Mon. Not. R. Astron. Soc. **381,** L1–L5 (2007) doi:10.1111/j.1745-3933.2007.00337.x

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

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Accepted 2007 May 14. Received 2007 May 14; in original form 2006 November 26

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 the precession of the pulsar as suggested previously within the framework of free precession as well as forced. 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 the mass of the pulsar ($M_{\rm psr}$), the mass of the planet ($M_{\rm pl}$) and the orbital radius of the planet ($r_{\rm pl}$). Five aspects are considered: the derived relation between $M_{\rm psr}$ and $r_{\rm pl}$, the movement of the pulsar around the centre of mass, the ratio of $M_{\rm psr}$ and $M_{\rm pl}$, the gravitational wave radiation time-scale of the planetary system, and the death-line criterion. We also calculate the range of the precession period derivative and the gravitational wave strength (at earth) permitted by the model. Under reasonable parameters, the observed phenomenon can be understood by a pulsar ($\sim 10^{-4}$–10^{-1} M$_\odot$) with a quark planet ($\sim 10^{-8}$–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 an orbiting planet) during its birth.

Key words: gravitational waves – planetary systems – pulsars: individual: PSR B1828−11.

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 d (Stairs, Lyne & Shemar 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. Akgun, Link & Wasserman (2006) modelled the timing behaviour with the inclusion of both geometrical and spin-down contributions to the residuals. However, investigations concerned with the internal structure of neutron stars show that free precession may be damped out if vortices pinned to the stellar crust and hydrodynamic (MHD) coupling are taken into consideration. In detail, the rotation of the superfluid, accounting for a large proportion of the moment of inertia of the pulsar, is contained in an array of vortices. Models, in which vortices pinned 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 time-scales of several hundred precession periods (Shaham 1977; Sedrakian, Wasserman & Cordes 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 need to answer the puzzle that damping out produces. However, there are still some problems when we come to the model of free precession. For example, the ellipticity (or dynamical flattening) of the pulsar derived from the free precession model is not fitted well with the one calculated by the Maclaurin approximation. Consider the pulsar as a rotational 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 $\epsilon = (I_z - I_x)/I_x = e^2/(2 - e^2) = P/P_{\rm prece} \approx 10^{-8}$, where P is the spin period, $P_{\rm prece}$ is the precession

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period of the pulsar and $e = \sqrt{1 - c^2/a^2}$ is the stellar eccentricity. It can be approximated as $e^2/2$ because $e \ll 1$. Meanwhile, from Maclaurin approximation, the stellar ellipticity can be determined by $\varepsilon = [1 - (c/a)^{2/3}]/(c/a)^{2/3} \approx e^2/3 \approx 2\epsilon/3 \approx 3 \times 10^{-3} P_{10\,\mathrm{ms}}^{-2} \approx 2 \times 10^{-6}$ (Xu 2006; Zhou et al. 2004). These two values, ϵ and ε, 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 disc was presented in Qiao et al. (2003).[1]

Here we present an alternative of 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 Section 2, first we establish the relation between the mass of the pulsar and the orbital radius of the planet, where 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 such as the Earth or Jupiter, when a planet model is referred to. Next we limit the movement of the pulsar around the centre of mass by errors in the TOAs (times-of-arrival). Death-line criterion and the limitation on the gravitational wave radiation time-scale are also considered so as to constrain the orbital radius, the mass of the pulsar and the mass of the planet. In Section 3, we calculate the precession period derivative and gravitational wave radiation strength of the pulsar for different masses of the pulsar and orbital radii of the planet. In Section 4, we conclude by discussing the formation of such a system and share expectations of further observations to test the model.

2 PRECESSION TORQUED BY A QUARK PLANET

First of all, we suppose that the pulsar PSR1828−11 could be either a neutron star or a quark star, as both are candidate models for a pulsar. In the case where 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 & Abbott 2004)

$$\dot{\alpha} = \frac{3GM_{\mathrm{pl}}}{2\omega r_{\mathrm{pl}}^3}\epsilon\cos\theta_{\mathrm{pl}}, \tag{1}$$

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

$$M_{\mathrm{pl}} = \frac{8\pi^2}{3GPP_{\mathrm{prece}}\epsilon\cos\theta_{\mathrm{pl}}}r_{\mathrm{pl}}^3, \tag{2}$$

where $P = 2\pi/\omega_{\mathrm{p}}$ is the spin period and $P_{\mathrm{prece}} = 2\pi/\dot{\alpha}$ is the 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 or 1 au and the corresponding value of M_{pl} is much larger than the solar mass. In Fig. 1, the relation between $M_{\mathrm{p}}\cos\theta_{\mathrm{pl}}$ and r_{pl} is shown derived from the 500-d precession period. We can see that if r_{pl} reaches 10^9 cm and θ_{pl} is not close to 90°, the mass of the planet will be greater than the solar mass. A planet located 1 au away from the pulsar

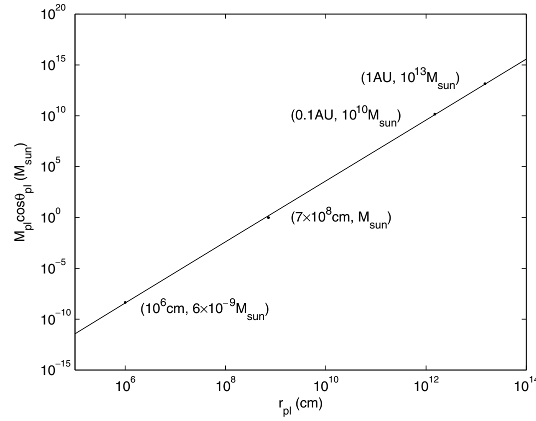

Figure 1. Relation between M_{pl} and r_{pl} for a 500-d precession period from equation (2). We can have $M_{\mathrm{pl}}\cos\theta_{\mathrm{pl}} \approx M_{\mathrm{pl}}$ if θ_{pl} is not close to 90°. The figure indicates that a reasonable value of $M_{\mathrm{p}}(M_{\mathrm{pl}} < \mathrm{M}_{\odot})$ may be found while r_{pl} is less than 10^9 cm.

needs to be of several billion $\mathrm{M}_{\odot}$ to provide enough torque. We cannot believe the existence of such a planet as 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 a quark planet as its orbital radius could mainly depend on the kick energy, which can vary over a large range (Section 4).

Therefore, we suppose that the orbital radius of the planet is between 10^6–10^9 cm, where 10^6 cm is typical radius of a normal neutron star. Besides, for PSR B1828−11, the errors in the TOAs are limited by random noise to about $\tau_{\mathrm{c}} \approx 0.2$ ms (Stairs et al. 2000). Thus in such a planetary system, the pulsar is not likely to move more than about $\tau_{\mathrm{c}}\,c \approx 6 \times 10^6$ cm around the centre of mass, and its orbital radius should be less than 3×10^6 cm. In addition, if the eccentricity of the orbit is not considerable, we can have $M_{\mathrm{pl}}r_{\mathrm{pl}} \approx M_{\mathrm{psr}}r_{\mathrm{psr}}$, where M_{psr} and r_{psr} are the mass of the pulsar and its orbital radius around the centre of mass, respectively. Because r_{psr} has a maximum $r_{\mathrm{psr,max}} = 3 \times 10^6$ cm, the relation can be derived as $M_{\mathrm{pl}}r_{\mathrm{pl}} < M_{\mathrm{psr}}r_{\mathrm{psr,max}}$. Finally, in such a planetary system, the mass of the pulsar should be much larger than that of the planet, so we assume approximately $M_{\mathrm{psr}}/M_{\mathrm{pl}} > k = 10$.

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 time-scale of the GWR is rather long, usually 10^4 yr (Hulse & Taylor 1975; Taylor & Weisberg 1982). However, in this quark planet system, due to the short distance between the two objects, the power of the GWR may be even larger. In double-star systems it is given by Misner, Thorne & Wheeler (1973)

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{32G^4}{5c^5}\frac{\mu^2m^3}{a^5} = \frac{32G^4M_{\mathrm{psr}}^2M_{\mathrm{pl}}^2(M_{\mathrm{psr}} + M_{\mathrm{pl}})}{5c^5a^5}, \tag{3}$$

where $a \simeq r_{\mathrm{pl}}$ is the semimajor axis of the orbit, $m = M_{\mathrm{pl}} + M_{\mathrm{psr}}$, and $\mu = M_{\mathrm{pl}}M_{\mathrm{psr}}/(M_{\mathrm{pl}} + M_{\mathrm{psr}})$ is the reduced mass. The total of potential energy and dynamic energy of the planetary system is

$$E_{\mathrm{tot}} = -\frac{GM_{\mathrm{pl}}M_{\mathrm{psr}}}{2r_{\mathrm{pl}}}. \tag{4}$$

[1] In this Letter, the authors obtained the stellar oblateness from the Maclaurin approximation and considered the precession as the whole star's motion, not only the crust's. Thus we think here that a solid quark star is a better idea than a neutron star, so as to prevent decay of precession.

Thus the time-scale of the GWR can be derived as

$$\tau = \frac{|E_{\rm tot}|}{{\rm d}E/{\rm d}t} = \frac{5c^5 r_{\rm pl}^4}{64G^3 M_{\rm pl} M_{\rm psr}(M_{\rm psr}+M_{\rm pl})}. \tag{5}$$

If the planetary system is to be stable, the time-scale must be at least a certain length. Here we approximately set that as $\tau > \tau_0 = 10^4$ yr $\approx 3 \times 10^{13}$ s.

Additionally, we consider the death-line criterion, which requests the potential drop at the polar cap of the pulsar be more than $\phi_0 \simeq 10^{12}$ V (Ruderman & Sutherland 1975; Usov & Melrose 1995). If we assume that PSR1828−11 is an aligned pulsar, the potential drop is

$$\phi \approx \frac{\pi R^2 B}{cP}\sin^2\theta, \tag{6}$$

where B is the polar magnetic field strength at the pulsar surface, $R \approx [3M_{\rm psr}/(4\pi\rho)]^{1/3}$ 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 $M_{\rm psr}$. The magnetic field can be approximated by Manchester & Taylor (1977)

$$B \approx \sqrt{\frac{3Ic^3 P\dot{P}}{8\pi^2 R^6}}, \tag{7}$$

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

$$\phi \approx \left(\frac{3}{5}\right)^{1/2}\left(\frac{3\pi^2}{4}\right)^{1/3}\left(\frac{\dot{P}}{cP^3}\right)^{1/2}\left(\frac{1}{\rho}\right)^{1/3} M_{\rm psr}^{5/6}. \tag{8}$$

While $\phi > \phi_0$, we have

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

Actually, the assumption of alignment in PSR B1828−11 is rather strong. The potential drop from equation (6) can be more than one order of magnitude larger if the inclination of the magnetic axis to the spin axis is not zero (Yue, Cui & Xu 2006). Consequently, constraint on the mass of the pulsar can be lower by about 1 mag and thus we have $M_{\rm s} > 10^{-4}\ {\rm M}_\odot$.

Now there are five limitations for $M_{\rm psr}$, $r_{\rm pl}$ and $M_{\rm pl}$:

$$M_{\rm psr}/M_{\rm pl} > k, \tag{10}$$

$$M_{\rm pl} r_{\rm pl} < M_{\rm psr} r_{\rm psr,max}, \tag{11}$$

$$\tau = \frac{5c^5 r_{\rm pl}^4}{64G^3 M_{\rm pl} M_{\rm psr}(M_{\rm s}+M_{\rm pl})} > \tau_0, \tag{12}$$

$$r_{\rm pl} \in (10^6\ {\rm cm},\ 10^9\ {\rm cm}), \tag{13}$$

$$M_{\rm psr} > 10^{-4}\ {\rm M}_\odot. \tag{14}$$

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

$$M_{\rm psr} > \frac{8k\pi^2}{3PP_{\rm prece}G\epsilon\cos\theta_{\rm pl}} r_{\rm pl}^3, \tag{15}$$

$$M_{\rm psr} > \frac{8\pi^2}{3PP_{\rm prece}G\epsilon\cos\theta_{\rm pl} r_{\rm psr,max}} r_{\rm pl}^4, \tag{16}$$

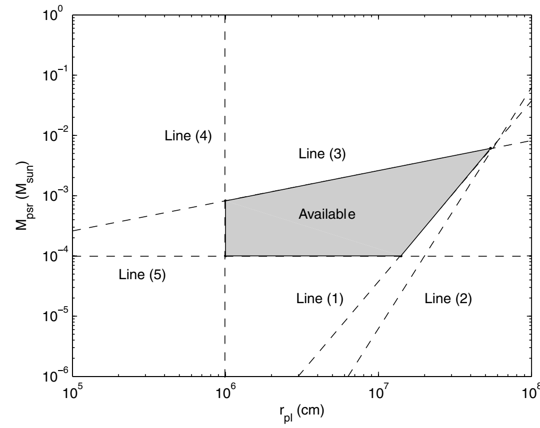

Figure 2. Constraint on $r_{\rm pl}$ and $M_{\rm psr}$ (by observations and theoretical arguments. The shadowed ‘Available’ region surrounded by Lines (1)–(5) is the parameter space for $r_{\rm pl}$ and $M_{\rm psr}$. The five lines are defined by equations (20)–(24). In this figure we use $\cos\theta_{\rm pl} = 1$, as the locations of Lines (1)–(3) will not change much with the variation of the average inclination of the planet orbit $\theta_{\rm pl}$ from 0° to 80° (see Table 1).

$$M_{\rm psr} < \left(\frac{15PP_{\rm prece}c^5\epsilon}{512\pi^2 G^2\tau_0\cos\theta_{\rm pl}} r_{\rm pl}\right)^{1/2}, \tag{17}$$

$$10^6\ {\rm cm} < r_{\rm pl} < 10^9\ {\rm cm}, \tag{18}$$

$$M_{\rm psr} > 10^{-4}\ {\rm M}_\odot. \tag{19}$$

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

$$\text{Line (1)}:\ M_{\rm psr} = \frac{8k\pi^2}{3PP_{\rm prece}G\epsilon\cos\theta_{\rm pl}} r_{\rm pl}^3, \tag{20}$$

$$\text{Line (2)}:\ M_{\rm psr} = \frac{8\pi^2}{3PP_{\rm prece}G\epsilon\cos\theta_{\rm pl} r_{\rm psr,max}} r_{\rm pl}^4, \tag{21}$$

$$\text{Line (3)}:\ M_{\rm psr} = \left(\frac{15PP_{\rm prece}c^5\epsilon}{512\pi^2 G^2\tau_0\cos\theta_{\rm pl}}\right)^{1/2} r_{\rm pl}^{1/2}, \tag{22}$$

$$\text{Line (4)}:\ r_{\rm pl} = 10^6\ {\rm cm}, \tag{23}$$

$$\text{Line (5)}:\ M_{\rm psr} = 10^{-4}\ {\rm M}_\odot. \tag{24}$$

From Fig. 2, the available value ranges of $r_{\rm pl}$, $M_{\rm psr}$ and $M_{\rm pl}$ are (10^6 cm, $5 \times 10^7 \cos^{1/7}\theta_{\rm pl}$ cm), ($10^{-4}\ {\rm M}_\odot$, $6 \times 10^{-3}\cos^{-3/7}\theta_{\rm pl}\ {\rm M}_\odot$) and ($6 \times 10^{-9}\cos^{-1}\theta_{\rm pl}\ {\rm M}_\odot$, $6 \times 10^{-4}\cos^{-4/7}\theta_{\rm pl}\ {\rm M}_\odot$), respectively. Here we use $\cos\theta_{\rm pl} = 1$ because the positions of Lines (1), (2) and (3) do not vary distinctly with the changing of $\theta_{\rm pl}$ from 0° to 80°. Different value ranges of $r_{\rm pl}$, $M_{\rm psr}$ and $M_{\rm pl}$ with different $\theta_{\rm pl}$ are shown in Table 1.

3 TO TEST THE MODEL BY FURTHER OBSERVATION

The loss of the total energy of the system caused by GRW will lead to the decay of the planet orbit. Correspondingly, the precession

Table 1. The parametric range of $r_{\rm pl}$, $M_{\rm psr}$ and $M_{\rm pl}$ for different inclination of planet orbit, $\theta_{\rm pl}$. The variation of the range is not significant for $\theta_{\rm pl}$ from 0° to 80°.

$\theta_{\rm pl}$	$r_{\rm p}$ (cm)	$M_{\rm s}$ ($M_\odot$)	$M_{\rm p}$ ($M_\odot$)
0°	$(10^6, 5\times10^7)$	$(10^{-4}, 6\times10^{-3})$	$(6\times10^{-9}, 6\times10^{-4})$
30°	$(10^6, 5\times10^7)$	$(10^{-4}, 6\times10^{-3})$	$(7\times10^{-9}, 7\times10^{-4})$
60°	$(10^6, 5\times10^7)$	$(10^{-4}, 8\times10^{-3})$	$(1\times10^{-8}, 9\times10^{-4})$
80°	$(10^6, 4\times10^7)$	$(10^{-4}, 1\times10^{-2})$	$(3\times10^{-8}, 2\times10^{-3})$

period will be reduced as the orbital radius decreases. 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 the precession period derivative ($\dot{P}_{\rm prece}$).

Thus we next calculate $\dot{P}_{\rm prece}$ and the characteristic amplitude of GWR source strength ($h_{\rm c}$) for different values of $r_{\rm pl}$ and $M_{\rm psr}$, respectively. From equation (2), if the orbital radius undergoes a slight change, the variation of $P_{\rm prece}$ can be expressed as

$$\Delta P_{\rm prece} = \frac{8\pi^2 r_{\rm pl}^2}{G P M_{\rm pl}\epsilon\cos\theta_{\rm pl}}\Delta r_{\rm pl}. \tag{25}$$

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

$$\Delta E_{\rm tot} = \frac{G M_{\rm pl} M_{\rm psr}}{2 r_{\rm pl}^2}\Delta r_{\rm pl}. \tag{26}$$

In addition, the slight change of mechanical energy is caused by GWR in a short period (see equation 3):

$$\Delta E_{\rm tot} = \frac{32 G^4 M_{\rm psr}^2 M_{\rm pl}^2 (M_{\rm psr}+M_{\rm pl})}{5c^5 r_{\rm pl}^5}\Delta t. \tag{27}$$

Considering $M_{\rm psr} \gg M_{\rm pl}$ and combining equations (25)–(27) give the period derivative of precession as below

$$\dot{P}_{\rm prece} = \frac{\Delta P_{\rm prece}}{\Delta t} = \frac{512\pi^2 G^2 M_{\rm psr}^2}{5c^5 P\epsilon\cos\theta_{\rm pl} r_{\rm pl}}. \tag{28}$$

Meanwhile, the rate of loss of angular momentum caused by GWR is (Ushomirsky, Cutler & Bildsten 2000)

$$N_{\rm gw} = \frac{\dot{E}}{\Omega} = \frac{c^3\Omega d^2 h_{\rm a}^2}{G}, \tag{29}$$

where $\dot{E}$ is the rate of loss of the total energy, $\Omega = \sqrt{G M_{\rm psr}/r_{\rm pl}^3}$ is the period of revolution of the planet and $d = 3.58$ kpc (Taylor & Cordes 1993) is the distance of the pulsar. $h_{\rm a}$ is the source's 'angle-averaged' field strength (at Earth) and approximately we have $h_{\rm a} \approx h_{\rm c}$ ($h_{\rm a} \approx 1.15 h_{\rm c}$, see Ushomirsky et al. 2000). Combining equations (2), (3) and (29) gives

$$h_{\rm a} = \frac{32\sqrt{2}\pi^2 G}{3\sqrt{5} d c^4 P P_{\rm prece}\epsilon\cos\theta_{\rm pl}} M_{\rm psr} r_{\rm pl}^2. \tag{30}$$

Besides, the frequency of GWR is

$$\nu = 2\frac{\Omega}{2\pi} = \sqrt{\frac{G M_{\rm psr}}{\pi^2 r_{\rm pl}^3}}. \tag{31}$$

In Fig. 3, relations between $r_{\rm pl}$ and $M_{\rm pl}$ from equation (28) for a group of $\dot{P}_{\rm prece}$, from equation (31) for a group of $h_{\rm a}$ and from equation (32) for a group of ν are shown ($\cos\theta_{\rm pl} \simeq 1$). The relations

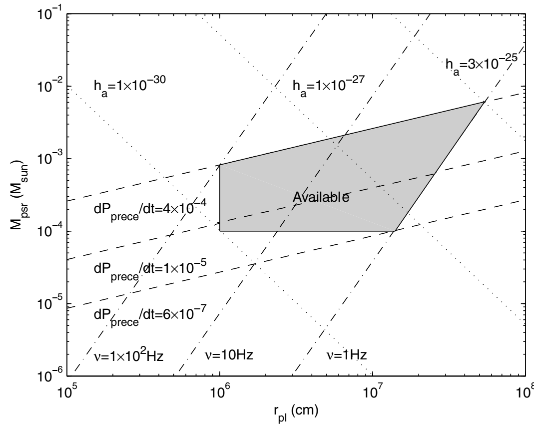

Figure 3. A zoomed parameter space for the 'Available' region. The procession period derivative ($\dot{P}_{\rm prece} = {\rm d}P_{\rm prece}/{\rm d}t$, dash lines), the perturbed metric ($h_{\rm a}$, dot lines), and gravitational wave frequency (ν, dash-dot lines) are drawn. Here we use $\cos\theta_{\rm pl} = 1$ in the calculations. The available area gives model-permitted parameter space for $\dot{P}_{\rm prece}$, $h_{\rm a}$ and ν.

are limited by the available area for point ($r_{\rm pl}$, $M_{\rm pl}$) from Fig. 1. As is shown, the maximum and minimum of $\dot{P}_{\rm prece}$ are 4×10^{-4} and 6×10^{-7} while those of $h_{\rm a}$ are 3×10^{-25} and 1×10^{-30}. The result indicates that the precession period changes much more quickly than spin period of the pulsar that and the GWR at Earth is not intense enough to be detected by LIGO at its working frequency. For example, at a frequency of 10 Hz, the value of $h_{\rm a}$ 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 mainly provides the precession torques. In principle, orbital radius of the quark planet should be between 10^6 and 10^8 cm while the mass ranges of the pulsar and the planet are approximately 10^{-4}–$10^{-1}\,M_\odot$ and 10^{-8}–$10^{-3}\,M_\odot$, respectively. These results might not be surprising, as other candidates of low-mass quark stars were also discussed previously (Xu 2005; Yue et al. 2006). We calculate the model-permitted precession period derivative and characteristic amplitude of GWR for the system. The precession period changes much more quickly than spin period of the pulsar; meanwhile, GWR strength at Earth may not be large enough to be detected by the 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 pulsar with a distance of several times the pulsar's radius. The pulsar mass should also be significantly lower than $M_\odot$, which may suggest that the pulsar would be a quark star. Such planets, orbiting closely to the centre pulsars, could be ejecta 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 a inclination of orbit very close to 90° and our previous analysis with $\theta_{\rm pl}$ varying from 0° to 90° can work effectively.

In this Letter 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 mass of the planet could be improved if the formation of the system is considered. However, precession periods of the pulsar cannot be exactly obtained from the seemingly periodic post-fit timing residuals now. 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 periods. Therefore, if the precession period derivative reaches its maximum in this model, the precession period may have changed by several days. In addition, we need observations of gravitational waves to test and improve the model. Whether it can be detected or not will both provide further limitations on the mass of the pulsar and the 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 $M_{\rm psr} \sim 10^{-3}\,{\rm M}_{\odot}$ and then $r_{\rm psr} \sim 2$ km, the rate of rotation energy loss could be only about 10^5 times smaller than that in the standard model where the pulsar is a normal neutron star. Assuming that only ~ 0.1 per cent of the spin-down power could turn into the non-thermal X-ray luminosity (Lorimer & Kramer 2005), the flux at earth should be about $1 \times 10^{-17}\,{\rm erg\,cm^{-3}\,s^{-1}}$ (less than 1 photon/60 h). (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 $\sim 5 \times 10^{-13}\,{\rm erg\,cm^{-3}\,s^{-1}}$ and $\sim 3 \times 10^{-14}\,{\rm erg\,cm^{-3}\,s^{-1}}$ for the pulsar with surface temperatures of 200 eV and 100 eV, respectively. Taking absorption into consideration, we can expect a flux of $\sim 10^{-14}\,{\rm erg\,cm^{-3}\,s^{-1}}$ (about 70 photons/6 h). However, if the pulsar is a neutron star with radius 10 km and surface temperature > 60 eV,[2] the flux is much higher, $> 10^{-13}\,{\rm erg\,cm^{-3}\,s^{-1}}$. 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 yr of the discovery. The reason for this situation is in both theory (the uncertainty of the non-perturbative nature of strong interaction) and observation (the difficulty of distinguishing 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 because quark stars with mass $<1\,{\rm M}_{\odot}$ are self-confined by colour interaction rather by gravity. An argument against the low-mass idea could be the statistical mass-distribution of pulsars in binaries ($\sim 1.4\,{\rm M}_{\odot}$). However, this objection might not be so strong due to (Xu 2005): (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 $\sim 1.4\,{\rm M}_{\odot}$. In this work, we just try to understand the peculiar precession nature of PSR B1828-11 in the quark star scenario, as the mainstream-scientific solution to precession might not be simple and natural.

[2] According to the standard cooling model of Page (1998), the temperature of this $\sim 10^5$ yr old pulsar is ~ 68 eV.

ACKNOWLEDGMENTS

We would like to thank the referee for his/her very constructive suggestion to test the model using X-ray observations, and K. J. Lee and G. J. Qiao for their help and appreciated various stimulating discussions in the pulsar group of Peking University. This work is supported by National Nature Sciences Foundation of China (10573002, 10778611), by the program of the Light in China’s Western Region (LCWR, No. LHXZ200602), and by the Key Grant Project of Chinese Ministry of Education (305001).

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