The micro-glitch in PSR B1821-24: A case for a strange pulsar?

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ABSTRACT

The single glitch observed in PSR B1821-24, a millisecond pulsar in M28, is unusual on two counts. First, the magnitude of this glitch is at least an order of magnitude smaller ($\Delta \nu/\nu \sim 10^{-11}$) than the smallest glitch observed to date. Secondly, all other glitching pulsars have strong magnetic fields with $B \gtrsim 10^{11}$ G and are young, whereas PSR B1821-24 is an old recycled pulsar with a field strength of $2.25 \times 10^9$ G. We have suggested earlier that some of the recycled pulsars could actually be strange quark stars. In this work we argue that the crustal properties of such a strange pulsar are just right to give rise to a glitch of this magnitude, explaining the scarcity of larger glitches in millisecond pulsars.

Key words: pulsars: glitch–pulsar: individual (B1821-24)–stars: neutron–stars: strange

1 INTRODUCTION

Timing irregularities seen in pulsar rotation rates are of two kinds - a) timing noise: continuous, noise-like fluctuations in rotation rate; and b) glitches, sudden increases in rotation rate, often followed by a period of relaxation towards the unperturbed pre-glitch rotation trend. It is widely believed that these events are caused by sudden and irregular transfer of angular momentum to the crust of the star by an interior super-fluid rotating faster (Baym, Pethick, & Pines 1969; Anderson & Itoh 1975; Alpar et al. 1981). The result is a fractional increase ($\delta \nu$) in the rotational frequency ($\nu$) of the pulsar, such that $\sim 10^{-10} \lesssim \delta \nu/\nu \lesssim 10^{-4}$ (Shemar & Lyne 1996; Lyne, Shemar, & Smith 2000; Janssen & Stappers 2006).

In the forty years since the pulsars were discovered almost 300 such glitches, large and small, have been seen in about a hundred pulsars. However, the March 2001 glitch of PSR B1821-24 (Cognard & Backer 2004) is a misfit both on account of the nature of the pulsar and the magnitude of the glitch. Typically glitches are experienced by young pulsars (majority have a characteristic age $\sim 10^4 - 10^5$ yr) with high magnetic fields ($B \sim 10^{13} - 10^{14}$ G) whereas PSR B1821-24 is an old (characteristic age $\sim 3 \times 10^7$ yr) pulsar with a magnetic field strength of $2.25 \times 10^9$ G. This is actually a millisecond pulsar ($P \sim 3$ ms) in the globular cluster M28 and a member of the recycled pulsar population. Moreover the glitch magnitude ($\delta \nu/\nu$) is calculated to be $9.5 \times 10^{-12}$ which is at least an order of magnitude smaller than the smallest glitch observed so far.

The idea that some of the pulsars could be strange stars, instead of neutron stars, has been around for many years (Alcock, Farhi, & Olinto 1986). There have also been specific cases like SAX J1808.4-3658 (Li et al. 1999) which have been proposed to be strange stars. Contrarily it has been argued that the magnetic field of a strange star is unlikely to decay whether isolated or in a binary (Konar 2000), whereas according to the standard scenario of pulsars accretion-induced field decay plays a very important role in the evolutionary history of a binary neutron star (Konar & Bhattacharya 2001). So there is no definite consensus on the case for strange stars. However, recycled millisecond pulsars (MSP) are stable objects with little or no evolution of the magnetic field and it is possible for some of them to be strange stars. In a recent work we have argued that the MSPs could actually be strange stars with a limiting value of the magnetic field (Ray Mandal et al. 2006). But one principal difficulty in explaining the observational properties of pulsars using strange star model has been the phenomenon of glitch. Therefore it is of some interest to note that the MSPs, barring B1821-24, are yet to show any significant glitch behavior even though the cumulative study of MSPs is close to $10^3$ years. This again goes well with our hypothesis that some of the highly evolved MSPs can be strange stars.

Therefore our aim is to establish that a typical strange star, with a thin hadronic crust, can sustain a glitch. And such a glitch, in addition to its magnitude being consistent with that seen in B1821-24, probably has a different origin than the rest of glitches observed so far.

To that intent, in Section 2 we discuss the standard theory of glitch and note how the micro-glitch seen in B1821-24 could be of a dif-
2 **Pulsar Glitch : The Energetics**

Glitches were first observed in the Crab and the Vela and they mainly occur in younger pulsars. While the classical glitch has been regarded as a sudden increase in rotational frequency followed by an exponential recovery of a large fraction, it is not typical of glitches in most pulsars. The dominant effect is an increase in frequency with very little recovery [Shemar & Lyne 1996, Lyne, Shemar, & Smith 2000, Krawczyk et al. 2003]. The standard theory describes a glitch as an event in which a significant number of vortices are suddenly unpinned from the crust nuclei, angular momentum is transferred to the crust, and the vortices are eventually re-pinned. Wherever recoveries are seen they typically have a relaxation time of the order of days to months which has been explained by invoking an interaction of the crust with the super-fluid component in the interior [Baym, Pethick, & Pines 1969, Sauls 1989]. In particular, the so-called vortex creep model is known to provide adequate description of the glitch relaxation [Alpar et al. 1981, Alpar, Langer, & Sauls 1984, Alpar et al. 1993, Alpar et al. 1996]. The actual mechanism that triggers the glitch remains unspecified in almost all models.

Though a large number of pulsars exhibit glitches, certain points about the glitching pulsars need to be noted. Fig.1 and Fig.2 show histograms of the characteristic ages and the inferred magnetic (dipolar) field strengths of the glitching pulsars (for a complete list of known glitching pulsars see table-I of Melatos et al. 2008). It is obvious that these pulsars are mostly relatively young. Only a few have spin-down ages similar to B1821-24, but none of them are of the recycled variety. And no pulsar, barring B1821-24, with a magnetic field smaller than $10^{11}$ G shows a glitch.

Moreover if we look into the energy budget of the glitching pulsars an interesting fact emerges. The rotational kinetic energy of a pulsar can be approximately given by,

$$E_{\text{rot}} \sim I \nu^2,$$

where $I$ is the moment of inertia of the star and $\nu$ is the observed spin-period, apart from a numerical factor of $\sim 10$. Of course, the observed $\nu$ refers to that of the crust. Since the super-fluid component rotates faster than the crust the actual rotational energy would be somewhat larger than the above estimate. But it would be of the same order and we shall ignore the difference for the present discussion. A glitch in the spin-period implies a change in the rotational energy, $\Delta E$, given by

$$\Delta E = \delta (I \nu^2) \sim I \nu^2 \left( \frac{\delta \nu}{\nu} \right) \sim \left( \frac{\delta \nu}{\nu} \right) E_{\text{rot}},$$

(1)

where $\delta \nu$ is the magnitude of the glitch. Evidently, $\Delta E$ is the energy scale associated with a glitch and it can be estimated for a glitching pulsar using the observed value of $\delta \nu$. In Fig.3 we plot $\Delta E$ assuming the stellar moment of inertia to be $\sim 10^{35}$ gm cm$^2$ for all the glitching pulsars (we shall again ignore the small differences in $I$), showing that the energy scale associated with glitches has a range of $10^{30} - 10^{44}$ erg.

At once the fact that B1821-24 is different from the other glitching pulsars becomes evident. Even though $\Delta E (\sim 10^{40}$ erg) itself falls quite within the above range it is extremely high for a glitch of such small magnitude. This is simply due to the fact that the rotational kinetic energy of an MSP is very large. require much larger energy change in an MSP than in a normal pulsar. Now if for some reason such large energy scales, required for large size glitches, are not available to MSPs it would explain the absence of such glitches in them. We show that exactly that would happen if MSPs are assumed to be strange stars.

In this context, it would be helpful to recapitulate the standard wisdom regarding the MSPs. A pulsar is understood to be a strongly magnetized rotating neutron star. The measured spin-period ($P$) and the estimated dipolar component of the magnetic field ($B \propto \sqrt{P\dot{P}}$, where $P$ is the period derivative) broadly classify the pulsars in two categories - a) isolated pulsars with rotation periods usually above 1s and very strong magnetic fields ($10^{11} - 10^{14}$ G); b) binary/millisecond pulsars with much shorter rotation periods and considerably weaker magnetic fields ($10^8 - 10^{10}$ G).
Observations suggest a connection between the second group with their being processed in binary systems, prompting theoretical modeling of accretion-induced reduction of the magnetic field (Konar & Bhattacharya 1997; Konar & Bhattacharya 1999a; Konar & Bhattacharya 1999b; Cumming, Zweibel, & Bildsten 2001; Choudhuri & Konar 2002; Payne & Melatos 2004; Payne & Melatos 2007). In fact, the discovery of SAX J1808.4-3658, a 2.49 ms X-ray pulsar, with an estimated dipole field strength of $\sim 10^{10}$ G is a direct pointer to the connection between low-mass X-ray binaries and MSPs (Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998). It is understood that this object would emerge as a typical millisecond radio pulsar once the mass accretion in the system stops, vindicating present theoretical expectations. For obvious reasons the members of the second group are also known as the recycled pulsars.

It should be noted that in our discussion, we have not included the 16ms pulsar J0537-6910 (Middlemist et al. 2006), observed to experience many large glitches, because this is a young pulsar associated with a supernova remnant and is not likely to belong to the recycled population of typical MSPs.

3 STRANGE STAR : CRUST-CRACKING AND GLITCH

It is understood that a strange star can form via the deconfinement of the nuclear matter in an accreting neutron star (Weber 1999). A 1.4$M_\odot$ neutron star requires to accrete $\sim 0.5 M_\odot$ or more to attain the deconfinement density ($\rho_{\text{deconfine}} \sim 8 \rho_{\text{nuc}}$) at the center (Cheng & Dai 1996). This is possible only if the companion is a low-mass star, as the amount of accretion has been shown to range from 0.1$M_\odot$ to 1$M_\odot$ in low-mass binaries (Bhattacharya & van den Heuvel 1991; Verbunt 1993; van den Heuvel & Bitzarik 1995). On the other hand, a neutron star in a low-mass binary is also known to produce the ubiquitous MSPs (Bhattacharya 2002; Wijnands & van der Klis 1998). Evidently, the MSPs are prime candidates for the strange stars.

The interior of a strange star supposedly consists of a u-d-s plasma with a small admixture of electrons, to make it charge-neutral, where each particle species is Fermi-degenerate. Strange star structure modeled with a realistic equation of state has been developed by Dey et al. (1998). Furthermore, the u-d-s plasma could be in a superconducting state where the rotation and the magnetic field are supported by formation of vortex bundles (Ray Mandal et al. 2006). Here, we consider such a rotating strange star which also supports a thin hadronic crust. The maximum density at the bottom of the hadronic crust of a strange star is that of the neutron drip ($\rho_{\text{nuc}} \sim 10^{-11}$ g cm$^{-3}$) (Glendenning, Kettner, & Weber 1999). This crust is separated from the interior by an electrostatic gap of few Fermi which prevents the nuclear matter from further conversion. In our model, a typical 1.4$M_\odot$ star would have a $\sim 100$ cm thick crust of mass $\sim 10^{-3} M_\odot$.

The primary region of interest in the case of any timing irregularity of a pulsar is the crust (whatever may be the nature of the coupling of the crust to the interior). Therefore it is of importance to understand the nature of the crust. For the sake of convenience we shall assume that the crust of a rotating strange star consists of cold-catalyzed matter (equilibrium nuclide corresponding to a particular density at zero temperature) where the density varies from 7.86 g cm$^{-3}$ to 4 $\times 10^{13}$ g cm$^{-3}$ (Baym, Pethick, & Sutherland 1971). The melting temperature of such a crust ranges from $10^8 - 10^{10}$ K and therefore it is reasonable to assume the crust to be in a crystallized state (Gudmundsson, Pethick, & Epstein 1983). The lattice spacing of this crystal is $\sim 10^{-5} - 10^{-10}$ cm which is much larger than the nuclear size implying that the crust behaves like a Coulomb crystal.

The shear stress of this crystal for a particular density is given by $\sigma_{\text{shear}} \sim \mu \theta$ where $\theta$ is the dimensionless strain (Kuderman 1991a; Kuderman 1991b). The shear modulus, $\mu$, is given by:

$$\mu \simeq \frac{0.3(Ze)^2}{a^4}, \quad \text{with} \quad a \sim \left( \frac{\rho}{m_a A} \right)^{-1/3}$$

where $(Z, A)$ correspond to the equilibrium nuclide at density $\rho$ and $m_a$ is the atomic mass unit (Ashcroft & Mermin 1979). The maximum shear stress which a crustal lattice can support is uncertain. It depends upon the number of lattice dislocations, and their location, pinning and mobility. In the case of a neutron star, it has been argued that the strain angle $\theta$ should typically be between $10^{-5}$ and $10^{-3}$ as the crustal lattice behaves like an alkali metal (Smoluchowski & Welch 1970; Smoluchowski 1970). The lower values are more probable as the crust is likely to have many defect points (impurity ions etc.). See Horowitz & Berry (2009) and Horowitz & Kadui (2009) for recent work on the strength of the crust of a neutron star. The hadronic crust of a strange star is expected to be very similar to the outer crust of a neutron star. We shall therefore assume the above values to hold for our discussion too.

The shear stress at the bottom of the hadronic crust of a strange star is then given by:

$$\sigma_{\text{shear}} \simeq 10^{29} \times \left( 10^{-4} - 10^{-5} \right) \text{ dyne cm}^{-2}.$$  

Figure 3. Change in the rotational energy ($\delta E$) vs. the glitch magnitude ($\delta \nu/\nu$) assuming the moment of inertia of the compact object to be $\sim 10^{45}$ gm cm$^2$. The maximum value of $\delta \nu/\nu$ has been used for pulsars experiencing multiple glitches. The point corresponding to PSR B1821-24 clearly stands out. The data has been taken from Melatos et al. (2008) (only those where a value of $\delta \nu/\nu$ is available) and the ATNF on-line catalog.
where we have assumed a range of $10^{-4} - 10^{-5}$ for $\theta$. However it should be noted that we are considering the case of a strange star that has formed via the deconfinement conversion of an accreting neutron star. The crust of an accreting neutron star is unlikely to be composed of cold-catalyzed matter. In addition to having a large number of defects (hence a very small value of $\theta$), the dominant nuclei at a given density could also have much lower values of $Z$ and $A$ as these are generated by local shell-burning processes induced by accretion (Brown & Bildsten 1998; Schatz et al. 2001). This might actually work to reduce the above value of shear stress further.

Therefore, the maximum energy associated with the shear stress of the entire hadronic crust of a strange star is

$$E_{\text{shear}} \sim \sigma_{\text{shear}} V_{\text{crust}} \sim 10^{40} - 10^{41} \text{ erg},$$

where $V_{\text{crust}}$ is the volume of the crust that has a thickness of $\sim 100$ m on a star of total radius $\sim 10$ km. It should be noted that this estimate is of the maximum shear energy available to the crust, as the calculation for the shear stress has been based on the bottom layer of the crust. In general the top layers have lower shear stress and the total shear energy could be smaller by one or two orders of magnitude. Still, it is clear that if the energetics of any process is such that the stress on the crust becomes very much larger than $\sigma_{\text{shear}}$ the crust would give in to plastic flow. Evidently, there could be no quake in such a situation. Therefore it could be concluded that while energy scales similar to that estimated in Eq. (3) would quite possibly give rise to micro-glitches (similar to that seen in B1821-24), energies much larger than this would most likely not be observed as star-quakes resulting in glitches.

### 4 DISCUSSIONS AND CONCLUSIONS

It is essential to realize that a very different physical phenomenon would give rise to a glitch in a strange star than in a neutron star. The glitch in a neutron star is essentially a result of the weak-coupling between the neutron super-fluid with the crust, which rotates slower than the neutral super-fluid. But such a situation does not arise in a strange star. Even if the quarks form super-condensates in the interior they would be coupled to the crust via electromagnetic interaction because the quarks are charged. The timescale for electromagnetic coupling is so small that for all practical purposes the core and the crust should co-rotate. However, it has been understood early on that some glitches could very well be signatures of star-quake phenomena (Baym, Pethick, & Pines 1969). We believe that could be the case for B1821-24 too.

It needs to be noted that there has been recent work to model directly the dynamics of crust cracking and vortex avalanches. Extended timing observations of J0537-6910 indicate that the time interval from one glitch to the next glitch is strongly correlated to the amplitude of the first glitch, a pattern that is quite similar to that of large quakes within the crust of our planet (Middleditch et al. 2006). It is also likely that at least some glitches, like those in the Crab and B0540-69 may be crust-quakes, where the equilibrium configuration for the solid crust departs from its geometrical configuration as the pulsar spins down until eventually the crust cracks and settles. Recent analysis of glitch data also suggest that glitches result from scale-invariant avalanches, which are consistent with a self-organized critical system (Melatos & Peralta 2007; Melatos, Peralta, & Wyithe 2008). An early model of such self-organized criticality was developed by Morley & Schmidt (1996) by assuming the crust of the neutron star to consist of a number of plates. These plates could be strained due to a deviation from the equilibrium configuration of the crust and their relaxation at the point of maximal stress would then induce a crust-cracking event. Recently this model has been investigated in detail by Warszawski & Melatos (2008) and their theoretical expectations match well with the observations of Middleditch et al. (2006).

In this context, it would be interesting to look at the crustal strength of a neutron star itself, in the spirit of the discussion in section 3. The crust of a neutron star is about $1km$ thick, has a density range of $7.86g \text{cm}^{-3}$ to $10^{14}g \text{cm}^{-3}$ (Baym, Pethick, & Sutherland 1971) and behaves like a coulomb crystal at all times (barring few years immediately after birth) (Gudmundsson, Pethick, & Epstein 1983; Page 1998). Following the line of reasoning above we find that the maximum energy associated with the shear stress of the entire hadronic crust of a neutron star is

$$E_{\text{shear}} \sim 10^{44} - 10^{45} \text{ erg},$$

where we have again assumed a range of $10^{-4} - 10^{-5}$ for $\theta$. From this we can estimate the maximum value of $\delta\nu/\nu$ for a pulsar of a given spin-period. $\delta\nu/\nu$ vs. $P$ has been plotted for all known pulsars in fig 3. For comparison we plot the theoretical curves for the maximum of $\delta\nu/\nu$ corresponding to a neutron star as well as a strange star. Not surprisingly, the magnitude of all the observed glitches are well below the maximum value calculated for a neutron star. It is interesting to note that even though there are a number of pulsars residing between the two lines, B1821-24 is not one of them. Even though this is a very happy situation, a word of caution is necessary. The crust in a neutron star is far more complex than that in a strange star. To begin with, one needs to consider the presence of the neutron superfluid beyond the neutron drip density.
(4 × 10^{11}\text{g cm}^{-3}). Then, in the deeper layers of the crust, as the nuclear density is approached, the nuclei themselves may have non-spherical shapes (Lorenz, Ravenhall, & Pethick 1993) giving rise to very different structural properties. Therefore, the above estimates for $\delta \nu/\nu$ maximum may not be very reliable.

However, it can be seen that it is possible to conceive of other causes giving rise to crust-cracking stresses in a strange star resulting in generalized star-quakes, even though there can be no vortex dynamics associated with the strange star crust. Such a mechanism for strange star quake has already been discussed by Peng & Xu (2008) in the context of the slow-glitches observed in PSR B1822-09. We too believe that some kind of crust-cracking event resulted in the star-quake which was observed as the March 2001 glitch in PSR B1821-24.

In fact, observations of a larger number of events like that in B1821-24 is required for a clearer picture of the MSP glitches to emerge. Though accumulated glitch data currently indicates a relation between the glitch rate ($\lambda$) and the spin-down age ($\tau$) no definite relation is available yet. However, it is understood that for older pulsars $\lambda$ is expected to be much smaller than 0.25 per year (Melatos, Peralta, & Wyithe 2008). Cognard & Backer (2004) estimate the cumulative number of years of MSP timing observations up to 2001 to be around 500 (hence a much larger value at the present date) for all objects. Thus, a maximum of about 125 glitches could have been observed in MSPs. So, the current data is consistent with the expectation that the older pulsar glitch infrequently. Only if a large number of MSP glitches are observed in future this idea would have to be re-evaluated. However, neither can the possibility that some of the MSPs are strange stars be ruled out as they too are not expected to experience frequent glitches except as some crust-quake events. Moreover, an assumption of strange star automatically explains the scarcity of larger glitches in MSPs.

It is evident from the discussions in section 2 that the energy-scales associated with the micro-glitch of B1821-24 is equivalent to the maximum shear stress of the entire crust. Therefore, if B1821-24 is indeed a strange star then we do not expect to see a glitch of larger magnitude in this pulsar. In fig. 5 the maximum value of $\delta \nu/\nu$, corresponding to the maximum shear stress in a strange star, has been plotted against the spin-periods of all known millisecond pulsars (Lorimer 2008). Any future observation of a glitch with $\delta \nu/\nu$ larger than the maximum calculated here should be a clear indication against the hypothesis of MSPs being strange stars.

To conclude we note that the absence of glitches in MSPs could be due to the simple fact that older pulsar glitch infrequently or because they are strange stars. But we need to observe many more glitches in MSPs to settle this question properly.

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Figure 5. The maximum value of $\delta \nu/\nu$ predicted for the known MSPs, assuming them to be strange stars. PSR B1821-24 is well below the predicted value. The MSP periods have been taken from the ATNF on-line catalog and Paulo C. Freire’s catalog of globular cluster pulsars (http://www.naic.edu/~pfreire/GCpsr.html).
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