Chin. J. Astron. Astrophys. Vol. 6 (2006), No. 3, 297–304
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

The Origin of Glitches in Pulsars — Phase Oscillation between Anisotropic Superfluid and Normal State of Neutrons in Neutron Stars *

Qiu-He Peng[1,2], Zhi–Quan Luo[1,3] and Chih-Kang Chou[4]

[1] School of Physics and Electronic Information, China West Normal University, Nanchong 637002
[2] Department of Astronomy, Nanjing University, Nanjing 210093; *qhpeng@nju.edu.cn*
[3] Department of Physics, Sichuan University, Chengdu 610065
[4] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012

Received 2005 October 23; accepted 2006 January 4

Abstract Considering neutron star heating by magnetic dipole radiation from $^3\mathrm{PF}_2$ superfluid neutron vortices inside the star, we propose a neutron phase oscillation model between the normal neutron Fermi fluid and the $^3\mathrm{PF}_2$ superfluid neutron vortices at the transition temperature of $T_{\rm trans} = (2-3)\times 10^8$ K. With this model we can qualitatively explain most of the observations on pulsar glitches up to date.

Key words: stars: neutron — pulsars: general

1 INTRODUCTION

The observed pulsar rotation periods often show that some young pulsars experience a glitch (or macro jump). The regular pulse signals could be occasionally shortened by glitches at typical amplitude of $\Delta\Omega_0/\Omega_0 \sim 10^{-6} - 10^{-10}$. These glitches are usually accompanied by a spin-down effect at a much larger rate: $\Delta\dot{\Omega}/\dot{\Omega} \sim 10^{-2} - 10^{-3}$ (Lyne et al. 2000). There are 189 glitches detected among 72 pulsars up to date (Yusup Ali, 2005, a talk on The 2005 Lake Hanas International Pulsar Symposium, Urumqi). Eighteen of these glitches detected in eight of the glitch pulsars are great glitches with $\Delta\Omega/\Omega > 10^{-6}$ (Lyne et al. 2000; Urama 2002), and nine of these were detected from PSR Vela over the last 26 years. There are also thirteen smaller glitches detected during the last 23 years from PSR Crab with smaller magnitudes (Lin & Zhang 2004). In some pulsars, besides such macro glitches, there are detected micro-glitches with jump amplitudes less than 10^{-12} in greater numbers.

Thus, there is a rough tendency for both the jump amplitude and the frequency of glitches to decrease with the pulse period as the pulsar ages (Lyne et al. 2000). Up to the present no glitches have been detected in pulsars with periods longer than 0.7 s.

Many papers have investigated the origin of the glitches and most of the proposed models are based on the interaction between superfluid neutron (mainly $^1\mathrm{S}_0$) vortices and the crust or proton superconductor magnetic flux tubes (Baym, Pethick & Pines 1969; Anderson & Itoh 1975; Alpar et al. 1981; Ruderman, Zhu & Chen 1998; Sedrakian & Cordes 1999). However, Andersson et al. declared that “the actual mechanism

* Supported by the National Natural Science Foundation of China.

that triggers the glitches remains unspecified in all these models" when they investigated their model based on the two stream superfluid instability (Andersson, Comer & Prix 2003).

In this paper, we will show that the great glitches are triggered by a neutron phase oscillation between the normal Fermi fluid and the $^3\mathrm{PF}_2$ superfluid vortices at phase transition temperature, $T_\lambda(^3\mathrm{PF}_2) = (2-3) \times 10^8$ K. This phase oscillation is derived and is based on our earlier research on the heating of neutron stars by the magnetic dipole radiation from the $^3\mathrm{PF}_2$ superfluid neutron vortices (Peng, Huang & Huang 1980; Huang et al. 1982).

2 SUPERFLUID NEUTRON VORTICES (SNV)

2.1 Formation of Superfluid Neutron Vortices

The interior of a nascent neutron star is in chaos with highly turbulent classical vortices at a temperature around 10^{11} K. At that time, the neutron system is in a normal non-superfluid Fermi gas state. However, the interior temperature will decrease rapidly due to some cooling process (Shapiro & Teukolsky 1984). A phase transition from the normal Fermi gas to the $^1\mathrm{S}_0$ superfluid neutron state occurs when the temperature T drops below the corresponding critical temperature $T_\lambda(^1\mathrm{S}_0(n))$ of the phase transition (at moment $t_0^{(S)}$)

$$T \le T_\lambda(^1\mathrm{S}_0(n)) = \Delta(^1\mathrm{S}_0(n))/(2k) \approx 1 \times 10^{10}\,\mathrm{K}\,, \quad (1)$$

where $\Delta(^1\mathrm{S}_0(n))$ is the neutron pairing energy gap in the $^1\mathrm{S}_0$ state and k is the Boltzmann constant. The density range of an isotropic $^1\mathrm{S}_0$ superfluid neutron state is constrained by $1 \times 10^{11} < \rho < 1.6 \times 10^{14}$ (g cm^{-3}).

Gap calculations show that the pairing gap varies with the density of neutrons. The transition temperature for neutrons to condense into the $^1\mathrm{S}_0$ state is a strong function of the density. In general, the condensation of the star is a gradual process. As the temperature decreases, the parts of the star with the highest pairing gap condense first, and the parts with the lowest pairing gap condense last. However, the situation of the anisotropic $^3\mathrm{PF}_2$ superfluid neutron state is different from that of the isotropic $^1\mathrm{S}_0$ superfluid neutron state.

The nucleonic $^3\mathrm{PF}_2$ pairing gaps in neutron stars have been investigated by Elgagøy et al. (1996) in detail (see fig. 8 of Elgagøy et al. 1996). Their essential results can be briefly summarized as follows:

(1) The maximum pairing energy gap of the $^3\mathrm{PF}_2$ neutron is about 0.048 MeV at $k_\mathrm{F} \approx 1.96\,\mathrm{fm}^{-1}$, ($k_\mathrm{F}$ is the Fermi wave number of the neutrons);
(2) The $^3\mathrm{PF}_2$ neutron energy gap is a constant to within 3% around the maximum in the wave number space over the rather wide range $1.8 < k_\mathrm{F} < 2.1$ (fm^{-1}), corresponding to the density range $3.3 \times 10^{14} < \rho < 5.2 \times 10^{14}$ (g cm^{-3});
(3) The $^3\mathrm{PF}_2$ neutron energy gap rapidly decreases outside the above range, i.e., when $\rho < 3.3 \times 10^{14}$ g cm^{-3} or $\rho > 5.2 \times 10^{14}$ g cm^{-3}.

Our model is based on the results calculated by Elgagøy et al. (1996). In particular, we note that the anisotropic $^3\mathrm{PF}_2$ superfluid neutron state appears (at the moment $t_0^{(P)}$, $t_0^{(P)} > t_0^{(S)}$), when the temperature decreases further below another critical temperature $T_\lambda(^3\mathrm{PF}_2(n))$.

$$T \le T_\lambda(^3\mathrm{PF}_2(n)) = \Delta(^3\mathrm{PF}_2(n))/2k \approx 2.8 \times 10^8\,\mathrm{K}\,. \quad (2)$$

This means that another phase transition will occur in the wide density regime $3.3 \times 10^{14} < \rho < 5.2 \times 10^{14}$ (g cm^{-3}) when the temperature is just at the maximum transition temperature $T_\lambda(^3\mathrm{PF}_2(n))$:

$$\text{Normal Fermi neutron system} \Rightarrow\ ^3\mathrm{PF}_2\ \text{Superfluid}\,. \quad (3)$$

2.2 Angular Momentum Deposited in Superfluid Neutron Vortices

It is widely recognized that angular momentum is difficult to transfer out of a rapidly collapsing neutron star core during the collapse phase of supernova explosion. It can be shown from the conservation law of angular momentum that a rotationally collapsed core of a supernova has an initial rotational period of sub-milliseconds (Zheng et al. 2004). Moreover, a significant fraction of the angular momentum of the rotational pre-supernova is reserved in the turbulent classical vortices of the nascent neutron star during supernova explosion. These classical vortices are immediately transformed to quantized (neutron) vortices once the superfluid neutron state appears in the neutron star.

The total angular momentum of the neutron star is

$$J_{\rm tot} \sim 1 \times 10^{47} I_{45} (\Omega / 10^2 {\rm s}^{-1}) \,, \tag{4}$$

where I_{45} is the moment of inertia of the neutron star in units of 10^{45} g cm^{-2}, Ω is its angular velocity of rotation. The angular momentum of the crust can be cast in the form

$$\begin{aligned} J^{(\rm Crust)} &\approx M^{(\rm Crust)} R_{\rm NS}^2 \cdot \Omega \sim \bar{\rho}_{\rm Crust} R_{\rm NS}^4 \Delta R \cdot \Omega \\ &\sim 1 \times 10^{39} (\bar{\rho}_{\rm Crust} / 10^8 \,{\rm g\,cm^{-3}}) R_{\rm NS,6}^5 (\Delta R / 0.1 R_{\rm NS}) (\Omega / 10^2 \,{\rm s}^{-1}) \,, \end{aligned} \tag{5}$$

where $R_{\rm NS}$ is the radius of the neutron star, $R_{\rm NS,6}$ is $R_{\rm NS}$ in units of 10^6 cm, and ΔR is the thickness of the crust.

The interior of the neutron star is believed to rotate faster than the crust. The angular momentum of the anisotropic ($^3{\rm PF}_2$) superfluid revolving around the axis of the neutron star is

$$\begin{aligned} J(^3{\rm PF}_2) &\approx M(^3{\rm PF}_2) R^2(^3{\rm PF}_2) \cdot \Omega_{\rm SF} \sim (4\pi/15) \bar{\rho}(^3{\rm PF}_2) R^5(^3{\rm PF}_2) \cdot \Omega_{\rm SF} \\ &\sim 2.3 \times 10^{41} \tfrac{\bar{\rho}(^3{\rm PF}_2)}{\rho_{\rm nuc}} R_5^5(^3{\rm PF}_2) (\tfrac{\Omega_{\rm SF}}{10^2 {\rm s}^{-1}}) \,, \quad \text{(c.g.s.)} \end{aligned} \tag{6}$$

where $\Omega_{\rm SF}$ is the angular velocity of the superfluid around the rotation axis, $\rho_{\rm nuc}$ is the nuclear density in units of 2.8×10^{14} g cm^{-3}, and R_5 is the radius of the anisotropic superfluid in units of 10^5 cm.

The total angular momentum deposited in all vortices (the superfluid neutrons evolved around the axis of the vortex) is

$$J_{\rm SNV} = N_{\rm nuetron} \cdot \bar{n} h \approx 4.7 \times 10^{30} \bar{n} \big[\bar{\rho}(^3{\rm PF}_2)/\rho_{\rm nuc}\big] R_{\rm NS,6}^3 \,, \quad \text{(c.g.s)} \tag{7}$$

where $\bar{n}$ is the average value of the quantum number for all the superfluid neutron vortices, and $N_{\rm neutron}$ is the total number of neutrons in the superfluid state.

For the $^1{\rm S}_0$ isotropic superfluid neutrons, $\rho \sim 1 \times 10^{11} - 1.6 \times 10^{14}$ g cm^{-3}, $R_s \sim 10^6$ cm. On the other hand, for the $^3{\rm PF}_2$ anisotropic superfluid neutron vortices, the density is $\rho \sim (3-5) \times 10^{14}$ g cm^{-3}. The radius of the anisotropic superfluid layer is $R(^3{\rm PF}_2) \sim 10^5$ cm and its thickness is about 10^4 cm. The angular momentum for these two types of superfluid neutron vortices are therefore

$$J_{\rm SNV}(^1{\rm S}_0) \sim 1.7 \times 10^{28} \bar{n} \bar{\rho}_{12} R_6^3(^1{\rm S}_0) \;, \qquad \text{(c.g.s.)} \tag{8}$$

$$J_{\rm SNV}(^3{\rm PF}_2) \sim 1.4 \times 10^{27} \bar{n} (\bar{\rho}/\rho_{\rm nuc}) R_5^2(^3{\rm PF}_2) \,. \qquad \text{(c.g.s.)} \tag{9}$$

It is well known that the superfluid neutron vortices are energetically more favored in the ground state of $n = 1$ when in thermodynamical equilibrium. However, we suppose that in young pulsars the superfluid vortices are in a highly non-equilibrium state. This is because a significant fraction of the angular momentum of the spinning pre-supernova is reserved in the turbulent classical vortices of the nascent neutron star during the supernova explosion. Therefore, the initial quantum number n_0 of these quantized vortices (both $^1{\rm S}_0$ and $^3{\rm PF}_2$ superfluid neutron vortices) are very large after the above-mentioned phase transitions. For typical superfluid neutron vortices, we have $J_{\rm NSV}(^3{\rm PF}_2) > 10^{-10} - 10^{-8} J(^3{\rm PF}_2)$ and $\bar{n} > 10^4 - 10^6$.

2.3 Heating by Magnetic Dipole Radiation from the $^3\mathrm{PF}_2$ Superfluid Neutron Vortices

Magnetic dipole radiation is emitted as a ^{3}PF$_2$ neutron Cooper pair with an abnormal magnetic moment revolves around the axis of the superfluid vortex (Peng, Huang & Huang 1980) and Huang et al. 1982). The radiation frequency is the same as the rotation frequency of the superfluid neutron rotating around its vortex line, $\omega(r) = n\hbar(2m_n r^2)^{-1}$ ($\hbar$ is the Planck constant divided by 2π, m_n is the neutron mass, and r is the radial distance from the vortex line). Most of the radiation are emitted in the X-ray range and absorbed by the surrounding matter, thereby heating the neutron star. The heating rate is

$$W_{\rm heat} = KQ(n)P_{\rm SF}^{-1}\,, \qquad Q(n) = \overline{n^3}\big/\bar{n}\,,$$

$$K \approx 1\times 10^{30}\left[\overline{\left(\frac{\Delta_n(^3\mathrm{PF}_2)}{0.05\,\mathrm{MeV}}\right)^2\left(\frac{B}{10^{13}\,\mathrm{G}}\right)^2}\right]R_5^3(^3\mathrm{PF}_2)\,. \qquad \text{(c.g.s.)} \tag{10}$$

Here B denotes the strength of the magnetic field in the interior of the neutron star.

2.4 Phase Oscillation of $^3\mathrm{PF}_2$ Neutron Superfluid Vortices

The phase transition happens at time $t_0^{(P)}$ when ^{3}PF$_2$ neutron superfluid vortices start to emerge. The entire angular momentum deposited in the classical turbulent vortex is transferred to the quantized vortices during this phase transition. Hence the initial quantum number of the ^{3}PF$_2$ neutron superfluid vortices is in the range of 10^4–10^6. Strong X-ray radiation is emitted by the rapidly rotating magnetic dipole of the ^{3}PF$_2$ Cooper pairs of neutrons revolving around the vortex line. The X-ray radiation is absorbed by the electrons in the normal Fermi gas on its way out, which heats the interior of the neutron star (Peng, Huang & Huang 1980; Huang et al. 1982). If the heating rate due to the X-ray emitted by the neutron ^{3}PF$_2$ Cooper pairs exceeds the cooling rate by other physical processes, the temperature may increase. For instance, as an example, the modified Urca cooling rate is (Shapiro & Teukolsky 1984)

$$L_\nu^{\rm (Urca)} = 8.5\times 10^{37}\,\mathrm{erg}\cdot\mathrm{s}^{-1}\cdot\frac{M}{M_\odot}\left(\frac{\rho_{\rm nuc}}{\rho}\right)^{1/3}\left(\frac{T}{6\times 10^8\,\mathrm{K}}\right)^8. \tag{11}$$

It should be noted that all of the cooling rate in the superfluid would be reduced by a factor $\beta_1 = \exp[-T/T_\lambda(^3\mathrm{PF}_2)]$. However, the heating rate (10) is probably not modified by the inclusion of the superfluid coherence. This is because the radiation by the ^{3}P$_2$ neutrons is different from that by the normal Fermi neutrons. This is a rather difficult question, however, and has not been solved so far as we are aware. The least we can say is this: even though the heating rate may be decreased by a factor β, with $1 \geq \beta > \beta_1$, both the β and β_1 values are not too small, because the difference of the ^{3}P$_2$ neutron superfluid temperature (T) with the transition temperature $T_\lambda(^3P_2F(n))$ is not large just after the phase transition in Equation (3).

Comparing Equation (10) $\times\beta$ with Equation (11) $\times\beta_1$, we may deduce that the heating power of the magnetic dipole radiation of ^{3}PF$_2$ neutron superfluid vortices may exceed the cooling rate (e.g., 10^{38} erg s^{-1}), when the initial vortex quantum $n_0 > 10^3$ and $P_{\rm SF}$ (the rotation period of ^{3}PF$_2$ superfluid around the axis of the neutron star) is 10 ms.

As long as the temperature resulting from the heating mechanism is slightly higher than the phase transition temperature, $T_\lambda(^3\mathrm{PF}_2(n))$, the ^{3}PF$_2$ Cooper pair will break up and the nascent ^{3}PF$_2$ neutron superfluid vortices disappear immediately at a time $t = t_1^{(P)} > t_0^{(P)}$. Then, the superfluid state suddenly returns to the normal Fermi gas state, namely

$$^3\mathrm{PF}_2\text{NSV state} \Rightarrow \text{ Normal neutron (Fermi) fluid}\,. \tag{12}$$

At the same time, the quantized vortices of the ^{3}PF$_2$ neutron superfluid are transformed to the classical turbulent vortices with high angular momentum, hence the magnetic dipole radiation heating mechanism disappears. This departure from thermodynamic equilibrium then cools the interior of the neutron star again. The temperature of the normal neutron system is barely (or a little) higher than the phase transition temperature, $T_\lambda(^3\mathrm{PF}_2(n))$, just after the phase transition (12), and it would soon decrease to $T_\lambda(^3\mathrm{PF}_2(n))$ by physical cooling processes in the absence of heating mechanism by the magnetic dipole radiation due to the $^3\mathrm{PF}_2$ neutron superfluid vortices. The $^3\mathrm{PF}_2$ neutron (anisotropic) superfluid state appears again at the moment $t = t_2^{(P)} \geq t_1^{(P)}$ when the decreasing temperature is just below the transition temperature $T_\lambda(^3\mathrm{PF}_2(n))$. In other words, the process depicted above shows a pattern of phase oscillation:

$$^3\mathrm{PF}_2\mathrm{NSV\ state} \Rightarrow \mathrm{Normal\ neutron\ (Fermi)\ fluid} \Rightarrow ^3\mathrm{PF}_2\ \mathrm{NSV\ state}\ . \quad (13)$$

The emergence of the intermediate normal neutron Fermi turbulent fluid is transitory and the duration of its existence is very short: $\Delta t = (t_2^{(P)} - t_1^{(P)})$ ($\sim$ several years). The turbulent classical vortices are transformed into the quantized vortices of $^3\mathrm{PF}_2$ neutron superfluid vortices again afterwards.

The phase oscillation repeats itself between these two states. It can be shown by Equation (10) that, the quantum number n of the $^3\mathrm{PF}_2$ neutron superfluid vortices in this case can be as high as $n > 10^3$, and then gradually decreases with repeated phase oscillations. After n decreases to the level when the heating rate by the magnetic dipole radiation of $^3\mathrm{PF}_2$ neutron superfluid vortices no longer exceeds the cooling rate, the phase oscillation will stop and the $^3\mathrm{PF}_2$ neutron superfluid vortices no longer return to the normal neutron Fermi fluid.

3 ESSENCE OF GLITCHES

3.1 Kick-off of the First Glitch

It is generally believed that the interior superfluid rotates around the axis of the neutron star faster than the crust. The difference in the two rotation rates can be maintained for a long time because the interaction between the superfluid neutrons and the crust plasma is very weak. This weak interaction originates from the interaction between the magnetic moment of the electrons either with the abnormal magnetic moment of normal neutrons in the core of the vortices or with the magnetic moment of $^3\mathrm{PF}_2$ neutron Cooper pair. However, the scenario of the short-lived normal neutron fluid oscillation between the two successive phase transitions described in Equation (13) is totally different.

The question of coexistence of the $^3\mathrm{PF}_2$ superfluid vortices and proton superconductor magnetic tubes is still open. Link (2003) came to the conclusion that there can be no coexistence of the $^3\mathrm{PF}_2$ superfluid vortices and proton superconductor magnetic tubes in the interior the pulsar according to the analysis of the timing observation for PSR B1818–11, although this coexistence may exist in the theoretical calculation in nuclear physics.

The calculation of the proton pair energy gap is rather uncertain, but it is certain that the region of the proton superconductor is not identical with the region of the $^3\mathrm{PF}_2$ superfluid (e.g., fig. 9 of Elgagøy et al. 1996; fig. 4 of Zhou et al. 2004 and fig. 1 of Grogorian & Voskresensky 2005). Therefore, there is a strong coupling between the normal neutrons (after the phase transition from the $^3\mathrm{PF}_2$ superfluid) with the normal protons in the region without the proton superconductor.

However, there are some normal protons in the core of the proton superconductor magnetic tubes due to the Heisenberg's uncertain principle (it is similar to the scenario of the neutron superfluid vortices) even in the region of the proton superconductor. The coupling between the normal neutrons (after the phase transition from the $^3\mathrm{PF}_2$ superfluid) with the normal protons in the core of the proton superconductor magnetic tubes is still very strong.

Due to this strong interaction, the short-lived rapid rotating normal neutron fluid in the deep interior will suddenly spin up the slowly rotating plasma crust in a very short period, Δt. This explains the glitch phenomenon observed in the glitch pulsars. More specifically, the amplitude of the glitch $\Delta\Omega_0/\Omega_0$, derived from the jumps of the crust rotation rate, is very small ($< 10^{-5}$). Hence the angular momentum transferred from the $^3\mathrm{PF}_2$ neutron superfluid with rapid rotation around the axis of the neutron star to the outer crust with slower rotation, is much smaller than the original angular momentum of the outer crust. The amplitude of the glitch is determined mainly by the following factors:

(1) The difference between the rotating frequency of the primary $^3\mathrm{PF}_2$ superfluid prior to the phase transition and that of the crust;
(2) The strength of the weak magnetic moment interaction between the neutrons and the electrons;

(3) The duration of the interaction, $\Delta t = (t_2^{(P)} - t_1^{(P)})$. It is rather difficult to calculate Δt, and that it is different for different pulsars and for different glitches. The typical time scale is about several years according to the observations.

3.2 Repeat of Glitches

The duration for the reiteration of the phase transitions Δt is very short, and the angular momentum deposited in the second classical turbulent vortices is still very large. Yet, the quantum number of the second $^3\mathrm{PF}_2$ neutron superfluid vortices is slightly smaller than that of the first $^3\mathrm{PF}_2$ neutron superfluid vortices, i.e., $n_2(^3\mathrm{PF}_2(n)) < n_1(^3\mathrm{PF}_2(n))$. As long as the heating rate of the magnetic dipole radiation of $^3\mathrm{PF}_2$ neutron superfluid vortices exceeds the cooling rate, the following processes will repeat over and over, with n decreasing each time: X-ray emitted from the magnetic dipole radiation due to the $^3\mathrm{PF}_2$ neutron superfluid vortices continuously heat the neutron star interior while the temperature increases and reaches the transition temperature $T_\lambda(^3\mathrm{PF}_2(n))$, the superfluid then transforms back to the normal neutron Fermi state via the sudden phase transition. Glitch phenomenon then follows and the temperature of the neutron star decreases down to $T_\lambda(^3\mathrm{PF}_2(n))$ by cooling physical processes and the normal neutron Fermi fluid transforms back to the $^3\mathrm{PF}_2$ neutron superfluid vortices through the phase transition.

The variation of the jump amplitude $\Delta\Omega_0/\Omega_0$ of the rotation rate for the successive glitches of the same pulsar is very small, since the angular momentum of the outer crust is much smaller than that of the $^3\mathrm{PF}_2$ superfluid. Moreover, the jump amplitude of the glitches has a tendency, though not an obvious one, due to some stochastic factors in the classical turbulent vortices of the neutron fluid.

3.3 Disappearance of the Glitches

The interval of the successive glitches is determined by the competition of the heating rate due to the X-ray by the $^3\mathrm{PF}_2$ NSV against the cooling rate. As described in the previous section, the quantum number, $n_i(^3\mathrm{PF}_2(n))$ of the i^{th} $3\mathrm{PF}_2$ neutron superfluid vortices, is smaller than that of the $(i-1)^{\mathrm{th}}$ $^3PF_2$ neutron superfluid vortices, so the heating rate of the X-ray by the $^3\mathrm{PF}_2$ neutron superfluid vortices is getting lower each time. The phase oscillation of neutron system will finally stop when the heating rate of the X-ray by the $^3\mathrm{PF}_2$ NSV is lower than the cooling rate. At this point, the $^3\mathrm{PF}_2$ state can no longer return to the normal state, and the glitches cease to appear. This result agrees with the observational facts that no glitch has ever been detected in the old pulsars with periods $P > 0.7\,\mathrm{s}$ (Lyne 2000).

4 NO GLITCH FROM MILLISECOND PULSARS

No glitches except micro-glitches have been detected in millisecond pulsars. This can be explained easily in our theory as follows.

It is generally believed that pulsars result either from type II supernova (SNII) or from the accretion-induced collapse (AIC) of a white dwarf (WD) in a binary (Lorimer 2005; Fryer et al. 1999; Qian & Wasserburg 2003). The SNII explosion is much more violent than the accretion-induced collapse. The mass of a neutron star is significantly greater than the mass of the latter. The reason is simply that either a longer delay in supernova explosion (due to the ram pressure of the falling material) causes most of this material to remain part of the neutron star, or that the neutron-rich material falls back on the neutron star (the fallback is driven by the reverse shock that is created as the supernova shock wave traversing the envelop of the massive star, e.g., Fryer et al. 1999). Hence, the central density of the former neutron stars with higher mass is much higher than that of the latter neutron stars with lower mass, and the former has a significant anisotropic ($^3\mathrm{PF}_2$) neutron superfluid region, while the latter has a very small, or even no region of $^3\mathrm{PF}_2$ neutron superfluid.

We believe that glitches are a general phenomenon for the first kind of the young pulsars with $P < 0.7\,\mathrm{s}$ (189 glitches have been detected among 72 pulsars up to date),while they are absent in those neutron stars originating from AICs of white dwarfs. This is an important deduction from our theory.

It is widely accepted that the millisecond (radio) pulsars are old recycled pulsars and that most of them are found in the binary systems with low mass companions (Lorimer 2005).

Out of a total of 66 millisecond pulsars found in the Galactic disk, 15 are isolated. It was proposed that these millisecond pulsars have ablated their companion via their strong relativistic winds as may be happening in the PSR B1957+20 (Kluzniak et al. 1988).

It is also known that only seven X-ray millisecond pulsars have been found among the low mass X-ray binaries, but no millisecond pulsars have been found in high mass X-ray binaries (Lorimer 2005). The companions in the low-mass X-ray binaries evolve and transfer matter onto the neutron stars on much longer time-scales, spinning them up to periods as short as a few ms. Therefore, almost all of the millisecond pulsars may be taken as initially being in binary systems with low mass companions.

From the virial theorem, however, the binary will be disrupted if more than half the total pre-supernova mass is ejected from the system during the (assumed symmetric) explosion (Hills 1983; Bhattacharya & van den Heuvel 1991; Lorimer 2005). Therefore, it is impossible to form a neutron star in a binary with low mass companions via an SNII explosion of a massive star and thus it is reasonable to assume that the initial neutron stars of the millisecond pulsars originate from the AICs.

In fact, AICs have been proposed as an alternative channel to form neutron stars in globular clusters and Galactic disk, and the most common of these are millisecond pulsars (Fryer et al. 1999 and their references). The old recycled pulsars (millisecond pulsars) originating from the AIC white dwarfs are low mass neutron stars with a very small or even no ^{3}PF$_2$ neutron superfluid. Moreover, their interior temperature had already decreased below the critical temperature of the phase transition in Equation (2) over a much longer time-scale.

Recent observation shows that millisecond pulsar can be massive with masses greater than 1 $M_\odot$, e.g., PSR J0737–3039A (Lyne et al. 2004). The central density of such a massive millisecond pulsar is far greater than the nuclear density, and the anisotropic ^{3}PF$_2$ neutron superfluid should appear if the star is in equilibrium structurally. Moreover, the interior temperature of some millisecond pulsars could increase to higher than 2×10^8 K via the accretion process. It seems that glitches could originate from these massive millisecond pulsars.

However, the timescale of readjusting the central density of the millisecond pulsar by accretion in a close binary is very long (may be much longer than the age of the Universe) due to the stiff structure with very high density for the massive millisecond pulsars. So no phase transition from the ^{3}PF$_2$ neutron superfluid to the normal Fermi neutron fluid can happen and no glitches can be seen from these millisecond pulsars.

Thus, we may come to the conclusion that no glitches can originate from the millisecond pulsars due to their ^{3}PF$_2$ neutron superfluid being very small in extent.

5 DISCUSSION

Our model is rather a preliminary one at the present; although it may qualitatively explain the pulsar glitches, more sophisticated quantitative analyses in terms of an exact statistical theoretical formalism for many particle systems are really needed. Nevertheless, it seems that our model on the basis of the theoretical results obtained by Elgagøy et al.(1996) is certainly very useful and very fruitful for studying pulsar glitches.

Our model may even be extended to explain some of the unusual glitches with gradual drop in amplitude. Instead of refining our model in terms of the exact and rigorous Green Function Formalism, we feel that it would be more fruitful to make more detailed investigation and quantitative predications on the basis of our model in its present form.

More recently, the nucleonic ^{1}S$_0$ and ^{3}PF$_2$ pairing gaps in neutron stars have been reinvestigated by Zhou et al. (2004). It is shown in fig. 2 of their paper that the ^{3}PF$_2$ neutron energy gap is indeed basically a constant in a rather wide interior region of the neutron stars in two cases: a) Using the free single particle approximation and taking into account the direct effect of the nucleonic three- body forces on the gap. b) Using the Brueckner- Hartree-Fock approximation containing contributions due to nucleon-nucleon two-body and three-body forces and nucleon-hyperon forces (using the Argonne V $_{18}$ potential).

The behavior of the ^{3}PF$_2$ pairing gap varies rapidly with the density when the Urbana UIX three body force is supplemented in their calculation. In view of the extra complications brought about by the inclusion of three-body effects, our picture in the present paper must be properly revised. This issue should be further investigated, and the ultimate test for our approach is comparing with observations.

Acknowledgements This research is supported by the National Natural Science Foundation of China (Nos. 10573011 and 10273006), and the Doctoral Program Foundation of State Education Commission of China.

References

Alpar M. A., Anderson P. W., Pines D., Shaham J., 1981, ApJ, 249L, 29
Andersson N., Comer G. L., Prix R., 2003, Phys. Rev. Lett., 90, 091101
Anderson P. W., Itoh N., 1975, Nature, 256, 25
Bhattacharya D., van den Heuvel E. P. J., 1991, Phys. Rep., 203, 1
Baym G., Pethick C. J., Pines D., 1969, Nature, 224, 673
Elgagøy Ø., Engvik L., Hjorth-Jensen M., Osnes E., 1996, Phys. Rev. Lett., 77, 1428
Fryer C., Benz W., Herant M., Colgate S. A., 1999, ApJ, 516, 892
Grogorian H., Voskresensky D. N., 2005, astro-ph/0105678
Hills J. G., 1983, ApJ, 267, 322
Huang J-H., Lingenfelter R. E., Peng Q.-H., Huang K.-L., 1982, A&A, 113, 9
Kluzniak W., Ruderman M., Shaham J., Tavani M., 1988, Nature, 334, 225
Lin J. R., Zhang S. N., 2004, ApJ, 615, L133
Link B., 2003, Phys. Rev. Lett., 91, 101101
Lorimer Duncan R., Binaries and Millisecond Pulsars, 2005, astro-ph/0511258
Lyne A. G., Shemar S. L., Smith, F. G., 2000, MNRAS, 315, 534
Lyne A. G., Burgay M., Kramer M. et al., 2004, Science, 303, 1153
Peng Q.-H., Huang K.-L., Huang J.-H., 1980, in: Proceedings of a Conference for High Energy Astrophysics
Qian Y.-Z., Wasserburg G. J., 2003, ApJ, 588, 1099
Ruderman M., Zhu T., Chen K., 1998, ApJ, 492, 267
Sedrakian A., Cordes J. M., 1999, MNRAS, 307, 365
Shapiro S. L., Teukolski S. A., 1984, A Wiley-Interscience Publication, p.321
Urama J. O., 2002, MNRAS, 330, 58
Zheng X.-P., Yang S.-H., Li J.-R. et al., 2003, ApJ, 585, L135
Zheng X.-P. et al., 2003, astro-ph/0310523
Zhou X.-R., Schulze H.-J., Zhao E.-G. et al., 2004, Phys. Rev. C, 70, 048802