Mon. Not. R. Astron. Soc. **365,** L16–L20 (2006) doi:10.1111/j.1745-3933.2005.00117.x

GCRT J1745−3009: a precessing radio pulsar?

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Accepted 2005 October 20. Received 2005 October 16; in original form 2005 August 15

ABSTRACT

A unique transient bursting radio source, GCRT J1745−3009, has been discovered near the direction of the Galactic Centre. The explanation of this phenomenon is still an open question, although some efforts to understand its nature have been made. This Letter shows that most of the observed features can be reproduced by our proposed precessing pulsar model. It is found that the precession angle of the pulsar should be larger ($\gtrsim 15°$) than that of previously known precessing pulsars, which have a precession angle $\lesssim 10°$, if the beam width of the pulsar is larger than 10°. The pulsar could be a nulling (or even extremely nulling) radio pulsars to account for the transient nature of the source. This model can be confirmed if a pulsar is detected at the position of the source. The pulsar could hardly be a normal neutron star (but could probably be a solid quark star) if the spin period of the pulsar is detected to be $\gtrsim 10$ ms in the future.

Key words: radiation mechanisms: non-thermal – stars: individual: GCRT J1745−3009 – pulsars: general.

1 INTRODUCTION

A bursting radio source, GCRT J1745−3009, was discovered at 0.33 GHz in a radio monitoring program of the Galactic Centre region made on 2002 September 30 (Hyman et al. 2005a). Five ∼10-min bursts with a peak flux of ∼1.67 Jy were detected at an apparently regular period of ∼77 min from the source. Activity (only one single ∼0.5-Jy burst) had been detected again by the Giant Metrewave Radio Telescope (GMRT) in 330 MHz on 2003 September 28 (Hyman et al. 2005b). The source appears to be transient because it was not active at the 1998 September 25 and 26 epochs of the Very Large Array (VLA) observation, and had not been detected in some other epochs of observation in 2002 or 2003. Observations indicate that (Hyman et al. 2005b) the burst detected in 2003 is an isolated one, although additional undetected bursts occurring with 77-min periods like the 2002 bursts can not be completely ruled out. Assuming that the 2003 burst is an isolated one, Hyman et al. (2005b) estimated crudely that the duty cycle of the transient behaviour is about 10 per cent.

Given that (i) the brightness temperature of the source would exceed 10^{12} K if it is farther than 100 pc away, and (ii) the observational properties of the source are not directly compatible with those of any known coherent emitters such as white dwarfs or pulsars, Hyman et al. (2005a) concluded that it it is not likely to be a incoherent emitter but rather might be one of a new class of coherent emitter. Kulkarni & Phinney (2005) argued that the source could be a nulling radio pulsar, such as PSR J1752+2359, which has quasi-periodic nulling behaviour (Lewandowski et al. 2004). It has been pointed out (Turolla, Possenti & Treves 2005) that the phenomenon is compatible with what is expected from the interaction of the wind and magnetosphere of two pulsars in a binary system. This scenario predicts that (i) a pulsar should be detectable at frequency higher than 1 GHz, and (ii) the X-ray luminosity from the shock should be 10^{32} erg s^{-1}, which is too low to be detectable by contemporary facilities. The source could be a white dwarf (Zhang & Gil 2005), which may actually behave like a pulsar and create the activity observed. This scenario predicts that deep infrared (IR) exposure with a large telescope may lead to the discovery of the counterpart of GCRT J1745−3009. A conclusive understanding, however, has not been achieved yet, and could only be accomplished through further observation.

An alternative effort is made in this paper to explain the observational features of GCRT J1745−3009. We propose that the source could simply be a spinning pulsar precessing with a period of ∼77 min. The duration and period of the bursts can be explained with a broad choice of parameters, as long as the precession angle is not very small (>15°). It is worth noting that the wobble angle of the pulsar could be typically of tens of degrees (Melatos 2000) if the free precession period is close to the radiation-driven precession period. Given that the brightness temperature could be as high as 10^{28}–10^{30} K, a pulsar could reproduce the observed flux even if it is as far as 10 kpc away. The transient nature of the source would be understandable if the pulsar is an extremely nulling radio pulsar (Backer 1970; Ritchings 1976; Manchester). Some of the discovered nulling pulsars could have a huge nulling fraction. PSR 0826−34 is a case in point, whose nulling fraction is 70 ± 35 per cent (Biggs 1992). PSR B1931+24 switches off for ∼90 per cent of time, and

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it appears quasi-periodically at ∼40 d (Cordes, Lazio & McLaughlin 2004; O'Brien 2005). Such a high fraction of nulling might be consistent with the 10 per cent duty-cycle estimated by Hyman et al. (2005b).

A similar idea was presented by Heyl & Hernquist (2002) who applied a precessing pulsar model to explain the 6-hr periodic modulation of X-ray flux from 1E 161348-5055, a neutron star candidate in the centre of the supernova remnant RCW 103.

The model is introduced in Section 2. Its application to the pulsar is discussed in Section 3. An extensive discussion on the population of nulling and precessing pulsars, as well as a comparison between our model and other contemporary models, is provided in Section 4. The results are summarized in Section 5.

2 THE MODEL

A precessing pulsar scenario is shown in the observer's rest frame in Fig. 1. The spin axis of the pulsar itself is rotating around a precession axis (which lies along the direction of total angular momentum). We denote the magnetic inclination angle as α, the angle between line of sight and the precession axis as β, and the precession angle as γ. One can also consider another frame, called the precessing frame, which rotates along Ω_p with the same period as the precession period. In this precessing frame, both the Ω_p and Ω_s axes are fixed, and the line of sight rotates about Ω_p. When the line of sight passes through the emission pattern (shaded region in Fig. 1), the observer detects burst activity. The points 'S' and 'T' represent the beginning and end of the observed burst activity, respectively. δ is the angle between 'S' and 'T' along the trajectory of the line of sight.

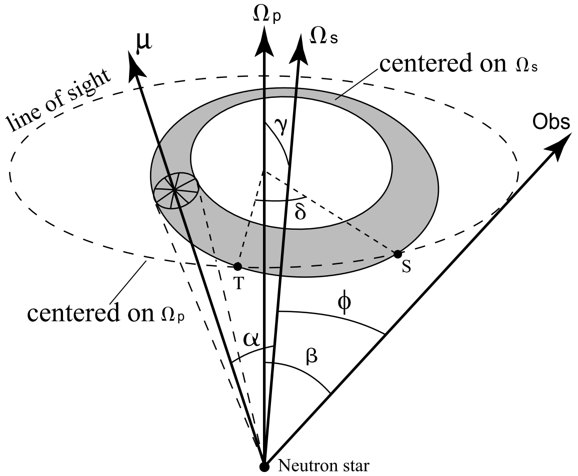

Figure 1. Geometry of a precessing pulsar. α is the angle between the magnetic axis μ and the spin axis Ω_s . β is the angle between the line of sight 'Obs' and the precession axis Ω_p . ϕ is the angle between the line of sight and Ω_s. An observer can only detect radio bursts between 'S' and 'T', over an angle δ, which, in our model, is set to be $\delta = 2\pi\,(10/77)$ to fit the ratio of the observed burst duration to the period.

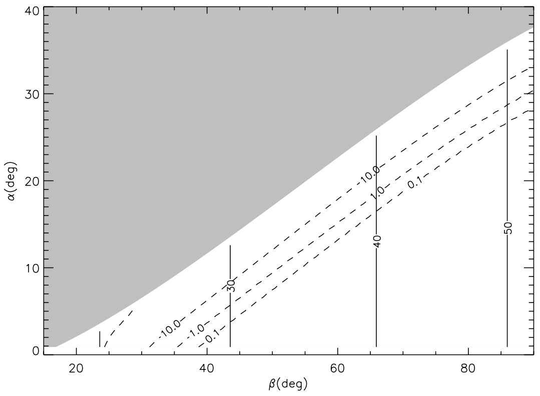

Figure 2. Possible parameter space to reproduce the bursting behaviour in our precession model. Here we set the beam radius of the pulsar to be 6°, the brightness temperature of radio emission to be 10^{30} K, and the spin angular velocity Ω_s to be 1 rad s^{-1}. The solid and the dashed lines are contours of γ (in °) and of source distance (in kpc), respectively, for given α and β. No appropriate γ value can be found in the shaded region. In this calculation, the smallest γ we obtain is about 15° in order to reproduce the first five bursts observed during 2002.

Let us consider the parameter space of α, β and γ, in which the observed flux variation can be successfully reproduced. The radio emissivity of the pulsar is assumed to be $f(\theta) = f_0 \mathrm{e}^{-\theta/\theta_\mathrm{p}}$, where θ is the angular distance from the magnetic axis μ and θ_p is a parameter characterizing the width of the emission beam. The observation is sampled every 30 s in the original observation of Hyman et al. (2005a). This sampling time is much shorter than the precession period (77 min) and if it is also longer than the spin period of pulsar then the 30-s sampled flux, F_{30}, can be regarded as a function of ϕ (i.e. the angle between line of sight and the spin axis of the pulsar). To simplify the problem, $F_{30}(\phi)$ is assumed to be proportional to the maximum flux possible in a spin period, $f(\phi - \alpha)$,[1]

$$F_{30}(\phi_1)/F_{30}(\phi_2) \sim f(\phi_1 - \alpha)/f(\phi_2 - \alpha). \qquad (1)$$

Given that the peak flux observed is 1.67 Jy, and the undetected limit is 15 mJy, the ratio of the minimum to maximum fluxes should thus be $F_{30}(\phi_\mathrm{max})/F_{30}(\phi_\mathrm{min}) \sim (15\ \mathrm{mJy})/(1.67\ \mathrm{Jy}) \simeq 0.01$, where ϕ_max and ϕ_min are the maximum and minimum values of ϕ during bursts (i.e. $F_{30} > 15$ mJy), respectively. Therefore, $f(\phi_\mathrm{max} - \alpha)/f(\phi_\mathrm{min} - \alpha) = \exp\,[(\phi_\mathrm{min} - \phi_\mathrm{max})/\theta_\mathrm{p}] \sim 0.01$. We have then $\phi_\mathrm{max} - \phi_\mathrm{min} = 4.7\theta_\mathrm{p}$, which is chosen to be ∼0.1 rad = 6°, as the typical beam width of a normal pulsar is ∼10° (Tauris & Manchester 1998). The consequence of choosing a larger θ_p will be discussed later. The angle δ should be set to $\delta = 2\pi(10/77)$ in order to fit the observed ratio of the burst duration to the precession period.

One has $\phi_\mathrm{min} = \beta - \gamma$ and $\phi_\mathrm{max} = \arccos(\cos\beta\cos\gamma + \cos(\delta/2)\sin\beta\sin\gamma)$, according to spherical geometry. Therefore, we have

$$\begin{aligned}\phi_\mathrm{max} - \phi_\mathrm{min} = {} & \arccos(\cos\beta\cos\gamma + \cos(\delta/2)\sin\beta\sin\gamma) \\ & + \gamma - \beta = 4.7\theta_\mathrm{p}.\end{aligned} \qquad (2)$$

The γ value can be found from equation (2) for given α, β and θ_p. The calculated result is shown in Fig. 2. No γ solution could be found for α and β in the shaded region in Fig. 2. The vertical solid lines in Fig. 2 are the contours of resulting γ from given α and β by choosing $\theta_\mathrm{p} = 0.1/4.7$ rad. With the assumption that the brightness temperature of the pulsar is 10^{30} K, contours (the dashed lines in Fig. 2) of pulsar distance can be calculated, provided that the 30-s sampled burst peak flux is 1.67 Jy. The distance is computed precisely by simulating the pulsar emission and integrating the flux over 30 s numerically. The smallest precessing angle γ with which a pulsar can reproduce the observed bursts is found to be ∼16° in this calculation, while its uncertainty should be ∼1°. Note that the above calculation is based on an assumed structure of pulsar

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[1] Note that $\phi > \alpha$ if one observes single-peak bursts. Otherwise, an observer should detect double-peak bursts if $\phi < \alpha$.

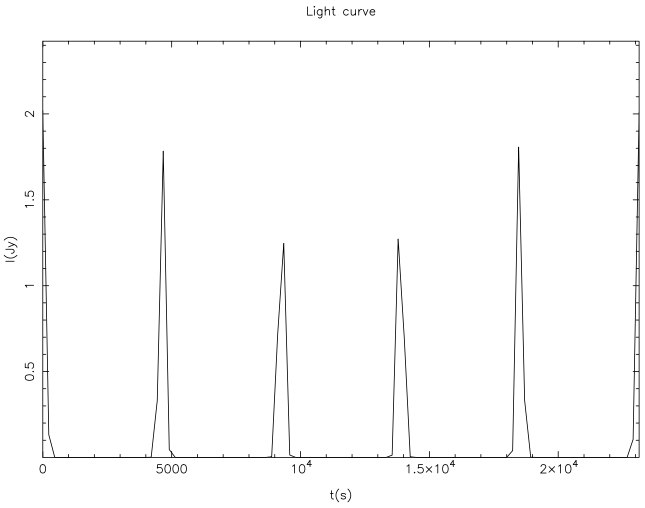

Figure 3. An example of the resulting light curves through simulation. The parameters chosen are $\alpha \simeq 10^\circ$, $\beta \simeq 44^\circ$, $\gamma \simeq 30^\circ$ and pulsar distance $\simeq$24 kpc. The angular velocity of the spinning pulsar, Ω_s, is set to be 1 rad s^{-1}.

beam. Without this assumption, one can also crudely estimate the smallest possible precessing angle (14° if $4.7\theta_p = 0.1$ rad and 7° for $4.7\theta_p = 0.05$ rad) by letting $\gamma = \beta$ in equation (2). Thus, we conclude that the pulsar should have a precessing angle that is larger than $\sim$15° if its beam width is larger than 10° in our model.

An example of simulated burst profiles is shown in Fig. 3, where the parameters are $\alpha \simeq 10^\circ$, $\beta \simeq 44^\circ$, $\gamma \simeq 30^\circ$ and the pulsar distance $\simeq$24 kpc.

3 THE PULSAR

We propose that the enigmatic source, GCRT J1745−3009, could be a precessing radio pulsar. A radio burst should be detected when the emission beam of the pulsar precesses through the line of sight. In the model, the distance to the source could be even larger than 10 kpc if the brightness temperature of the pulsar is $\sim 10^{30}$ K. We find that the precession angle, γ, must be rather large ($> \sim 15^\circ$) in order to reproduce the generally observed behaviour. Higher values of the beam radius ($4.7\,\theta_p > 0.1$) have also been considered. We find that, as the beam radius increases, the lower limit of the precession angle and the upper limit of the source distance also increase.

GCRT J1745−3009 was discovered at 0.33 GHz in 2002 September, but was not detected at 1.4 GHz, with a threshold of 35 mJy, in 2003 January (Hyman et al. 2005a). Xiang Liu and Huaguang Song also tried to observe the source at 5 GHz with the 25-m radio telescope of the Urumqi station in Xingjiang, China. They did not detect the source (upper limit of 50 mJy) in observations from 21:20 to 23:55 UT, 2005 March 20, with an integration time of 30 s. If the source bursting behaviour at 0.33 GHz adhered to this observation, then its spectral index α should be smaller than −1.29. This value is somewhat smaller than that of the Galactic Centre radio transients ($\alpha = -1.2$). The estimated index ($\alpha < -1.29$) of the source is in agreement with the typical pulsar spectrum ($\alpha = -1.75$) obtained using statistics of the spectral indices of 285 radio pulsars between 400 and 1400 MHz (Seiradakis & Wielebinski 2004).

For a conventional neutron star, a 15° precession angle will induce significant magnus force and unpin the crust of the neutron star and the superfluid inside (Link & Cutler 2002). In this case, the relative deformation of the neutron star crust is $\epsilon \sim P_s/P_p$, where P_s is the spin period, and P_p is the 77-min precession period. Then the deformation will be too large for a conventional neutron star to have unless the spin period of the star is $\sim$1 ms, because Owen (2005) derived the maximum elastic deformation, $\epsilon_{\max}$, of conventional neutron stars that is induced from shear stresses (Ushomirsky, Cutler & Bildsten 2000) is only 6.0×10^{-7} [(i) fiduciary values of mass and radius are assumed, and (ii) the breaking strain is chosen to be 10^{-2}]. A neutron star with a period of 1 ms and $\epsilon \sim 10^{-7}$ would emit gravitational waves that are potentially observable by long-baseline interferometers such as the Laser Interferometer Gravitational Wave Observatory (LIGO; Cutler & Jones 2001; Melatos & Payne 2005; Payne & Melatos 2005). Ostriker & Gunn (1969) and Heyl & Hernquist (2002) derived that the maximum deformation of a conventional neutron star that is induced from magnetic field is $\epsilon \simeq 4 \times 10^{-6}\ (3\ \langle B^2_{p,15}\rangle - \langle B^2_{\phi,15}\rangle)$, where B_{15} is the magnetic field in units of 10^{15} G. This means that if the pulsar has a magnetic field similar to a magnetar then its period can be as large as 10 ms.

It is pointed out by Jones & Andersson (2002) that the upper limit of the precession angle for a neutron star crust is $\gamma_{\max} \sim 0.45(100\,\mathrm{Hz}/f)^2\ (u_{\mathrm{break}}/10^{-3})$, where u_{break} is the breaking strain that the solid crust can withstand prior to fracture. This means that the value of u_{break} of this pulsar should be at least 10^{-2}, which is consistent with the value chosen for derive the maximum elastic deformation from sheer strain by Owen (2005). In conclusion, a precessing normal neutron star may reproduce the observational features only if it is a millisecond pulsar with a $\sim 10^{-2}$ breaking strain.

It has been found that the precession of normal neutron stars may be damped quickly (on the time-scale of $\sim 10^2$–10^4 precession periods) via various coupling mechanisms between the solid crust and the fluid core (Shaham 1977; Levin & D'Angelo 2004). If the fast rotating neutron star we are considering here would also damp that fast (10^6–10^8 s), then the dissipated energy (about $\sin\gamma\, I_{\mathrm{crust}}\, \omega_s^2 \sim 10^{50}$ erg) is too huge to be unseen in the X-ray band (Hyman et al. 2005a). Therefore, if the bursting activity was produced by a precession millisecond pulsar, then the pulsar should still be precessing and possibly detectable by future observation. If the existence of it is confirmed by future observation, then the damping time-scale of a large-amplitude precessing millisecond pulsar should be reconsidered.

Alternatively, it is not necessary for the pulsar to rotate very fast if the pulsar is a solid quark star (Xu 2003; Zhou et al. 2004), because a solid quark star could have a larger elastic deformation, $\epsilon_{\max} \sim 10^{-4}$ (Owen 2005). Suppose there is no other dissipation mechanism other than gravitational wave radiation, then the typical damping time-scale of precession is $\tau_\theta^{\mathrm{rigid}} = 1.8 \times 10^6\ \mathrm{yr}(\epsilon/10^{-7})^{-2}(P/0.001\ \mathrm{s})^4(\mathrm{I}/10^{45}\ \mathrm{g\,cm^2})^{-1} \sim 10^6$–$10^{12}$ yr (Bertotti & Anile 1973; Cutler & Jones 2001). Therefore the bursting activity should remain with approximately the same period and duration provided that it is a solid quark star.

4 DISCUSSION

The source had only been observed in activity twice, the first time from 2002 September 30 to October 1, in which five 10-min duration bursts are detected in a period of 77 min (Hyman et al. 2005a). The second detection is in 2003 September 28; only one burst is detected at its decay phase (Hyman et al. 2005b). The source is likely in quiescent state during other observation epochs, such as the 1998 September 25 and 26 epochs (Hyman et al. 2005a,b). The sum of the observing time for GCRT J1745−3009 is only 70 h from 1989 to 2005. According to this sparse sampling, Hyman et al. (2005b) made their first crude estimation on the duty-cycle of the source activity (i.e. ∼10 per cent).

We propose that GCRT J1745−3009 is a precessing nulling radio pulsar because of the following reasons.

On the one hand, as we have demonstrated in Section 2, a precessing pulsar with a set of slightly constrained parameters could act like a bursting radio source if the time-resolution of the observation is not high enough to resolve the spin period of the pulsar. The period, duration, intensity and distance of the intriguing source, as well as the current limitation on its spectra, could be understood in this picture (Section 2). The transient nature of the source could be accounted for if the pulsar is an extremely nulling pulsar. Additionally, there is a possible link between the sources and the supernova remnant because the image of the source shows that the source is only 10 arcmin away from the centre of a shell-type supernova remnant (SNR) G359.1−0.5 (Hyman et al. 2005a,b). The proper motion of the source further inferred from the age of the supernova is ∼225 km s $^{-1}$, which is consistent with the typical kick velocities of neutron stars. This observation supports that GCRT J1745−3009 should be relevant to neutron stars.

On the other hand, the possibility of such a pulsar existing would not be too low. Precessing is rare in pulsars, as there are only a few pulsars which show tentative evidence for precession (Lyne, Pritchard & Smith 1988; Cadez, Galicic & Calvani 1997; Jones & Andersson 2001; Heyl & Hernquist 2002), i.e. the Crab pulsar, the Vela pulsar, PSR B1642−03, PSR B1828−11, the remnant of SN 1987A, Her X-1 and 1E 161348−5055. An extreme nulling phenomenon with ∼10 per cent duty cycle is also not common for known pulsars. Within the old data (Biggs 1992), we can only find two pulsars which show extremely nulling phenomena (PSR 0826−34 and PSR 1944+17). PSR B1931+24 is suggested to be in a nulling state for about 90 per cent of time (Cordes et al. 2004). Ali (2004) discovered extremely nulling phenomena (nulling fraction ∼70–95 per cent) from five pulsars (PSR J1502−5653; PSR J1633−5102, PSR J1853−0505; PSR J1106−5911; PSR J1738−2335) and 25 more candidates by analyzing Parkes Multibeam survey data. Accordingly, one could estimate the possibility of a precessing (or extremely nulling) pulsar to be $7/2000 \simeq 0.0035$, because the total number of discovered pulsars is ∼2000. Therefore, there should be one precessing and extremely nulling pulsar in every 10^5 pulsars, if the two phenomena are completely independent ($0.0035^2 \sim 10^{-5}$). However, the above possibility might have been underestimated, because of the following two arguments.(ii) Precessing pulsars and nulling pulsars are more difficult to detect than ordinary pulsars. Long-term and precise timing is necessary to confirm precessing phenomena, and a special searching method should be applied to discover an extremely nulling pulsar. This selection effect should thus reduce significantly the percentage of these kind of pulsars. (2). The ∼10 per cent duty-cycle of the source is a rough estimation because of the sparse sampling (Hyman et al. 2005b), based on the assumption that the burst in the 2003 September 28 observation is isolated. But, in the second activity, additional undetected bursts other than the one detected still cannot completely be ruled out. Therefore it is possible that the nulling fraction could be smaller (even much smaller) than ∼90 per cent. Therefore, it could be reasonable for us to detect a radio pulsar with both precessing and extremely nulling phenomena now.

Is our model less likely than others presented (models of double neutron star systems and of pulsar-like white dwarfs)? Note that the double neutron star model also needs one of the neutron stars to precess in order to account for the transient nature. The geodesic precession in the model predicts a 3-yr period of transient behaviour, which was not confirmed by the redetection of the source in 2003 Hyman et al. (2005b). Furthermore, the double neutron star model requires (i) an obital eccentricity of ∼0.3–0.6 in order to change the distance between the stars significantly, and (ii) the period of one of the neutron stars to be close to 0.3 s so that the shock distance from it can be close to its light-cylinder radius in order to trigger the on/off switch of the shock emission (Turolla et al. 2005). This would reduce the population of such double neutron star systems significantly. Whereas, our model allows the period, the inclination angle (i.e. α) and the angle of the line of sight (i.e. β) to vary in very large domains. It could be hasty to conclude that the double neutron star model is more likely than ours. The pulsar-like white dwarf model presented by Zhang & Gil (2005) is interesting. However, we have never seen any evidence before for the activity of a pulsar-like white dwarf in the large population of white dwarfs observed. The peculiarity, origin and population of pulsar-like white dwarfs need further investigation.

Future observations may uncover the nature of the source. Predictions for confirming or falsifying our model are provided below. It is predicted that a normal or millisecond pulsar should be detected if the bursting activity is observed in a much higher timing resolution.

To detect such a pulsar may be a little difficult given the small duty-cycle of the source and the low frequency of the burst activity. It is said that, in the direction of Galactic Centre, scattering would prevent the detection of a pulsating radio signal at the frequency of 330 MHz if the distance of the pulsar is in a range of ∼6–12 kpc (Turolla et al. 2005, and reference therein). However, it is still possible that pulsing signals could be observed due to the following reasons. (i) The distance of the source could be <6 kpc in our model, thus the scattering effect may be not strong enough to smear the pulses. (ii) It is possible that the pulsar can be detected by some gamma-ray detector if it has strong magnetospheric activity. (iii) Pulsed X-ray emission from the magnetosphere (due to magnetospheric activity) and/or the surface (due to polar cap heating) could be high enough to be detected by future instrument with a larger collecting area ($10^{-3}\dot{E}_{\rm rot}$ of a 10-ms period 10^{12}-G surface magnetic field pulsar gives 0.2 milli-Crab unabsorbed X-ray flux in a distance of 8 kpc).

In our model, the bursts induced by precession should rise in almost the same time in different frequencies if the radio beam is nearly frequency-independent. One could then observe that the bursting activity begins almost simultaneously in different channels after the dispersion measure is considered. The single pulse searching technique developed by Cordes et al. (2005) is also a good method for checking this prediction. It is said that this new method is expected to find radio transients (such as GCRT J1745−3009) and a significant number of pulsars which are not easily identifiable though the period searching technique (Cordes et al. 2005).

Finally, if the source is a precessing pulsar, its bursts should be *statistically* symmetric, as the emissivity of radio pulsars is generally variable. If future observation confirm the asymmetric fitting of the burst profile by Hyman et al. (2005a) and statistically rule out the possibility of average symmetric profile, then our model should be falsified.

If pulsing signals are detected by future observation, one could distinguish our model from that by Turolla et al. (2005) because a precessing pulsar behaves differently from a pulsar in a binary system in many aspects. Our model predicts that (i) the frequency shift induced by precession should be $\Delta\nu/\nu \sim P_{\rm s}/P_{\rm p} \sim 10^{-4}$ if $P_{\rm s} \sim 0.1$ s (while the shift due to orbital motion in a binary is $\Delta\nu/\nu$

10^{-3}); (ii) the pulse width of the pulsar should vary as the line of sight goes in and out of the beam of the pulsar; and (iii) the timing residual of the pulsar should vary in the precessing period, with an amplitude of the scale of neutron star radius[2] ($<10\,\mathrm{km}\,c^{-1}$, where c is the speed of light) which is much smaller than the timing residual induced by orbital motion ($10^5\,\mathrm{km}\,c^{-1}$). A fitting to the timing data of observation could distinguish between these two models. In summary, it will not be a problem to falsify our model if more observations are taken in the future.

5 SUMMARY

It is shown in this paper that the observed features of GCRT J1745−3009 can be explained by a precessing nulling radio pulsar with a precessing angle larger than 15°. No observation known hitherto could lead one to rule out the model presented or other models (e.g. wind–magnetosphere interaction in a neutron star binary, or a pulsar-like white dwarf). We also provided some theoretical predictions in the model and possible ways for falsifying our idea, which could be tested by future observations.

The discovery of a precessing pulsar with a large precession angle is interesting, which could provide evidence for a solid quark star if the pulsar spins at a period of $\gtrsim$10 ms. This is certainly very helpful to understand the nature of matter with supranuclear density.

ACKNOWLEDGMENTS

The authors thank Dr Xiang Liu and Mr Huagang Song for taking the observation in Nanshan. We are in debt to Professor Joel Weisberg for his stimulating comments and suggestions, and for improving the language. The helpful suggestions from an anonymous referee are sincerely acknowledged. This work is supported by NSFC (10273001), the Special Funds for Major State Basic Research Projects of China (G2000077602), and by the Key Grant Project of Chinese Ministry of Education (305001).

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[2] The timing residual and neutron star radius have the same dimension in the case where one sets $c = 1$.

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