star's wind with velocity $v_w \sim 500\ {\rm km\ s^{-1}}$, the circularization radius (Frank et al. 2002) in this case is only $R^{\rm w}_{\rm circ} \simeq G^3 M_p^3 \Omega^2_{\rm orb}/v_w^8 \sim 200 M_{p1}^3$ cm, which is much smaller than the pulsar's radius, where $\Omega_{\rm orb} = 2\pi/P_{\rm orb}$. Therefore, a disk around the pulsar is not likely to form by accretion from the Be star's wind [2]. However, if the gas in the Be star's disk moves in a Keplerian orbit and the pulsar has an orbital velocity near periastron ($r_p \sim 24R_c \sim 10^{13}$ cm) of $v_{\rm peria} = \sqrt{GM_c(2/r_p - \sin 35°/x_p)} \sim 157\ {\rm km\ s^{-1}}$, the accretion radius $r_{\rm acc}$ is different for material inside and outside periastron. The Keplerian velocity at periastron is $v_k(r_p) = \sqrt{GM_c/r_p} \sim 115\ {\rm km\ s^{-1}}$, but the sonic speed of the line-emission disk with temperature $\sim 10^4$ K is only $v_s \sim 10\ {\rm km\ s^{-1}} \ll v_k$. Therefore, we will neglect the pressure of disk material in the following consideration. Assuming that the pulsar orbits in the same direction as the circumstellar medium around the Be star, for $M_p = 1M_\odot$, the Keplerian velocity at the accretion boundary outside or inside the periastron is $v_k = \sqrt{GM_c/(r_p \pm r_{\rm acc})}$. Using Equation (5) and $v_{\rm rel} \simeq v_k - v_{\rm peria}$, one can find $r_{\rm acc} \sim 3.8 \times 10^{12}$ cm and $\sim 6.7 \times 10^{12}$ cm for outside and inside the periastron, respectively. The specific angular momentum [3] is then of the order of $l \sim r_{\rm acc} v_{\rm rel}$, and the circularization radius is then $R^{\rm d}_{\rm circ} = l^2/(GM_p) \sim 10^{11}$ cm for $r_{\rm acc} \sim 10^{12}$ cm, which is much larger than $r_{\rm m}$ (Fig. 1, $r_{\rm lc} \sim 10^8$cm). One can still have $R^{\rm d}_{\rm circ} \sim 10^{11} \gg r_{\rm lc}$ even for a small pulsar mass of $M_p = 10^{-3} M_\odot$ ($r_{\rm acc} \sim 7.7 \times 10^9$ cm and $\sim 7.2 \times 10^{12}$ cm for outside and inside the periastron, respectively), in this case. Therefore, an accretion disk can form around the pulsar if the circumstellar disk of the Be star is Keplerian, even without the inclusion of magnetospheric interaction [4], since the circularization radii are usually much larger than the magnetospheric ones.

Propeller torque and the pulsar's spindown.

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[2] Even in the case of negligible momentum of accreting wind, a disk might form due to interaction between the infalling medium and the rapidly spinning pulsar's magnetosphere, by which the rotational angular momentum of the pulsar is transferred to the accreted material.

[3] Note that $v_k({\rm outside}) \simeq 98\ {\rm km\ s^{-1}} < v_{\rm peria} < v_k({\rm inside}) \simeq 201\ {\rm km\ s^{-1}}$ in this case.

[4] This interaction transfers angular momentum from pulsar to accretion matter, and thus favors disk formation.

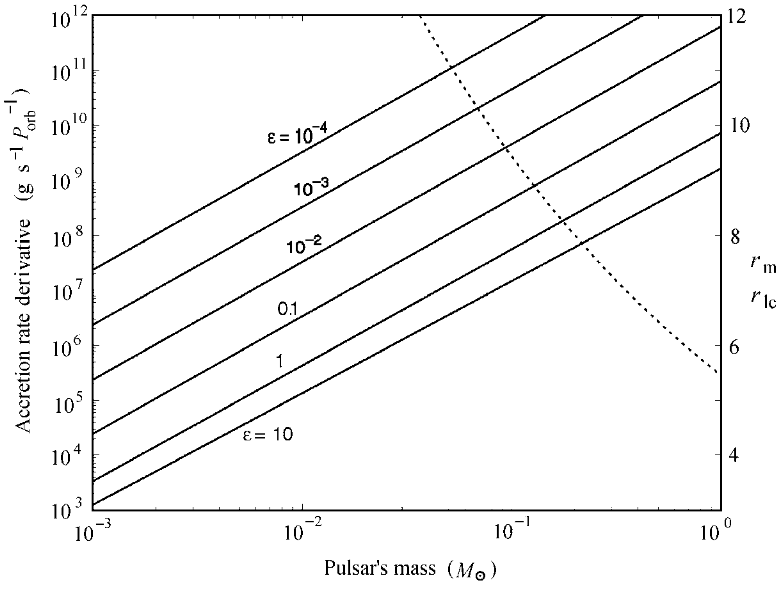

Fig. 1 Accretion rate derivative (solid lines, in units of $\mathrm{g} \cdot \mathrm{s}^{-1} \cdot P_{\rm orb}^{-1}$), $\ddot{M}$ is computed as a function of pulsar's mass in order for the observed braking index to be –36.7 by Eq. (10). Each curve is for a different value of ε, the meaning of which can be found in Equation (9). In the calculation, we choose an average accretion rate of $\dot{M} = (20\ {\rm days}/P_{\rm orb})\dot{M}_0$, assuming the pulsar accretes for 20 days with a rate $\sim \dot{M}_0$. The dotted line shows the magnetospheric radius r_m in units of the light cylinder radius $r_{\rm lc}$. It is shown that $r_m/r_{\rm lc} \simeq 5.5$ for $M_p = M_\odot$, but increases as M_p decreases.

For simplicity, we assume that the angular momentum of the pulsar's disk is parallel to the spin axis of PSR B1259–63. If the circumstellar matter around the Be star is a hydrogen plasma, the mass density would be (Wex et al. 1998) $\rho(r) \simeq 7.5 \times 10^{-12}(r/R_c)^{-4.2}$ g cm^{-3}, where the Be star's radius $R_c \sim 6R_\odot$. When the pulsar passes through the dense disk near periastron, the accretion rate could be

$$\dot{M}_0 \sim \pi r_{\rm acc}^2 v_{\rm rel}\rho(24R_c) \sim 5 \times 10^{15} M_{p1}^2\ {\rm g\, s^{-1}}, \tag{6}$$

where we choose $v_{\rm rel} \sim \sqrt{(v_k - v_{\rm peria})^2 + v_s^2} \sim 50$ km s^{-1} for the following estimates. The pulsar could then accrete $\Delta M \sim 9 \times 10^{21} M_{p1}^2$ g for ~ 20 days near each periastron passage. An effective accretion rate averaged over the orbital period would then be $\dot{M} \simeq (20\ {\rm days}/P_{\rm orb})\dot{M}_0$.

The magnetic momentum can be estimated from $\Omega = 2\pi/P$ and $\dot{\Omega}$,

$$\mu \simeq \left(\frac{4\pi c^3}{5} \frac{-\dot{\Omega}}{\Omega^3} \bar{\rho} R_p^5\right)^{1/2} \sim 3 \times 10^{29} M_{p1}^{5/6}\ {\rm G\, cm^3}, \tag{7}$$

for a pulsar with radius R_p and mass M_p (averaged density $\bar{\rho} = 3M_p/(4\pi R_p^3) \sim 4 \times 10^{14}$ g cm^{-3} for quark stars with mass $\lesssim M_\odot$). The magnetospheric radius would then be

$$r_m \simeq (2GM_p)^{-1/7} \mu^{4/7} \dot{M}^{-2/7} \sim 1.2 \times 10^{13} M_{p1}^{1/3} \dot{M}^{-2/7}\ {\rm cm}, \tag{8}$$

which is likely to be much larger than $r_{\rm lc}$, and is thus $\gg r_{\rm co}$. A lower pulsar mass results in a higher ratio of $r_m/r_{\rm lc}$ (Fig. 1). This means that an accretion with a rate of even $\dot{M} \simeq 5 \times 10^{15}$ g s^{-1} can not drive matter to reach the pulsar surface, but is in a propeller phase. That $r_m \gg r_{\rm lc}$ could be a direct cause for PSR B1259–63's being a *radio* pulsar. Magnetospheric interaction between a pulsar and its surrounding disk is still not well understood. Menou et al. (2001) discussed disk torque for the case of $r_{\rm m} \sim r_{\rm lc}$, and recognized that the torque would likely be largely reduced or entirely suppressed if $r_{\rm m} \gg r_{\rm lc}$. Both the magnetodipole radiation and the propeller effect may result in the pulsar's spindown,

$$\dot{\Omega} = -A\Omega^3 - \varepsilon B \dot{M}^{3/7}\Omega, \tag{9}$$

with

$$A = 2\mu^2/(3c^3 I), \;\; B \simeq 2.88 \times 10^{26} M_{p1}^{2/3}/I,$$

where $I = 2M_p R^2/5$ is the moment of inertia, and the propeller torque, $\dot{\Omega} = -2\dot{M} r_m^2 \Omega/I$ of the second term in Equation (9), proposed by Menou et al. (1999), is applied, with a suppression factor introduced, ε. The magnetodipole torque is generally smaller but almost of the same order, as the propeller torque for $\varepsilon = 1$. In other words, the magnetodipole torque is generally larger than the propeller torque for $\varepsilon < 0.1$. The calculation of μ in Equation (7) is therefore consistent.

One can also calculate the braking index from Equation (9),

$$n = \frac{\Omega\ddot{\Omega}}{\dot{\Omega}^2} = -\frac{\Omega}{\dot{\Omega}^2}\Big[(3A\Omega^2 + \varepsilon B \dot{M}^{3/7})\dot{\Omega} + \frac{3}{7}\varepsilon B \Omega \dot{M}^{-4/7}\ddot{M}\Big]. \tag{10}$$

Since $\dot{\Omega} < 0$ it is evident that the braking index $n > 0$ for an accretion with constant rate, $\ddot{M} = 0$. However, the observed index is negative, $n = -36.7 < 0$, which means the effective accretion rate increases, $\ddot{M} > 0$.

Since the accretion rate derivative, $\ddot{M}$, and the suppression factor, ε, are two parameters hitherto unknown, let us find the relationship between them in order to explain the observed braking index $n = -36.7$. The results, numerically calculated via Equation (10), are shown in Figure 1. It is found that high ε and/or low pulsar-mass (M_p) would result in a small $\ddot{M}$. The averaged accretion rate of $\dot{M} = (20\ {\rm days}/P_{\rm orb})\dot{M}_0 \sim 8 \times 10^{13}\ {\rm g\ s^{-1}}$. PSR B1259–63 could be a low-mass quark star (with $M < 0.1M_\odot$) if $\varepsilon \lesssim 10^{-4}$ and $\ddot{M} < 10^{12}\ {\rm g\ s^{-1}}/P_{\rm orb}$.

The change of accretion rate on long timescales ($\gtrsim P_{\rm orb}$) was considered in the previous paragraph. It is natural to suggest that the accretion rate also increases before (but decays soon after) the periastron, e.g., exponentially, $\dot{M} \sim \dot{M}_0 e^{\pm t/\tau}$ on a short timescale $\tau < P_{\rm orb}$. This short-term variation of $\dot{M}$ could significantly affect the timing behaviors close to the periastron, which can be the reason that a few timing points have systematic discrepancies at periastron passages.

4 CONCLUSIONS AND DISCUSSION

Several scenarios for understanding the x-jumps at the periastron are presented, including planet-like objects around the Be star, asymmetric mass-distribution by the Be star's oscillations, and a density-wave pattern in the Be star's disk excited by objects orbiting the Be star. The first one could be the most likely one. We showed that an accretion disk forms around the rapidly rotating, strongly magnetized pulsar because the circularization radius is much larger than the radius of the pulsar's magnetospheric radius. The inner region of the disk is also beyond the light-cylinder, provided that the pulsar's accreted matter is replenished in the Keplerian disk of the companion SS 2883. Propeller torque would therefore result in the pulsar's spindown, besides that due to magnetodipole radiation, though it may be suppressed by a factor ε. The accretion rate should increase on a timescale of $\gtrsim P_{\rm orb}$ in order to explain the negative braking index $n = -36.7$, but the reason for this increase is not certain (for example it may be due to a secular changing of $a_{\,p}$ via tidal effects). Timing models with the inclusion of disk propeller effects would be necessary for fitting the timing data, and further observations would in turn check the model.

The PSR J0045–7319 binary system (Kaspi et al. 1996) is similar to PSR B1259–63, in which tidal interactions may also be enhanced near the periastron in that system (Witte & Savonije 1999). Then, why are their timing behaviors so different? This could be due to (1) a difference in the pulsar mass (the mass of PSR J0045–7319 might be much higher than that of PSR B1259–63, $M_{1259} \ll M_{0045}$), (2) a difference in the companion's mass ($M^c_{1259} > M^c_{0045}$), and (3) different evolutionary stages of the companions (a younger Be star may oscillate with a higher amplitude, or, planet-like objects could have been captured or evaporated by an old B star).

A large negative braking index might be a feature of a disk with increasing mass. Long-term timing of AXP/SGRs and CCOs is proposed to see if there are propeller disks around them (the index $n > 0$ for a decaying disk). In addition, this work has implications for studying *long*-term timing behavior of radio pulsars with propeller disks formed from either supernova fall-back onto young neutron stars or accretion of interstellar medium by old neutron stars (probably near the death line in the $P - \dot{P}$ diagram).

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