PSR B1828–11: a precession pulsar torqued by a quark planet?

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ABSTRACT
The pulsar PSR B1828–11 has long-term, highly periodic and correlated variations in both pulse shape and the rate of slow-down. This phenomenon may provide evidence for precession of the pulsar as suggested previously within the framework of free precession as well as forced one. On a presumption of forced precession, we propose a quark planet model to this precession phenomenon instead, in which the pulsar is torqued by a quark planet. We construct this model by constraining mass of the pulsar ($M_{\text{psr}}$), mass of the planet ($M_{\text{pl}}$) and orbital radius of the planet ($r_{\text{pl}}$). Five aspects are considered: derived relation between $M_{\text{psr}}$ and $r_{\text{pl}}$, movement of the pulsar around the center of mass, ratio of $M_{\text{psr}}$ and $M_{\text{pl}}$, gravitational wave radiation timescale of the planetary system, and death-line criterion. We also calculate the range of precession period derivative and gravitational wave strength (at earth) permitted by the model. Under reasonable parameters, the observed phenomenon can be understood by a pulsar ($10^{-4} \sim 10^{-1} M_{\odot}$) with a quark planet ($10^{-8} \sim 10^{-3} M_{\odot}$) orbiting it. According to the calculations presented, the pulsar would be a quark star because of its low mass, which might eject a lump of quark matter (to become a planet around) during its birth.

Key words: Pulsars: individual (PSR B1828–11) — stars: planetary systems — gravitational waves

1 INTRODUCTION
The pulsar PSR B1828–11 shows long-term, highly periodic and correlated variations in both the pulse shape and the slow-down rate. Its variations are best described as harmonically related sinusoids, with periods of approximately 1000, 500 and 250 days (Stairs et al. 2000). The phenomenon indicates the most compelling evidence for precession (Link & Epstein 2001).

To explain this phenomenon, some authors (Jones & Andersson 2001; Rezania 2003) have proposed different models within the framework of free precession. The observation could not be a problem in the standard view of neutron stars if the star’s crust is free to precess. In (Link & Epstein 2001), the correlated changes in the pulse duration and spin period derivative can be explained as a precession of the star’s rigid crust coupled to the magnetic dipole torque. Akegan et al. (2006) modelled the timing behavior with the inclusion of both geometrical and spin-down contributions to the residuals. However, investigations concerned on internal structure of neutron stars show that free precession may be damped out if vortices pinning to the stellar crust become unpinned during a glitch, might have described the occurrence of and recovery from glitches (Alpar et al. 1984). The vortex pinning will damp out free precession on timescales of several hundred precession periods (Shaham 1977, Sedrakian et al. 1999) if the pinning force is as strong as suggested in the glitch models. Additionally, the MHD coupling between the crust and the core will also strongly affect precession of the pulsar (Levin & D’Angelo 2004). The decay of precession, caused by the mutual friction between the neutron superfluid and the plasma in the core, is expected to occur over tens to hundreds of precession periods and may be measurable over a human lifetime. As noted by Link (2003, 2006), the picture of vortex lines entangled in flux tubes appears to be incompatible with observations of long-period precession, which indicates that the standard scenario of the outer core (superfluid neutrons in co-existence with type II, superconducting protons) should be reconsidered.

An alternative way is to consider the pulsar as a solid quark star (Xu 2003), where precession models will not re-
ce puzzle that damping out brings. But there are still some problems when here we come to the model of free precession. For example, the ellipticity (or dynamical flattening) of the pulsar derived from free precession model is not fitted well with the one calculated by Maclaurin approximation. Consider the pulsar as a rotation ellipsoid with the principal moment of inertia \(I_x = I_y < I_z\) and the corresponding radii \(a = b > c\). In free precession models, the stellar dynamical flattening is \(\epsilon = (I_x - I_y)/I_x = c^2/(2 - e^2) = P/P_{\text{prece}} \approx 10^{-8}\), where \(P\) is the spin period, \(P_{\text{prece}}\) is the precession period of the pulsar and \(\epsilon = \sqrt{1 - c^2/a^2}\) is the stellar eccentricity. It can be approximated as \(e^2/2\) since \(e \ll 1\). Meanwhile, from Maclaurin approximation, the stellar ellipticity can be determined by \(\epsilon = [1 - (c/a)^2]^{3/2}/(c/a)^2 \approx c^2/3 \approx 2e/3 \approx 3 \times 10^{-3} P_{\text{10ms}}^{-2} \approx 2 \times 10^{-6}\) [Xu 2006, Zhou et al. 2004]. These two values, \(\epsilon\) and \(e\), which are expected to be generally matched if free precession model is available, are quite different. Therefore, new ideas need to be devised to explain the phenomenon of precession instead of the free precession ones. Actually, a forced precession model driven by an fossil disk was presented in Qiao et al. (2003). Here we alternatively present a quark planet model to explain the phenomenon of precession. In this model, forced precession is caused by a quark planet orbiting the pulsar. In Sect. 2, we first establish the relation between mass of the pulsar and orbital radius of the planet in case that the dynamical flattening is obtained from Maclaurin approximation (Xu 2006). Then we explain why the planet should be a quark planet, rather than a normal one like the earth or Jupiter when planet model is referred to. Next we limit movement of the pulsar around the center of mass by errors in the TOAs (time-of-arrival). Death-line criterion and limitation on gravitation wave radiation timescale are also considered so as to constrain orbital radius, mass of the pulsar and mass of the planet. In Sect. 3, we calculate the precession period derivative and gravitational wave radiation strength of the pulsar for different mass of the pulsar and orbital radius of the planet. In Sect.4, we conclude by discussing the formation of such system and expecting further observation to test the model.

2 PRECESSION TORQUED BY A QUARK PLANET

First of all, we suppose that the pulsar PSR1828–11 could be either neutron star or quark star since both are candidate models for pulsar. In case that the precession period is much more than the spin period and the orbital period, the angular velocity of forced precession can be expressed as (Menke & Abbot 2004)

\[
\dot{\alpha} = \frac{3GM_{pl}}{2r_{pl}^3} \cos \theta_{pl} \epsilon,
\]

where \(\dot{\alpha}\) is the precession angular velocity, \(\omega\) is the rotational angular velocity of the spinning pulsar, \(r_{pl}\) is orbital radius of the planet, \(G\) is gravitational constant, \(M_{pl}\) is mass of the planet, \(\epsilon \approx 3e/2 \approx 3 \times 10^{-6}\) is the stellar dynamical flattening and \(\theta_{pl}\) is average inclination of planet orbit. From Eq. (1) we can have

\[
M_{pl} = \frac{8\pi^2}{3GP\epsilon P_{\text{prece}} \cos \theta_{pl}} r_{pl}^3,
\]

where \(P = 2\pi/\omega_p\) is spin period and \(P_{\text{prece}} = 2\pi/\dot{\alpha}\) is precession period of the pulsar. If we consider a normal planet similar to the earth or Jupiter, the typical value of \(r_{pl}\) should be 0.1 AU or 1 AU and the corresponding value of \(M_{pl}\) is much larger than the solar mass. In Fig. 1, the relation between \(M_{pl} \cos \theta_{pl}\) and \(r_{pl}\) is shown derived from the 500-day precession period. We can see that if \(r_{pl}\) reaches 10\(^6\) cm and \(\theta_{pl}\) is not close to 90\(^\circ\), mass of the planet will be over the solar mass. A planet needs to be of several billion times of \(M_{pl}\) to provide enough torque if it locates at 1 AU away from the pulsar. We cannot believe the existence of such a planet since it would definitely induce huge orbital timing effects in the pulse residuals. However, the result is not surprising because the pulsar has a much shorter forced precession period and thus the torque that dominates the precession needs to be much stronger. Meanwhile, precession torque is reduced when the distance between the pulsar and the planet becomes longer. Consequently, if there is a planet close to the pulsar, it may be able to provide enough torque to cause the short-period precession. That is the reason that we consider quark planet since its orbital radius could mainly depend on the kick energy, which can vary in a large range (Sect. 4).

Therefore, we suppose that the orbital radius of the planet is between (10\(^6\) cm, 10\(^7\) cm), where 10\(^6\) cm is typical radius of a normal neutron star. Besides, for PSR B1828–11, the errors in the TOAs (time-of-arrival) are limited by random noise to about \(\tau_c \approx 0.2\) ms [Stairs et al. 2000]. So in such a planetary system, the pulsar is not likely to move more than about \(\tau_c c \approx 6 \times 10^6\) cm around the center of mass, and its orbital radius should be less than 3 \times 10\(^6\) cm. In addition, if the eccentricity of the orbit is not considerable, we...
can have $M_{pl} r_{pl} \approx M_{psr} r_{psr}$, where $M_{psr}$ and $r_{psr}$ are mass of the pulsar and its orbital radius around the center of mass, respectively. Since $r_{psr}$ has a maximum $r_{psr, max} = 3 \times 10^6$ cm, the relation can be derived as $M_{pl} r_{pl} < M_{psr} r_{psr, max}$. Finally, in such a planetary system, mass of the pulsar should be much larger than that of the planet so we approximately assume $M_{psr} / M_{pl} > k = 10$.

Next we consider the gravitational wave radiation (GWR) of the planetary system for further limitation. In normal double neutron star system, the distance between the two stars is about $10^{10}$ cm. Therefore the timescale of GWR is rather long, usually $10^4$ years (Hulse & Taylor 1975; Taylor & Weisberg 1982). However, in this quark planet system, due to the short distance between the two objects, the power of GWR may be significantly larger. In double-star system it is given by (Misner et al. 1973)

$$\frac{dE}{dt} = \frac{32G^4 \mu^2 m^3}{5c^3 a^5} = \frac{32G^4 M_{psr}^2 M_{pl}^2 (M_{psr} + M_{pl})}{5c^3 a^5},$$

where $a \approx r_{pl}$ is the semi-major axis of the orbit, $m = M_{pl} + M_{psr}$ and $\mu = M_{psr} (M_{pl} + M_{psr})$ is the reduced mass. The GWR costs the total of potential energy and dynamic energy of the planetary system

$$E_{tot} = \frac{GM_{psr} M_{pl}}{2r_{pl}}.$$ 

So timescale of GWR can be derived as

$$\tau = \frac{|E_{tot}|}{dE/dt} = \frac{5c^3 r_{pl}}{64G^3 M_{psr} M_{pl} (M_{psr} + M_{pl})}.$$ 

If the planetary system is stable, the timescale must be long enough. Here we approximately set it as $\tau > \tau_0 = 10^4$ years $\approx 3 \times 10^{13}$ s.

Additionally, we consider the death-line criterion, which requests the potential drop at the polar cap of the pulsar be more than $\phi_0 \approx 10^{12}$ V (Ruderman & Sutherland 1972; Usov & Melrose 1992). If we assume that PSR1828−11 is an aligned pulsar, potential drop is

$$\phi \approx \frac{\pi R^2 B}{cP} \sin^2 \theta,$$

where $B$ is the polar magnetic field strength at pulsar surface, $R \approx (3M_{psr} / (4\pi \rho))^{1/3}$ is the pulsar radius, $\rho \approx 7 \times 10^{14}$ g/cm$^3$ is the density of the pulsar and $\theta = \arcsin \sqrt{2\pi R/(cP)}$ is the opening half-angle of the polar cap. Here we use the density for quark stars to obtain the lower limit of $M_{psr}$. The magnetic field can be approximated by (Manchester & Taylor 1977)

$$B \approx \sqrt{\frac{31c^3 P}{8\pi^2 R^6}},$$

where $I \approx (2/5) M_{psr} R^2$ is the principal moment of inertia. From Eq. (6) and (7), the relation between potential drop and mass of the pulsar can be derived as below

$$\phi \approx \left(\frac{3}{5}\right)^{1/2} \left(\frac{3\pi^2}{4}\right)^{1/3} \left(P \frac{\rho}{cP^2}\right)^{1/2} \frac{1}{\rho} \frac{1}{M_{psr}^{5/6}}.$$ 

While $\phi > \phi_0$, we have

$$M_{psr} > \left(\frac{2000c^3 \rho^2 P^9 \phi_0^6}{243\pi^4 P^4}\right)^{1/5} \approx 3 \times 10^{-3} M_{\odot}.$$ 

Actually, the assumption of alignment in PSR1828−11 is rather strong. The potential drop from Eq. (6) can be larger by more than one order of magnitude if the inclination of the magnetic axis to the spin axis is not zero (Yue et al. 2006). Consequently, constraint on mass of the pulsar can be lower by about one magnitude and thus we have $M_{psr} > 10^{-4} M_{\odot}$. Now there are five limitations for $M_{psr}$, $r_{pl}$ and $M_{pl}$:

$$M_{psr} / M_{pl} > k,$$

$$M_{pl} r_{pl} < M_{psr} r_{psr, max},$$

$$\tau = \frac{5c^3 r_{pl}}{64G^3 M_{psr} M_{pl} (M_{psr} + M_{pl})} > \tau_0,$$

$$r_{pl} \in (10^6 \text{ cm}, 10^9 \text{ cm}),$$

$$M_{psr} > 10^{-4} M_{\odot}.$$ 

If we consider $M_{psr} \gg M_{pl}$ and substitute for $M_{psr}$ in term of $r_{pl}$ according to Eq. (2), then the limitations can be derived as

$$M_{psr} > \frac{8\pi^2}{3PP_{prece} c \cos \theta_{pl}} r_{pl}^3, \quad (15)$$

$$M_{psr} > \frac{8\pi^2}{3PP_{prece} c \cos \theta_{pl} r_{psr, max}} r_{pl}^4, \quad (16)$$

$$M_{psr} < \left(\frac{15PP_{prece} \epsilon}{512\pi^2 G^2 \tau_0 \cos \theta_{pl} r_{pl}}\right)^{1/2},$$

$$10^6 \text{ cm} < r_{pl} < 10^9 \text{ cm},$$

$$M_{psr} > 10^{-4} M_{\odot}. \quad (19)$$

In Fig. 2 we consider the above limitations and figure out the available range for $M_{psr}$ and $r_{pl}$. Accordingly, point $(r_{pl}, M_{psr})$ should be above Line (1) and (2), below Line (3) and (5) and on the right of Line (4). So we have the shadowed area as the "Available" area for point $(r_{pl}, M_{psr})$. Line (1)-(5) are defined as below

Line (1) : $M_{psr} = \frac{8\pi^2}{3PP_{prece} c \cos \theta_{pl}} r_{pl}^3$, 

Line (2) : $M_{psr} = \frac{8\pi^2}{3PP_{prece} c \cos \theta_{pl} r_{psr, max}} r_{pl}^4$. 

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Meanwhile, rate of loss of angular momentum caused by
\[ \Delta L \]

\[ \approx \frac{15PM_{\text{psr}}c^5}{512\pi^2G^2\tau_{\theta \text{pl}}} \frac{1}{r_{\text{pl}}^{1/2}}, \]

(22)

Line (3): \( M_{\text{psr}} = (10^6 \text{ cm}, 5 \times 10^6 \text{ cm}, 10^{-4} M_{\odot}, 6 \times 10^{-6} \cos^3 \theta_{\text{pl}} M_{\odot}) \)

Line (4): \( r_{\text{pl}} = 10^6 \text{ cm}, \)

Line (5): \( M_{\text{psr}} = 10^{-4} M_{\odot}. \)

(23)

(24)

From Fig. 2, the available value range of \( r_{\text{pl}}, M_{\text{psr}} \) and \( M_{\odot} \) are \( (10^6 \text{ cm}, 5 \times 10^6 \text{ cm}, (10^{-4} M_{\odot}, 6 \times 10^{-6} \cos^3 \theta_{\text{pl}} M_{\odot}) \) and \( (6 \times 10^{-9} \cos^{-1} \theta_{\text{pl}} M_{\odot}) \). Here we use \( \cos \theta_{\text{pl}} = 1 \) because the positions of Line (1), (2) and (3) do not vary distinctly with the changing of \( \theta_{\text{pl}} \) from 0° to 80°. Different value ranges of \( r_{\text{pl}}, M_{\text{psr}} \) and \( M_{\odot} \) with different \( \theta_{\text{pl}} \) are shown in Table 1.

3 TO TEST THE MODEL BY FURTHER OBSERVATION

Loss of the total energy of the system caused by gravitational wave radiation will lead to decay of the planet orbit. Correspondingly, precession period will be reduced with the decreasing of orbital radius. Meanwhile, the planetary system may act as a detectable gravitational wave source. Therefore, it is possible to test and improve the model by GWR detection and long-period observation for precession period derivative \( (P_{\text{prece}}/dt) \).

So next we calculate \( P_{\text{prece}} \) and the characteristic amplitude of GWR source strength \((h_a)\) for different \( r_{\text{pl}} \) and \( M_{\text{psr}} \), respectively. From Eq. (2), if orbital radius has a slight change, the variation of \( P_{\text{prece}} \) can be expressed as

\[ \Delta P_{\text{prece}} = \frac{8\pi^2}{GM_{\text{psr}} \cos \theta_{\text{pl}}} \Delta r_{\text{pl}}. \]

(25)

In this case we do not consider the change of spin period (The result will prove its reasonableness). Similarly, from Eq. (4) we have

\[ \Delta E_{\text{tot}} = \frac{GM_{\text{psr}}M_{\text{pl}}}{2r_{\text{pl}}} \Delta r_{\text{pl}}, \]

(26)

In addition, the slight change of mechanical energy is caused by GWR in a short period (see Eq. [3])

\[ \Delta E_{\text{tot}} = \frac{32G^2M_{\text{psr}}^2M_{\text{pl}}}{5c^2r_{\text{pl}}^2} \frac{\Delta t}{(M_{\text{psr}} + M_{\text{pl}})}, \]

(27)

Considering \( M_{\text{psr}} \gg M_{\text{pl}} \) and combining Eq. (25)–(27) give the period derivative of precession as below

\[ \dot{P}_{\text{prece}} = \frac{\Delta P_{\text{prece}}}{\Delta t} = \frac{512\pi^2G^2M_{\text{psr}}^2}{5c^2P_{\text{prece}} \cos \theta_{\text{pl}}r_{\text{pl}}}. \]

(28)

Meanwhile, rate of loss of angular momentum caused by GWR is \( (\Omega_{\text{GW}} = \frac{c^2 \Omega d^2 h_a^2}{G}) \)

\[ N_{\text{GW}} = \frac{c^2 \Omega d^2 h_a^2}{G}, \]

(29)

where \( \dot{E} \) is the rate of loss of the total energy, \( \Omega = \sqrt{G M_{\text{psr}}/r_{\text{pl}}} \) is the period of revolution of the planet and \( d = 3.58 \text{ kpc} \) \( (\text{Taylor & Cordes} \ 1993) \) is the distance of the pulsar. \( h_a \) is the source’s ‘angle-averaged’ field strength (at earth) and approximately we have \( h_a \approx h_a \). \( (h_a \approx 1.15 h_c, \text{see} \ Ushomirsky \ et \ al \ (2000)) \). Combining Eq. (2), (3) and (29) gives

\[ h_a = \frac{32\sqrt{2}\pi G}{3\sqrt{5}d c^4 P_{\text{prece}} \cos \theta_{\text{pl}}} M_{\text{psr}} r_{\text{pl}}. \]

Besides, the frequency of GWR is

\[ \nu = \frac{2\pi}{\Omega_{\text{GW}}}. \]

(31)

In Fig. 3, relations between \( r_{\text{pl}}, M_{\text{pl}} \) from Eq. (28) for a group of \( P_{\text{prece}} \), from Eq. (31) for a group of \( h_a \), and from Eq. (32) for a group of \( \nu \) are shown \( (\cos \theta_{\text{pl}} \approx 1) \). The relations are limited by the available area for point \((r_{\text{pl}}, M_{\text{pl}})\) from Fig. 1. As is shown, the maximum and minimum of \( P_{\text{prece}} \) are \( 4 \times 10^{-37} \) and \( 6 \times 10^{-27} \) while those of \( h_a \) are \( 3 \times 10^{-25} \) and \( 1 \times 10^{-23} \). The result indicates that the precession period changes much quickly than spin period of the pulsar and GWR on earth is not intense enough to be detected by LIGO at its working frequency. For example, a frequency of 10 Hz, value of \( h_a \) is about \( 10^{-27} \), which is below the current detection limit of the LIGO at the same frequency (about \( 10^{-22} \)).

4 CONCLUSION AND DISCUSSION

Within the framework of forced precession, we propose a quark planet model to explain the precession of PSR B1828–11. The observed phenomenon can be understood by a pulsar (probably a quark star) together with a quark planet which torques dominantly the pulsar to precess. In principle, orbital radius of the quark planet should be between \( 10^6 \) cm and \( 10^8 \) cm while the range of mass of the pulsar and the planet are approximately \( (10^{-4} M_{\odot}, 10^{-1} M_{\odot}) \) and \( (10^{-6} M_{\odot}, 10^{-8} M_{\odot}) \), respectively. These results might not be strange since other candidates of low-mass quark stars were also discussed previously \( (Xu \ et al \ 2003) \). We calculate the model-permitted precession period derivative and characteristic amplitude of GWR for the system. The precession period changes much quickly than spin period of the pulsar; meanwhile, GWR strength at earth may not be large enough to be detected by current LIGO.

If there is a quark planet providing torque for the forced precession of pulsar PSR B1828–11, it should be close to the
such kind of planets, orbiting closely to the center pulsars, which may suggest that the pulsar would be a quark star. Such kind of planets, orbiting closely to the center pulsars, could be ejected during the formation of the quark stars with strong turbulence if the surface energy is reasonably low (Xu 2006). Considering the orientation of the system’s angular momentum, the planet is not likely to have an inclination of $\theta_{pl}$ very close to $90^\circ$ and our previous analysis with $\theta_{pl}$ varying from $0^\circ$ to $90^\circ$ can work effectively.

In this paper we do not consider the possibility of more than one planet, which may provide a way to explain the other two possible precession periods of the pulsar. The limitation on orbital radius and ratio of the pulsar mass to the planet one could be improved if the formation of the system is considered. However, precession periods of the pulsar cannot be exactly obtained now from the seemingly periodic post-fit timing residuals. Long-period timing observations in the future are necessary in order to obtain more accurate precession period derivative of the system. Since 2000, the pulsar has accomplished several precession period. Therefore, if precession period derivative reaches its maximum in this model, the precession period may have changed several days. In addition, we need observation for gravitational wave to test and improve the model. Whether it can be detected or not will both provide further limitation on mass of the pulsar and orbital radius of the planet.

The model could also be tested by X-ray observation. (1) If the pulsar is a solid quark star with $M_{psr} \sim 10^{-3} M_\odot$ and then $r_{pl} \sim 2 \text{ km}$, the rate of rotation energy loss could be only about $10^3$ times smaller than that in the standard model where the pulsar is a normal neutron star. Assuming that only $0.1\%$ of the spin-down power could turn into the non-thermal X-ray luminosity (Lorimer & Kramer 2003), the flux at earth should be about $1 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$ (less than 1 photon/60 hours). (2) The thermal X-ray emissivity from the pulsar could also be lower. If thermal emission is from the global star, the flux should be $\sim 5 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$, and $\sim 3 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ for the pulsar with surface temperatures of 200 eV and 100 eV, respectively. Taking absorption into consideration, we can expect a flux of $\sim 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ (about 70 photons/60 hours). But if the pulsar is a neutron star with radius 10 km and surface temperature $> 60$ eV the flux is much higher, $> 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$. Future observations of the pulsar by Chandra or XMM-Newton could certainly bring us more details about the real nature.

Finally, we note that the nature of pulsars (to be neutron or quark stars) is still a matter of debate even after 40 years of the discovery. The reason for this situation is in both theory (the uncertainty of non-perturbative nature of strong interaction) and observation (the difficulty to distinguish them). It is a non-mainstream idea that pulsars are actually quark stars, but this possibility cannot be ruled out yet according to either first principles or observations. “Low-mass” is a natural and direct consequence if pulsars are quark stars since quark stars with mass $< 1 M_\odot$ are self-confined by color interaction rather than by gravity. An argument against the low-mass idea could be the statistical mass-distribution of pulsars in binaries ($\sim 1.4 M_\odot$). However this objection might not be so strong due to (Xu 2003): (1) if the kick energy is approximately the same, only solar-mass pulsars can survive in binaries as low-mass pulsars may be ejected by the kick; (2) low-mass bare strange stars might be uncovered by re-processing the timing data of radio pulsars if the pulsars’ mass is not conventionally supposed to be $\sim 1.4 M_\odot$. In this work, we just try to understand the peculiar precession nature of PSR B1828-11 in the quark star scenario, since the mainstream-scientific solution to precession might not be simple and natural.

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\[\text{Table 1. The parametric range of } r_{pl}, M_{psr} \text{ and } M_{pl} \text{ for different inclination of planet orbit, } \theta_{pl}. \text{ The variation of the range is not significant for } \theta_{pl} \text{ from } 0^\circ \text{ to } 80^\circ.\]

| $\theta_{pl}$ | $r_{pl}$ | $M_{psr}$ | $M_{pl}$ |
|--------------|----------|-----------|----------|
| $0^\circ$    | (10^6 cm, 5 x 10^7 cm) | (10^{-4} M_\odot, 6 x 10^{-3} M_\odot) | (6 x 10^{-9} M_\odot, 6 x 10^{-4} M_\odot) |
| $30^\circ$   | (10^6 cm, 5 x 10^7 cm) | (10^{-4} M_\odot, 6 x 10^{-3} M_\odot) | (7 x 10^{-9} M_\odot, 7 x 10^{-4} M_\odot) |
| $60^\circ$   | (10^6 cm, 5 x 10^7 cm) | (10^{-4} M_\odot, 8 x 10^{-3} M_\odot) | (1 x 10^{-9} M_\odot, 9 x 10^{-4} M_\odot) |
| $80^\circ$   | (10^6 cm, 4 x 10^7 cm) | (10^{-4} M_\odot, 1 x 10^{-2} M_\odot) | (3 x 10^{-9} M_\odot, 2 x 10^{-4} M_\odot) |

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