Small glitches: the role of strange nuggets?

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Abstract Pulsar glitches, i.e. the sudden spin-ups of pulsars, have been detected for most known pulsars. The mechanism giving rise to this kind of phenomenon is uncertain, although a large data set has been built. In the framework of the starquake model, based on Baym & Pines, the glitch sizes (the relative increases of spin-frequencies during glitches) $\Delta\Omega/\Omega$ depend on the released energies during glitches, with less released energies corresponding to smaller glitch sizes. On the other hand, as one of the dark matter candidates, our Galaxy might be filled with so called strange nuggets (SNs) which are relics from the early Universe. In this case collisions between pulsars and SNs are inevitable, and these collisions would lead to glitches when enough elastic energy has been accumulated during the spin-down process. The SNs-triggered glitches could release less energy, because the accumulated elastic energy would be less than that in the scenario of glitches without SNs. Therefore, if a pulsar is hit frequently by SNs, it would tend to have more small glitches, whose values of $\Delta\Omega/\Omega$ are smaller than those in the standard starquake model (with larger amounts of released energy). Based on the assumption that in our Galaxy the distribution of SNs is similar to that of dark matter, as well as on the glitch data in the ATNF Pulsar Catalogue and Jodrell Bank glitch table, we find that in our Galaxy the incidences of small glitches exhibit tendencies consistent with the collision rates between pulsars and SNs. Further testing of this scenario is expected by detecting more small glitches (e.g., by the Square Kilometre Array).

Key words: pulsars — glitches — quark-cluster stars — strange nuggets

1 INTRODUCTION

Glitches are one type of pulsar timing irregularity, observed as discrete changes in the pulsar rotation rate. Although a large data set for glitches has been built, the physical picture behind them still remains to be well understood. Generally, there are two main models for the origin of glitches. The first one is the starquake model which regards a glitch as a starquake of a spinning down pulsar resulting from the rearrangements of its crust (Baym & Pines 1971). The second one regards glitches as the result of a rapid transfer of angular momentum between the inner superfluid and the outer crust (Anderson & Itoh 1975). Although the starquake model is now less popular and fails to give a reasonable explanation for the glitch activity of the Vela pulsar (PSR B0833-45) (Baym & Pines 1971; Alpar et al. 1996), the rearrangements of the crust could be the trigger for the transfer of angular momentum described in the second model (Espinoza et al. 2011). What is certain to us is that glitch behaviors reflect the interior structure of pulsars, and data about glitches can give important information on the dense matter inside pulsars. Some correlations between glitch activities and the charac-

teristic age of pulsars have been found, e.g., younger pulsars would have larger glitch spin-up rates $\dot\Omega$ and glitch rates $\dot N_g$ (Espinoza et al. 2011). The data on glitches make us believe that glitches are caused by changes in interior structures. Nevertheless, can glitches be related to some exterior trigger?

Another topic, seemingly having no relation with the phenomenon of glitches, is connected to relics of the early Universe. In the Standard Model of cosmology, during its expansion history, our Universe underwent several kinds of phase transitions. The quantum chromodynamics (QCD) phase transition, which occurred when the age of the Universe was about 1 millisecond and the temperature was about 200 MeV, would leave a huge amount of relics, if the phase transition was of the first order (Witten 1984; Madsen 1999). Witten (1984) suggested that most of the deconfined quarks would be concentrated in the form of dense and invisible strange nuggets (SNs). In fact, the formation and evolution of SNs depend on the physical properties of hot quark-gluon plasma and the state of dense matter, so the exact baryon number A of each SN (or the mass spectrum of SNs) is hard for us to determine. Although some calculations have been

made, e.g. Bhattacharjee et al. (1993); Bhattacharyya et al. (2000); Lugones & Horvath (2004), the results were model dependent. On the other hand, the properties of SNs could be constrained by astrophysics, if they do exist in the Universe.

As proposed by Witten, SNs could be a kind of dark matter candidate (Witten 1984). Although being baryonic matter, SNs could behave like dark matter because of the very low charge-to-mass ratio, which comes from the fact that SNs are made of nearly equal numbers of u, d and s quarks. As will be shown in this paper, the mass of each SN could be as high as $\sim 10^7$ g (with baryon number $A \sim 10^{34}$ and size $\sim 10^{-2}$ cm). Whether such macroscopic and baryonic particles are compatible with observations, such as the formations of galaxies and stars, should be studied in some detail, but unfortunately even numerical simulations in the framework of conventional microscopic dark matter particles have not reached a consensus about the cosmic structure formation (e.g. see Gao & Theuns (2007)). Similar macroscopic dark matter candidates are the so called massive compact halo objects (MACHOs) (Paczynski 1986), and some constraints from observations have been found. Very heavy MACHOs with masses above $10^{-7} M_\odot$ have been excluded from being primary dark matter particles (Tisserand et al. 2007; Metcalf & Silk 2007), but dark matter could be made out of baryons and antibaryons in the form of compact stellar type objects or primordial black holes with a sufficiently wide mass spectrum (Dolgov et al. 2009). The latest constraints on MACHOs can be found in Monroy-Rodríguez & Allen (2014), which define the upper bound for the mass to be $5 M_\odot$. Studies about MACHOs that can be used to infer whether macroscopic dark matter particles with masses below $10^{-7} M_\odot$ are in conflict with either observations or simulations remain to be seen, and the related problem about how the SNs affect the structure formation is worth exploring in the future.

SNs as dark matter should not lead to conflicts with observations, and on the other hand observations could give constraints on the properties of SNs. Madsen & Riisager (1985) found that if dark matter is completely composed of SNs, consistency between the prediction of Big Bang Nucleosynthesis (BBN) and the observational result for the helium abundance would not be affected if the radius of SNs exceeds $\sim 10^{-5}$ cm, corresponding to the baryon number A of each SN being $A \gtrsim 10^{24}$ (assuming that matter inside SN has a density comparable to nuclear matter density). SNs in the early Universe would affect structure formation. On the other hand, SNs could help us to understand some astrophysical phenomena. The formations of high-redshift ($z \sim 6$) supermassive black holes ($10^9 M_\odot$) (Fan et al. 2003) could be the result of SNs (Lai & Xu 2010), and in this picture the baryon number of each SN should be smaller than about 10^{35}. Another astrophysical consequence of SNs in our present Universe is that if they pass Earth, some seismic signals would be detected (Anderson 2003; Herrin et al. 2006). More detailed studies about the effects of SNs on some important processes, such as the formation of early galaxies and black holes, are expected.

In this paper, we propose that another astrophysical consequence is related to pulsar glitches. If SNs formed in the early Universe and survived during cosmic evolution, they would fill the Milky Way (MW), and they would inevitably be accreted by stars. With a strong gravitational field, the accretion of SNs by pulsars would not be rare events. In fact, the accretion of dark matter particles by the Sun as well as by pulsars has been studied (Press & Spergel 1985; Kouvaris 2008), and some interesting consequences have been discussed (i.e. Goldman & Nussinov 1989; Huang et al. 2014). Assuming that in our Galaxy the distribution of SNs is similar to that of dark matter, we can then know the accretion rates of SNs by pulsars. Whether such accretion would affect the properties of glitches depends both on the states of matter inside pulsars and the glitch mechanism. In this paper, we assume that pulsars are solid strange stars and apply the starquake model (Baym & Pines 1971) as the glitch mechanism. In fact, starquake glitch models of solid strange stars have been studied (Zhou et al. 2004; Peng & Xu 2008; Zhou et al. 2014), which show that glitch behaviors and the energy released are consistent with observations. Moreover, in the starquake model, the recovery process after a glitch could be explained through damped oscillations (Zhou et al. 2004). Interestingly, glitches as the result of some external triggers are not proposed by us first. Huang & Geng (2014) proposed an scenario that the anti-glitch of the magnetar 1E 2259+586 (Archibald et al. 2013) could be induced by collision of a solid body.

In the framework of the starquake model (Baym & Pines 1971), the relation between glitch sizes (the relative increases of spin-frequencies during glitches) $\Delta\Omega/\Omega$ and the released energy during glitches can be derived straightforwardly, which shows that less amount of released energy during glitches would correspond to smaller glitch sizes. Pulsar structure would be affected by collisions between the pulsar and SNs, which could help the pulsar to release its elastic energy that accumulated during the spin-down process, probably manifesting as detected glitches. In this scenario, the amount of energy released in this glitch E_{re} would be smaller than that in the scenario without SNs, as the energy released by the SN itself is negligible. Therefore, for a particular pulsar, the incidence of small glitches should be the same as its accretion rate of SNs. Here the sizes of glitches are relatively small, and the values of $\Delta\Omega/\Omega$ are smaller than those in the standard starquake scenario without SNs.

In this paper, we demonstrate the relation between accretion of SNs and the incidences of small glitches in the starquake model. Based on the assumption that in our Galaxy the distribution of SNs is similar to that of dark matter, as well as on the glitch data available in the ATNF Pulsar Catalogue and Jodrell Bank glitch table, we find that in our Galaxy the incidences of small glitches exhibit a

tendency consistent with the collision rates of pulsars and SNs. It should be noted that, although in this paper we assume pulsars only have a solid structure, our conclusions would not change quantitatively if pulsars only have solid crusts.

This paper is arranged as follows. In Section 2 we will derive the relation between glitch sizes and the released energies during a glitch, in a starquake described by the solid strange star model. Based on this, the relation between accretion of SNs and small glitches will be demonstrated in Section 3. In Section 4 we will obtain the expected accretion rates of SNs by pulsars and compare them with the observed event rates for small glitches. Conclusions and discussions are made in Section 5.

2 GLITCHES IN THE STARQUAKE MODEL

Following Baym & Pines (1971), we will derive the released energies in terms of the glitch sizes (the relative increases of spin-frequencies during glitches) $\Delta\Omega/\Omega$. In addition, we do the calculation in the framework of the solid strange star model, which means that all parts of the stars have a solid structure, but the results would not change quantitatively in the model of neutron stars with only solid crusts. When a solid star spins down, strain energy develops until the stresses reach a critical value. At that moment, a starquake occurs and the stresses are relieved, and its rotation rate is suddenly increased by conservation of angular momentum (similar calculations can be found in Zhou et al. (2004) and Zhou et al. (2014)).

The total energy of a rotating star with mass M, radius R and angular momentum L is

$$E = E_0 + \frac{L^2}{2I} + A\epsilon^2 + B(\epsilon - \epsilon_0)^2, \qquad (1)$$

where E_0 is the total energy in the non-rotating case, and

$$\epsilon = \frac{I - I_0}{I_0}, \qquad (2)$$

is the oblateness of the star with moment of inertia I, which reduces to $I_0 = 0.4MR^2$ in the non-rotating case, and ϵ_0 is the initial oblateness. The coefficient measuring the departure of gravitational energy relative to the non-rotating case is $A = \frac{3}{25}GM^2/R$, and the coefficient measuring the strain energy is $B = \frac{57}{50}VC_{44}$ where C_{44} is the shear modulus and $V = 4\pi R^3/3$ is the whole volume of the star (Baym & Pines 1971). The angular momentum is conserved during a glitch, so the sudden change in oblateness $\Delta\epsilon$ is directly related to the relative jump in angular momentum Ω

$$\Delta\epsilon = \epsilon_{-i} - \epsilon_{+i} = -\frac{\Delta\Omega_i}{\Omega_{+i}} = \frac{\Omega_{+i} - \Omega_{-i}}{\Omega_{+i}}, \qquad (3)$$

where the spin-up rate mentioned above, $\Delta\Omega/\Omega$, is just $\Delta\Omega_i/\Omega_{+i}$ during the i-th glitch, and the subscripts "$+i$" and "$-i$" denote quantities right before and right after the

i-th glitch respectively. The initial oblateness before the i-th glitch ϵ_{0i} is (Baym & Pines 1971)

$$\epsilon_{+i} = \frac{I_0\Omega_{+i}^2}{4(A + B)} + \frac{B}{A + B}\epsilon_{0i}. \qquad (4)$$

The evolution of ϵ with time is shown in Zhou et al. (2004).

For simplicity we assume that when a starquake occurs, all stresses are relieved and the released energy is E_{re}. Energy conservation gives

$$\frac{1}{2}I_{+i}\Omega_{+i}^2 + A\epsilon_{+i}^2 + B(\epsilon_{+i} - \epsilon_{0i})^2$$
$$= \frac{1}{2}I_{-i}\Omega_{-i}^2 + A\epsilon_{-i}^2 + E_{re}, \qquad (5)$$

then it is easy to get

$$\frac{\Delta\Omega_i}{\Omega_{+i}} = \frac{E_{re}\mu}{2B\sigma_c} = \frac{2E_{re}(A + B)}{BI_0}\frac{1}{\Omega_{0i}^2 - \Omega_{+i}^2}, \qquad (6)$$

where σ_c is the critical mean stress of the star, which corresponds to the occurrence of a glitch, and $\mu = 2B/V$ is the mean shear modulus of the star.

The value of parameter B for solid strange stars is uncertain now, because the structure and state of quark matter inside pulsars are still unsolved problems. The shear modulus C_{44} for a body centered cubic lattice of nuclei with number density n, charge Ze and lattice constant a, interacting via an unscreened Coulomb interaction, could be written as (Baym & Pines 1971) $C_{44} \sim 0.4Z^2e^2n/a \sim 10^{30}$ erg cm^3. Based on the fact that the strong interaction is about 2 to 3 orders of magnitude stronger than the electromagnetic interaction, we infer that the value of C_{44} for solid strange stars is about in the range $10^{32} - 10^{33}$ erg cm^{-3} (Xu 2003), then $B = \frac{57}{50}VC_{44} \sim 10^{52}$ erg $(C_{44}/10^{33}$ erg cm$^{-3})(R/10$ km$)^3$. Comparing with $A \sim 6 \times 10^{52}$ erg $(M/1.4\ M_\odot)^2(10$ km$/R)$, we can approximate that $(A + B)/B \simeq 10$, then

$$\frac{\Delta\Omega_i}{\Omega_{+i}} \simeq \frac{E_{re}(A + B)}{BI_0\Omega_{0i}}\frac{1}{|\dot\Omega|\Delta t}$$
$$\simeq 10^{-6}\left(\frac{E_{re}}{10^{34}\ \text{erg}}\right)\left(\frac{10^{45}\ \text{g cm}^2}{I_0}\right)\left(\frac{P}{1\ \text{s}}\right)^3$$
$$\left(\frac{10^{-15}}{\dot P}\right)\left(\frac{10^7\ \text{s}}{\Delta t}\right), \qquad (7)$$

where $P = 2\pi/\Omega$ is the spin period, and Δt is the time interval between two successive glitches. The result is consistent with figure 2 in Zhou et al. (2014) which shows the upper limit of the released energy during glitches (for the bulk invariable case).

3 STRANGE NUGGETS AND GLITCHES

3.1 Cosmological QCD Phase Transition and SNs

The cosmological QCD phase transition, which took place when the age of the Universe was about 10^{-6} seconds and

the temperature was about 200 MeV, could have interesting astrophysical consequences. If it was of first order, a huge amount of SNs would form and survive the cooling of the Universe. SNs have been proposed as dark matter candidates (Witten 1984) although they are baryonic, due to their extremely low charge-to-mass ratio (a detailed review of SNs can be found in Madsen (1999)). SNs are composed of up, down and strange quarks, with densities higher than nuclear matter density. The state of SNs is uncertain, because this problem is related to low-energy QCD theories, which is the same problem as the interior structure of pulsar-like compact stars.

SNs with small baryon number A would have evaporated in the early Universe, but the lower limit for the baryon number A of stable SNs is difficult for us to derive. On the other hand, some constraints on the size of SNs have been made by considering their possible astrophysical consequences. If the existence of SNs would not break the consistency between prediction of BBN and the observed result for the helium abundance, the baryon number of each SN should be larger than about 10^{24} (assuming that SNs have a uniform size) (Madsen & Riisager 1985). Using some more accurate data, the lower limit on baryon number has been improved to be $\sim 10^{25}$ (Lai & Xu 2010). If the formations of high-redshift ($z \sim 6$) supermassive black holes ($10^9 M_\odot$) (Fan et al. 2003) were the results of SNs, then the baryon number of each SN should be smaller than about 10^{35} (Lai & Xu 2010).

What effects would SNs cause in our present Galaxy? As shown in Witten (1984), the mass fraction of SNs could be as large as that of dark matter. If SNs are stable and survive in the present Universe, they would fill our Galaxy, with a total mass comparable with that of dark matter. Circulating in the Galaxy, they would be accreted by stellar objects, especially pulsars whose gravitational fields are strong, and the accretion rate by a particular pulsar is then related to its position in the Galaxy.

We will thus derive the accretion rates of SNs by pulsars. We assume that SNs have the same distribution as that of dark matter, and the fraction of the total mass of SNs compared to the total mass of dark matter is η, whose value is chosen to be 0.1 in the following calculations. For the dark matter density distribution as a function of the distance from the Galaxy center r, we choose the NFW form (Navarro et al. 1997)

$$\rho_{\rm dm}(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)\left[1 + \left(\frac{r}{r_s}\right)^2\right]}, \qquad (8)$$

where $\rho_s = 0.26\,{\rm GeV\,cm^{-3}}$ and $r_s = 20\,{\rm kpc}$. The number density of SNs is $n_x = \eta\rho_{\rm dm}/m_x$, where m_x is the mass of each SN. For simplicity, we assume that all SNs have the same mass, with $m_x = Am_b$ where A is the baryon number of each SN and $m_b \sim 1$ GeV is the average mass of a baryon. The circular velocity v of each SN is then

$$v(r) = \sqrt{\frac{GM(r)}{r}} \qquad (9)$$

where $M(r) = \int_0^r \rho(r')4\pi r'^2 dr'$ is the total mass inside a sphere with radius r. To derive the accretion rates of SNs by pulsars, we can borrow results for the accretion rates of dark matter particles by stars/pulsars. The accretion rate of SNs with number density n_x by a pulsar with mass M and radius R is (Press & Spergel 1985; Kouvaris 2008)

$$\mathcal{F} = 4\pi^2 n_x \left(\frac{3}{2\pi v^2}\right)^{3/2} \frac{2GMR}{1 - 2GM/R}\frac{1}{3}v^2, \qquad (10)$$

where $(1 - 2GM/R)^{-1}$ is a factor taking into account the effect of general relativity.

3.2 SNs and Glitches

The sample of all of the observed glitches also shows that the glitch sizes $\Delta\Omega/\Omega$ are spread between 10^{-11} and 10^{-4} with a bimodal distribution which peaks at approximately 10^{-9} and 10^{-6}, respectively (Espinoza et al. 2011; Yu et al. 2013). The glitch sizes have not been well explained, but Equation (7) tells us that the glitch sizes are related to the energies that are released during glitches. When the stresses reach a critical value, the star releases strain energies $E_{\rm re}$, which are stored in the star during the spinning down process due to the rigidity of the star. The released energy $E_{\rm re}$ in a glitch can be inferred from observations, if it is large enough for us to detect. For example, a constraint on the X-ray flux enhancement of the Vela pulsar 35 days after a glitch with $\Delta\Omega/\Omega \sim 10^{-6}$ has been calculated (Helfand et al. 2001), which indicates that the upper limit of the energy released is about 10^{36} erg.

If a pulsar accretes an SN, its structure would be affected, as the SN would interact with particles inside the pulsar. The details of such an interaction are hard to derive, because they are related to both the interior states of pulsars and SNs. For an estimation we take the parameters used by Zhou et al. (2004), where glitches occur as a consequence of starquakes in solid strange stars. When the stress reaches a critical value σ_c, $(\epsilon - \epsilon_0) \sim 10^{-3}$, then the strain energy density $\rho_{\rm strain}$ could be approximated as

$$\rho_{\rm strain} \simeq C_{44} \cdot (\epsilon - \epsilon_0)^2 \simeq 10^{-7}\,{\rm MeV\,fm^{-3}}$$
$$\left(\frac{C_{44}}{10^{32}\,{\rm erg\,cm^{-3}}}\right)\left(\frac{\epsilon - \epsilon_0}{10^{-3}}\right)^2. \qquad (11)$$

If the lattice (quark or quark-cluster) density inside a pulsar is ~ 0.3 fm^{-3}, then to break the lattice structure each lattice should obtain about 10^{-6} MeV. Just before hitting the surface of a pulsar, the energy of an SN is about $(A/10^{33}) \times 10^{35}$ MeV, so if each lattice it goes through gains energy V, then the total number of lattices it would interact with is $N \sim 10^{41} \cdot (A/10^{33}) \cdot (10^{-6}\,{\rm MeV}/V)$. The cross section of the interaction between an SN and the particles inside the pulsar could be approximated as the geometric cross section of the SN, which is $\sim 10^{-4}$ cm$^2 \cdot (A/10^{33})^{2/3}$, so the length of the trajectory is ~ 10 km $\cdot (A/10^{33})^{1/3} \cdot (10^{-6}\,{\rm MeV}/V)$.

Although the exact behavior related to the breaking criterion is unknown, the above estimation shows that it is

possible for an SN with $A \gtrsim 10^{33}$ to break the whole solid body (or crust) of the star, which would give rise to a glitch. The amount of energy released by such glitches triggered by SNs would be smaller than that of normal glitches, as the latter occur when the elastic energy accumulated reaches a critical value. According to Equation (7), in the starquake model the glitch size $\Delta\Omega/\Omega$ is proportional to the amount of energy released E_{re}, so the sizes of SN-triggered glitches should be smaller than those of normal glitches.

The amount of energy released E_{re} in normal glitches is also difficult for us to quantify. It should be different from pulsar to pulsar, and could even be different between different glitch-events in one pulsar. The released energy is mainly from accumulated elastic energy, and it could be inferred that more massive pulsars should release more energy during glitches. This dependence of E_{re} on the pulsar mass M could eliminate some uncertainties in both E_{re} and the moment of inertia I_0. Consequently, from Equation (7) we can infer that we could use typical values of both E_{re} and I_0 to reduce the difference in $\Delta\Omega/\Omega$ between different pulsars. Because the upper limit of the energy released in one glitch event of the Vela pulsar is about 10^{36} erg (Helfand et al. 2001; Zhou et al. 2014), it seems reasonable to set $E_{\mathrm{re}} = 10^{35}$ erg for normal glitches.

Based on the above arguments, we could estimate the occurrence rates of SN-triggered glitches, which may be identified as those with $\Delta\Omega/\Omega < \Delta\Omega/\Omega(E_{\mathrm{re}} = 10^{35}$ erg$)$. On the other hand, we take Equation (10) to have the expected occurrence rates for SN-triggered glitches. Combined with observational data, we could then compare these two rates for different pulsars.

It is worth mentioning that although the accretions of SNs by pulsars would lead to bursts in X-rays, it is not easy for them to be detectable. The gravitational energy released by accretion of an SN with $A = 10^{34}$ on a typical pulsar is about 10^{30} erg. With degenerate electrons having Fermi energy ~ 10 MeV, the heat conductivity of strange matter must be very high, which means that strange stars will be thermalized by any heat flow. The process of thermalization is complicated, but the time-scale τ_{enh} for releasing enhanced X-ray bursts resulting from the accretions could be estimated as $\tau_{\mathrm{enh}} \gg \tau \sim 10^{30}$ erg$/L_{\mathrm{bol}} \sim 0.1$ s $\cdot (10^{31}$ erg s$^{-1}/L_{\mathrm{bol}})$, where L_{bol} is the bolometric X-ray luminosity (see Yu & Xu (2011) and references therein). The luminosity of an enhanced X-ray burst resulting from one accretion is then $L_{\mathrm{enh}} = 10^{30}$ erg$/\tau_{\mathrm{enh}} \ll 10^{30}$ erg$/\tau \sim 10^{31}$erg s^{-1}, i.e., L_{enh} is much smaller than the bolometric X-ray luminosity. Therefore, the accretions of SNs by some near and well-monitored compact stars, such as RX J0720.4-3125 and RX J1856-3754, would lead to X-ray variability which is difficult to detect, so the accretions would not be in conflict with observations.

4 COMPARISON OF ACCRETION RATES OF SNS BY PULSARS AND GLITCH DATA

As demonstrated in Section 3, the collision between an SN and a pulsar could result in small glitches compared to those in the scenario without SNs. To compare with glitch data, we choose 25 pulsars whose recorded numbers of glitches are larger than 5 (Espinoza et al. 2011). The data for glitch sizes $\Delta\Omega/\Omega$ are from the Jodrell Bank glitch table (Espinoza et al. 2011) (*http://www.jb.man.ac.uk/pulsar/glitches/html*), and the rotation periods and period derivatives, as well as the locations of pulsars compared to the barycenter of the solar system (which are used to derive the distances of pulsars from the center of the MW) are from the ATNF Pulsar Catalogue (Manchester et al. 2005) (*http://www.atnf.csiro.au/people/pulsar/psrcat/*).

The accretion rates of SNs by a pulsar (which are taken to be the expected event rates of small glitches) with mass $M = 1.4M_\odot$ and radius $R = 10$ km, which are located at a distance r from the Galaxy center, are shown in Figure 1, where solid, dashed and dash-dotted lines correspond to three values of baryon number A for each SN respectively. These lines denote the expected occurrence rates for small glitches with $\Delta\Omega/\Omega < \Delta\Omega/\Omega(E_{\mathrm{re}} = 10^{35}$ erg$)$. The data points (blue asterisks) show the observed event rates of small glitches with $\Delta\Omega/\Omega < \Delta\Omega/\Omega(E_{\mathrm{re}} = 10^{35}$ erg$)$ and the distances from the center of the MW of the corresponding pulsars. Here the event rates are derived as the ratio of the number of glitches satisfying $\Delta\Omega/\Omega < \Delta\Omega/\Omega(E_{\mathrm{re}} = 10^{35}$ erg$)$ to the whole time interval from the first to the last observed glitches. The axes in Figure 1 are scaled in logarithm, so the points corresponding to zero observed value are not shown in the figure, except for J0537-6910. The observed value of J0537-6910 is shown on the horizontal axis although the value is zero, because it is the most distant one from the MW center among all these pulsars, and is consistent with our expectation. In the calculations, we assume that SNs constitute 10% of dark matter ($\eta = 0.1$). Although the mass ratio of SNs to dark matter η is unknown, it is proportional to A under a certain accretion rate. For instance, if $\eta = 0.01$, then the values of A should be one tenth of those in Figure 1.

We can see that, except for the pulsars with a zero event rate, the event rates for glitches with $\Delta\Omega/\Omega < \Delta\Omega/\Omega(E_{\mathrm{re}} = 10^{35}$ erg$)$ decrease with distances of pulsars from the center of the MW, which show the same tendency as the accretion rates of SNs by pulsars. To demonstrate the correlation of glitch rates with the distances from the Galactic center, we use the Pearson correlation coefficient ρ, which is a measure of the linear dependence between two variables.[1] The result for data in Figure 1 (excluding J0537-6910) is $\rho \simeq -0.5$. Although the interpretation of a

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[1] For two variables x and y, ρ is defined as $\rho = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2}\sqrt{\sum_i (y_i - \bar{y})^2}}$. In general $|\rho| \leqslant 1$, where $\rho = 1$ represents total positive correlation, $\rho = 0$ represents no correlation, and $\rho = -1$ represents total negative correlation.
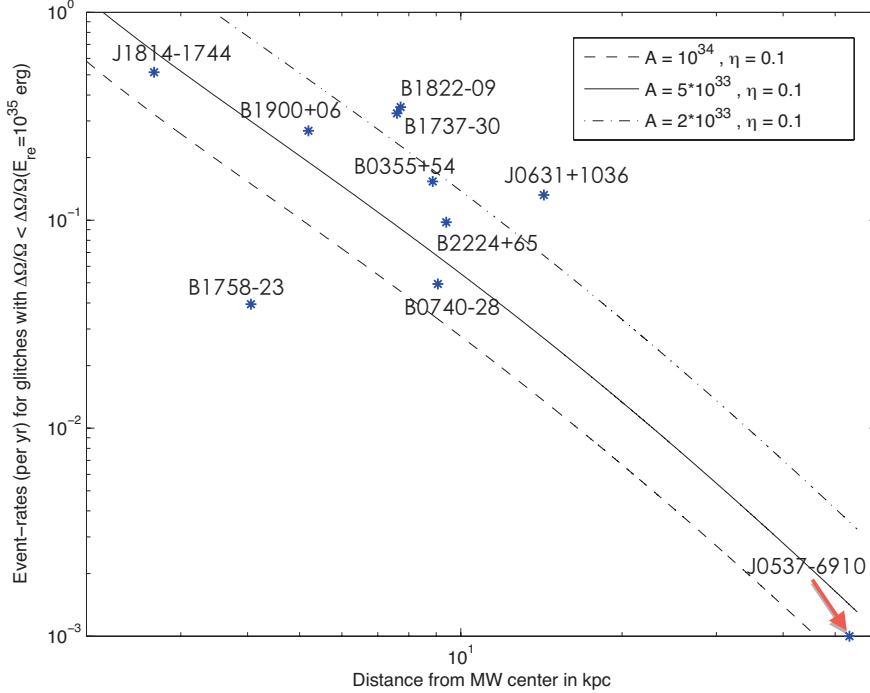
Fig. 1 The accretion rates of SNs, with baryon number $A = 10^{34}$, $A = 5 \times 10^{33}$ and $A = 2 \times 10^{33}$, by a pulsar located at the distance of r from the center of the MW, are plotted in dashed, solid and dash-dotted lines respectively. In this paper, these lines denote the expected occurrence rates for pulsars with $\Delta\Omega/\Omega < \Delta\Omega/\Omega(E_{\mathrm{re}} = 10^{35}$ erg). Data points: Observed rate per year of glitch-events with $\Delta\Omega/\Omega < \Delta\Omega/\Omega(E_{\mathrm{re}} = 10^{35}$ erg), for pulsars whose recorded number of glitches is larger than 5. The data point corresponding to J0537-6910 in the horizontal axis corresponds to zero observed value.

certain value of ρ will be different in different contexts and is not applicable to all problems, the value -0.5 may imply the trend that the more distant a pulsar is from the Galactic center, the smaller rate of small glitches it will have.

The dispersion of data points might mainly result from two factors: (1) the fact that not all the SNs have the same baryon number A; and (2) the mass and radius of each pulsar would be different from typical values. All of the 25 pulsars are listed in Table 1, including their spin-down ages, numbers of glitches (NGlt) and distances from the center of the MW. The upper part of the table includes nine pulsars that have glitch events with $\Delta\Omega/\Omega < \Delta\Omega/\Omega(E_{\mathrm{re}} = 10^{35}$ erg), and the lower part of the table includes 16 pulsars that have no glitch event with $\Delta\Omega/\Omega < \Delta\Omega/\Omega(E_{\mathrm{re}} = 10^{35}$ erg).

Now we discuss why some pulsars defy our expectation, i.e. have no glitches satisfying $\Delta\Omega/\Omega < \Delta\Omega/\Omega(E_{\mathrm{re}} = 10^{35}$ erg). Comparing the data in Table 1, we can see that the spin-down ages of pulsars in the lower part of Table 1 are generally smaller than those in the upper part. As demonstrated before, we identify the SN-triggered glitches as the ones whose sizes satisfy $\Delta\Omega/\Omega < \Delta\Omega/\Omega(E_{\mathrm{re}} = 10^{35}$ erg), which means we assume that all of the pulsars have the same amount of released energy during normal glitches. This assumption is certainly oversimplified, and different pulsars should have differ-

ent values of E_{re}. The values of E_{re} for young pulsars should be larger than those of old pulsars, because the former ones are more active. The pulsars in the lower part of Table 1 might mean that we should impose some larger values of E_{re} for the normal glitches. However, at the present stage we lack a reliable description about the difference in E_{re} between different pulsars, so we only use the criterion $\Delta\Omega/\Omega < \Delta\Omega/\Omega(E_{\mathrm{re}} = 10^{35}$ erg) to identify the SN-triggered glitches.

The result shown in Figure 1 is only the first attempt to reveal the correlation between glitch behaviors and the location of pulsars inside the MW. Whether a collision between SNs and pulsars could be a glitch trigger needs to be tested by further observations.

5 CONCLUSIONS AND DISCUSSIONS

In this paper we propose a possibility that small glitches in pulsars could be the result of accreting SNs which are relics of QCD phase transition in the early Universe. This kind of glitch-trigger mechanism could be a possible astrophysical consequence of SNs that formed in the early Universe and survive today in our present Galaxy. The trigger mechanism is demonstrated in the framework of a starquake in solid strange stars. With typical parameters for a solid strange star model, the collision between an SN and a pulsar could lead to the solid body (or crust) of the star

Table 1 25 Pulsars Whose Recorded Number of Glitches (NGlt) Is Larger Than 5

Pulsar name	Spin-down age[1] (yr)	NGlt[2]	Distance from the MW center[1] (kpc)
B0355+54	5.64×10^5	6	8.87
J0631+1036	4.36×10^4	15	14.29
B0740–28	1.57×10^5	8	9.06
B1737–30	2.06×10^4	33	7.60
B1758–23	5.83×10^4	12	4.06
J1814–1744	8.46×10^4	7	2.67
B1822–09	2.32×10^5	6	7.72
B1900+06	1.38×10^6	6	5.19
B2224+65	1.12×10^6	5	9.39
J0205+6449	5.37×10^3	6	10.21
B0531+21	1.26×10^3	25	9.99
J0537–6910	4.93×10^3	23	53.16
J0729–1448	3.52×10^4	5	11.30
B0833–45	1.13×10^4	17	8.04
B1046–58	2.03×10^4	6	7.66
J1105–6107	6.33×10^4	5	7.50
B1338–62	1.21×10^4	23	7.18
J1413–6141	1.36×10^4	7	6.37
J1420–6048	1.30×10^4	5	6.32
B1757–24	1.55×10^4	5	3.44
B1800–21	1.58×10^4	5	5.05
B1823–13	2.14×10^4	6	4.28
J1841–0524	3.02×10^4	5	5.50
B1951+32	1.07×10^5	6	7.46
J2229+6114	1.05×10^4	6	9.31

Notes: [1] From ATNF Pulsar Catalogue (Manchester et al. 2005)(*http://www.atnf.csiro.au/people /pulsar/psrcat/*); [2] From the Jodrell Bank glitch table (Espinoza et al. 2011) (*http://www .jb.man.ac.uk/pulsar/glitches/html*)

breaking, which would give rise to a glitch. The amount of energy released in such SN-triggered glitches would be smaller than that in normal glitches, as the latter occur when the elastic energy accumulated reaches a critical value. In the starquake model the glitch size $\Delta\Omega/\Omega$ is proportional to the amount of energy released E_{re}, so the sizes of SN-triggered glitches should be smaller than those of normal glitches. Taking into account that some uncertainties in both E_{re} and the mass M for different pulsars could be mutually eliminated to some degree, we distinguish the SN-triggered glitches from normal glitches by their sizes with $\Delta\Omega/\Omega < \Delta\Omega/\Omega(E_{\mathrm{re}} = 10^{35} \text{ erg})$, with typical values for the mass M and radius R.

Combining the assumption that a huge amount of dark matter (we assume 10% in this paper) is in the form of SNs with glitch data in the ATNF Pulsar Catalogue and Jodrell Bank glitch table, we compare the collision rates of pulsars and SNs (i.e. the expected rates of glitches with $\Delta\Omega/\Omega < \Delta\Omega/\Omega(E_{\mathrm{re}} = 10^{35} \text{ erg})$) and the observational data. Among 25 pulsars that we choose whose recorded numbers of glitches are larger than 5, nine pulsars have glitch events with $\Delta\Omega/\Omega < \Delta\Omega/\Omega(E_{\mathrm{re}} = 10^{35} \text{ erg})$ whereas 16 pulsars have no such event. The incidences of glitches with $\Delta\Omega/\Omega < \Delta\Omega/\Omega(E_{\mathrm{re}} = 10^{35} \text{ erg})$ for the nine pulsars exhibit a tendency consistent with the col-

lision rates of pulsars and SNs, if the baryon number of each SN is $A \sim 10^{33}$. The remaining 16 pulsars are generally younger than the nine pulsars, so the zero event rate might result from the fact that younger pulsars should release more energy during glitches.

The mass (or baryon number A) of each SN is unknown, which depends on the properties of hot quark-gluon plasma and the state of dense matter. From an astrophysical point of view, we want to give some constraints combined with observations. It seems that the constraints from BBN ($A \gtrsim 10^{25}$), from supermassive black holes at high redshifts ($A \lesssim 10^{35}$) and in this paper from pulsar glitches ($A \sim 10^{33}$) are consistent. Certainly, SNs should have some mass spectrum instead of a uniform mass, so the mass corresponding to the baryon number we give above could be seen as the peak value of a very steep spectrum. More detailed studies about the spectrum are expected in the future.

The result we give in this paper is the first attempt to show the possibility that SNs could be a kind of glitch trigger, demonstrated by the fact that there are some correlations between glitch behaviors and the location of pulsars inside the MW. The crude assumptions we make in this paper should be improved in further work, e.g. by providing some more quantitative descriptions about the depen-

dences of E_{re} on pulsar masses and ages. In addition, a detailed description about the mechanism of small glitches that result from collisions between SNs and pulsars also depends on the states of matter inside both pulsars and SNs. At any rate, whether the SNs could be a kind of glitch trigger remains to be explored.

Glitches with small sizes are now difficult for us to detect, so in some sense, to demonstrate the relation between SNs and glitches by a comparison between expected and observed events from recent data should be inadequate. However, we still try to do this because some positive results have been shown, which makes it possible that more data in the future would give us a clear answer. A more convincing demonstration about whether SNs could trigger small glitches can only be done when more small glitches are detected. This work emphasizes the importance of detecting small glitches, which is also one of the goals of the Square Kilometre Array (SKA) that is expected to have exquisite timing precision and will dramatically increase the number of sources detected in surveys (Watts et al. 2015). We are expecting to test our model in the future by advanced radio facilities, e.g., SKA and a facility in China, the Five-hundred-meter Aperture Spherical Telescope (FAST).

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