Glitch recoveries in radio-pulsars and magnetars

B. Haskell\textsuperscript{1,2,☆} and D. Antonopoulou\textsuperscript{3}

\textsuperscript{1}Max Planck Institut für Gravitationsphysik, Albert Einstein Institut, Am Mühlenberg 1, D-14476 Potsdam, Germany
\textsuperscript{2}School of Physics, The University of Melbourne, VIC 3010, Australia
\textsuperscript{3}Astronomical Institute ‘Anton Pannekoek’, University of Amsterdam, Postbus 94249, NL-1090GE Amsterdam, the Netherlands

Received 2013 September 14; in original form 2013 June 22

ABSTRACT

Pulsar glitches are sudden increases in the spin frequency of an otherwise steadily spinning down neutron star. These events are thought to represent a direct probe of the dynamics of the superfluid interior of the star. However glitches can differ significantly from one another, not only in size and frequency, but also in the post-glitch response of the star. Some appear as simple steps in frequency, while others also display an increase in spin-down rate after the glitch. Others still show several exponentially relaxing components in the post-glitch recovery. We show that if glitches are indeed due to large-scale unpinning of superfluid vortices, the different regions in which this occurs and respective time-scales on which they recouple can lead to the various observed signatures. Furthermore, we show that this framework naturally accounts for the peculiar relaxations of glitches in Anomalous X-ray Pulsars.

Key words: stars: magnetars – stars: neutron – pulsars: general.

1 INTRODUCTION

Neutron stars (NSs) are some of the few objects that allow us to study the physics of matter at extreme densities and in strong gravity. Not only do the central densities of these objects exceed nuclear saturation density, but the core temperature of a mature NS is also expected to be below the superfluid transition temperature (Baym, Pethick & Pines 1969; Page et al. 2011; ShTERNIN et al. 2011). The presence of a superfluid component significantly modifies the dynamics, allowing for the superfluid in the star to flow relative to the ‘normal’ component and act as a reservoir of angular momentum. A direct manifestation of this is given by pulsar glitches, i.e. sudden increases in the frequency of an otherwise steadily spinning down NS.

Glitches are generally attributed to a large-scale superfluid component in the interior of the star that is only loosely coupled to the crust and the magnetosphere. The sudden recoupling of such a component would then lead to the rapid transfer of angular momentum and to a glitch (Anderson & Itoh 1975). In particular, a superfluid rotates by forming an array of quantized vortices, which are being expelled as it slows down. In an NS however, vortices can ‘pin’ to the ions in the crustal lattice or to magnetic flux tubes in the outer core (Alpar 1977; Link 2003). If this is the case vortices cannot move out, the superfluid does not follow the spin down of the crust and lags behind, storing an excess of angular momentum. Once a sizeable lag builds up, hydrodynamical lift forces (Magnus forces) acting on the vortices will unpin them, giving rise to sudden vortex motion and the glitch. Recent work has shown that this mechanism can successfully account for the distribution in glitch sizes and waiting times (Melatos, Peralta & Wyithe 2008; Melatos & Warszawski 2009) and model giant glitches in the Vela and other pulsars (Pizzochero 2011; Haskell, Pizzochero & Sidery 2012; Seveso, Pizzochero & Haskell 2012). Glitches have also been observed in several Anomalous X-ray Pulsars (AXPs), which are thought to be strongly magnetized NSs, magnetars. In terms of absolute sizes, AXP glitches do not differ much from those observed in regular radio pulsars; however, they are often associated with radiative events (Israel et al. 2007; Livingstone, Kaspi & Gavriil 2010; Gavriil, Dib & Kaspi 2011), and the post-glitch recoveries are also remarkable in many ways, with many featuring recoveries with large fractional increases in the spin-down rate over long time-scales (weeks or months) (Dall’Osso et al. 2004; Dib, Kaspi & Gavriil 2008).

In this Letter, we address two issues. First of all, we use numerical simulations to show that, as also discussed by Alpar & Baykal...
(2006), the vortex unpinning paradigm can explain the different kinds of relaxation, depending on the coupling time-scale of the region that unpins. Secondly, we will show that the same mechanism giving rise to glitches in radio pulsars can naturally produce smaller glitches in hotter stars such as magnetars and young pulsars like the Crab, but also lead to a strong relaxation in magnetars.

We model the NS as a two-fluid system of superfluid neutrons and a charged component, composed of ions, protons, electrons and all components tightly coupled to them (Andersson & Comer 2006). The two components are coupled by an interaction known as mutual friction (MF), which is mediated by the quantized vortices of the neutron superfluid (Andersson, Sidery & Comer 2006). Following Haskell et al. (2012), we can write the equations of motion for the angular frequency of the two components ($\Omega_p$ for the charged component, $\Omega_n$ for the superfluid neutrons) in the form:

$$\dot{\Omega}_p(\tilde{r}) = \frac{Q(\tilde{r})}{\rho_p} - f(\epsilon_n)A \frac{\Omega_p^4}{\rho_p} \Omega_n^3,$$

$$\dot{\Omega}_n(\tilde{r}) = -\frac{Q(\tilde{r})}{\rho_p} - g(\epsilon_n)A \frac{\Omega_p^4}{\rho_p} \Omega_n^3,$$

where $\tilde{r}$ is the cylindrical radius and $I_p$ the moment of inertia of the charged component. We have $Q(\tilde{r}) = \rho_p n_m B (\Omega_p - \Omega_n)/(1 - \epsilon_n - \epsilon_p)$ with $\kappa$ the quantum of circulation, $n_m$ the density of ‘free’ vortices (which contribute to MF) and $A = B^2 \sin^2 \theta R^4/6c^3$ with $B$ the surface magnetic field strength, $\theta$ the inclination angle between the field and the rotation axis and $R$ the stellar radius. The coefficient $B$ is the dissipative MF coefficient, which quantifies the strength of the interaction between vortices and the charged component. The entrainment coefficients are $\epsilon_n$ and $\epsilon_p$, and describe the non-dissipative coupling between the fluids (Andersson & Comer 2006). The functions $f(\epsilon_n)$ and $g(\epsilon_n)$ are such that in the limit of vanishing entrainment $g(\epsilon_n) = 1$ and $f(\epsilon_n) = 0$ (Andersson et al. 2012). Strong entrainment, however, also reduces the maximum lag that can be built up between the two fluids, thus providing a strong constraint for glitch models that only involve the NS crust (Andersson et al. 2012; Chamel 2013). This constraint is not so severe for models such as those presented here in which the larger glitches involve the decoupling of part of the core (Haskell et al. in preparation; Hooker, Newton & Li 2013). In the presence of a pinning force vortices are not free to move unless the lag between the two components exceeds a threshold. We shall use the realistic profiles obtained by Pizzochero (2011) for the critical lag $\Omega_p - \Omega_n$. Below this threshold vortices are pinned and we set $\dot{\Omega} = 0$ in equation (1). Once vortices have unpinned they are free to move out, but in the crust many will repin and only a fraction will be free to move and contribute to the drag force. Following Jahan-Miri (2006), we assume that the instantaneous number density of free vortices $n_m$ is given by $n_m = \xi n_v$ where $n_v$ is the total number density of vortices, and $\xi$ is the fraction of unpinned vortices at a given time. By averaging over time, we can obtain an effective drag parameter $\tilde{B} = \xi B$.

The mechanisms that give rise to MF, and thus determine $\tilde{B}$, are different in different regions of the star and can vary by several orders of magnitude. In the core, MF is expected to be due to electron scattering of magnetized vortex cores (Alpar, Langer & Sauls 1984b) with a value $B_{\text{co}} \approx 10^{-4}$ (Andersson et al. 2006). In the crust, on the other hand, the main dissipative mechanism is the excitation of sound waves in the lattice, which leads to a weak drag $B_{\text{cr}} \approx 10^{-6}$ (Jones 1992). If the relative velocity between vortices and ions is high ($\approx 10^2$ cm s$^{-1}$), it becomes possible to excite Kelvin waves of the vortices, leading to fast coupling and $B_{\text{cr}} \approx 10^{-3}$ (Epstein & Baym 1992; Jones 1993). Given the uncertainties we will take constant values of the drag parameters (one for the core and one for the crust) and average them over the length of a vortex, as described in Haskell et al. (2012). We follow the setup of Haskell et al. (2012) and consider a 1.4 M$_\odot$ NS, with a radius $R = 12$ km. The equation of state is an $n = 1$ polytrope and the crust/core transition is assumed to take place at $\rho = 1.6 \times 10^{16}$ g cm$^{-3}$. The proton fraction is taken to be $x_p = 5 \times 10^{-12} \rho$.

Note that entrainment enters into the problem in three ways: in equation (1) via the functions $f$ and $g$, as a rescaling of the parameter $\tilde{B}$ in the definition of $Q(\tilde{r})$ and indirectly in the microphysical calculations that lead to the value of $B_{\text{co}}$ (Alpar et al. 1984b). For simplicity, we will neglect any explicit dependence on entrainment by setting $f(\epsilon_n) = 0$ and $g(\epsilon_n) = 1$, as these impact mainly on the lag that can be built up before the glitch. We then study how the solutions vary as we vary the value of $B_{\text{co}}$.

Let us now examine how our setup could give rise to different classes of glitches. The general picture is the following: vortices are pinned in certain regions of the star (possibly the crust). In these regions vortex motion is impeded, leading to a significant lag building up. A glitch will occur when vortices are rapidly unpinned in such a region and the superfluid neutrons can then exchange angular momentum with the normal component. We argue that the signature of the glitch can depend strongly on how fast the superfluid can react to the unpinning event, and where it takes place.

We can obtain a good approximation to the local coupling time-scale in each region of the star (Haskell et al. 2012) by neglecting differential rotation and taking a constant proton fraction $x_p = \rho_p/(\rho_p + \rho_n)$ in equations (1) and (2). Given an initial lag $D_0$, this leads to a solution of the form $\Omega_p - \Omega_n = D_0 \exp(-t/\tau)$, where the coupling time-scale is

$$\tau \approx \frac{x_p}{2\Omega_0 \tilde{B}}.$$

In Fig. 1, we schematically illustrate two possible scenarios by considering how the coupling time-scale in equation (3) varies throughout the star. We assume that the pinned region is in the crust, but the argument is qualitatively identical if it is in the outer core. We assume that vortices close to the rotation axis cross through the core and are only weakly pinned in the crust, while MF in the core leads to short coupling time-scales between the superfluid and the rest of the star. As one moves towards the equatorial region, the coupling time-scale increases and becomes long for those regions where most vortices are pinned. At the moment of the glitch, a number of vortices unpin, leading to an increased fraction of free vortices $\xi$ and thus to a larger MF parameter $\tilde{B}$ and a reduced coupling time-scale, leading to an observable spin-up of the star. In the middle panel of Fig. 1, we can see the case in which the coupling time-scale in the region that gives rise to the glitch becomes shorter than the time-scale on which the outer regions of the core are coupled. These regions cannot follow the glitch and decouple, giving rise to a strong relaxation as they recouple on the local time-scale. In the right-hand panel, we can instead see the case in which one simply assumes that the increase of $\xi$ in a region gives rise to a coupling time-scale that is short compared to that of the pinned region, but still longer than that of most of the core. In this case, only the pinned region will decouple at the glitch, and the recovery will proceed on the much slower time-scale associated with it and thus appear as a ‘permanent’ step in the spin-down rate of the star. In the presence of a wide range of pinning potentials, the response of the crust alone can give rise to a variety of post-glitch behaviours, as discussed in Alpar et al. (1984a), such models however cannot account for large
2 RELAXING GLITCHES

We now focus on the glitches that show a significant relaxation. The prototype system for this kind of glitch is the Vela pulsar, which shows relatively large glitches followed by an exponential recovery. The frequency $\nu$ after the glitch takes the form $\nu(t) = \nu_0(t) + \Delta \nu + \Delta \nu t + \sum \Delta_i \exp(-t/\tau_i)$, where $\nu_0(t)$ is the pre-glitch spin-down solution. In recent glitches, up to five decaying terms have been fitted, with time-scales $\tau_i$ that range from minutes to months. The shorter time-scales are associated with strong increases in the spin-down rate, which can be comparable to or larger than the pre-glitch rate (Dodson et al. 2007). Relaxing glitches in AXPs appear to be a ‘scaled-down’ version of Vela giant glitches, in as much as they are smaller (Vela glitches have steps of the order of $\Delta \nu \approx 10^{-5}$ Hz, compared to $\Delta \nu \approx 10^{-8}$ Hz typically in AXPs) and show the kind of strong relaxation that Vela glitches show on time-scales of minutes to hours, but on much longer time-scales of days to weeks (Dib et al. 2008). It is thus interesting to ask whether the mechanisms that is giving rise to them is the same as in the Vela.

The assumption is that such glitches are triggered once the maximum lag that the pinning force can sustain is exceeded. Then vortices will move out rapidly, exciting Kelvin waves. This leads to a glitch rise time-scale shorter than the time-scale on which the outer regions of the core are coupled. The outer core thus decouples and will subsequently recouple on the local time-scale given in equation (3), giving rise to the observed relaxation. Such a mechanism was studied in detail by Haskell et al. (2012), who were able to predict the correct size and relaxation for the Vela giant glitches.

Let us now investigate whether relaxing glitches in magnetars can be due to the same mechanism. We start by noting that the strong increase in the spin-down rate observed on time-scales of months in AXPs occurs naturally if one assumes that the relaxation is given by regions of the outer core recoupling on the local coupling time-scale given by superfluid MF. If we consider the time-scale in equation (3), it is clear that the same process will be much faster in a pulsar, such as the Vela, with $\nu \approx 10$ Hz than in a magnetar rotating at $\nu \approx 0.1$ Hz. One would thus expect that given that in the Vela 2000 and 2004 glitches there are increases in the spin-down rate of the order $\Delta \nu/\nu \approx 0.5$ associated with decay time-scales of $\tau \approx 0.5$ d (Dodson et al. 2007), such an increase would be associated with a decay time-scale of $\approx 50$ d for a magnetar, as is observed for example in the AXP 1RXS J17084 (Dall’Osso et al. 2004; Dib et al. 2008).

The other main difference between Vela giant glitches and relaxing glitches in magnetars is the size of the step in frequency, which is smaller for magnetars ($\Delta \nu \approx 10^{-8}$ Hz) than for the Vela and other radio pulsars that exhibit giant glitches ($\Delta \nu \approx 10^{-5}$ Hz). Several models predict smaller glitches for younger, hotter objects (Alpar et al. 1984a; Glampedakis et al. 2009; Haskell et al. 2012) and it is thus plausible that the same mechanism giving rise to the giant glitches in Vela will produce smaller glitches in hotter stars, such as magnetars and young pulsars.

To test this hypothesis, we use the code developed by Haskell et al. (2012), and solve equations (1) and (2) as in the models considered for the Vela, but using a spin frequency typical for magnetars and a higher background MF parameter $B_{cr}$ in the crust. The latter is to account for a larger vortex creep rate, due to the magnetar’s higher temperature. This leads to a smaller region of the crust that has not relaxed and can participate in the glitch. We use $B_{cl} = 10^{-3}$ for the rise. The results can be seen in Table 1, in which we show the size

| $\Delta \nu / \nu$ | $\nu$ (Hz) | $\nu$ (Hz) | $\nu$ (Hz) | $\nu$ (Hz) |
|-----------------|-----------|-----------|-----------|-----------|
| $\Delta \nu (\times 10^{-7})$ | 20        | 8.2       | 141       | 41.6      |
| $\Delta \nu / \nu$ (1 d) | 0.37      | 0.19      | 64        | 20        |
| $\Delta \nu / \nu$ (50 d) | 0.07      | 0.13      | 0.08      | 0.13      |

Table 1. Size of the glitch and magnitude of the increase in spin-down rate after 1 and 50 d for a (magnetar-like) star spinning at 0.011 Hz, for varying MF parameters in the crust ($B_{cr}$) and core ($B_{co}$). Weaker MF parameters in the core, such as those predicted if one has a type II superconductor in the outer core (Link 2012), would result in larger glitches and a strong increase in the spin-down rate after the glitch.
Glitches recoveries in pulsars and magnetars

L19

of the glitch and the step in frequency derivative after 1 d and after 50 d. We can see that the results are consistent with the kind of glitches seen in magnetars. Furthermore, we predict that one should be able to observe stronger increases in spin-down rate on short time-scales, if the MF in the outer core is weak, as could be the case if protons are in a type II superconducting state (Link 2012).

Better coverage of AXP glitches thus has the potential to constrain the MF parameters and determine the nature of the pairing in the NS interior.

3 SLOW ‘STEP-LIKE’ GLITCHES

Let us now turn our attention to glitches that are associated with ‘permanent’ increases in the spin-down rate but with no appreciable relaxation. Our assumption is that this kind of glitch is not due to the vortices that have accumulated close to the maximum of the critical lag, but rather involves regions far from the maximum, in which vortices are ‘creeping’ out. While the sudden release of vortices close to the maximum of the critical lag could excite Kelvin waves and lead to short coupling time-scales, in the case we consider now, the coupling time-scale of the region giving rise to the glitch would decrease compared to that of the crust, but still be longer than the coupling time-scale of the core, as shown in the right-hand panel of Fig. 1. The core will thus not decouple and give rise to a visible relaxation, but rather the crust will be decoupled on long time-scales, leading to what will appear as a permanent increase in the spin-down rate.

We will study this problem by once again using the code of Haskell et al. (2012) to solve the equations (1) and (2). First of all, we allow for the crust to reach a steady state, in which the two fluids are spinning down together with a lag between the two of \( \Delta \Omega \approx 0.01 \). In this background configuration, we use \( B_{\text{cr}} = 5 \times 10^{-9} \). We now take a region of varying thickness at the base of the crust and switch the MF parameter to \( B_{\text{cr}} = B_{\text{gl}} \approx 10^{-6} \). This will be the situation if, for example, a sudden event, such as a crust quake or a vortex avalanche (Ruderman 1969; Melatos & Warszawski 2009), frees the vortices in this region, leading to \( \xi \approx 1 \).

The results can be seen in Fig. 2. In the left-hand panel, we see that the size of the region over which vortices are freed (i.e. the extent of the avalanche or quake) has a strong influence on the size of the glitch, but little influence on the increase in spin-down rate. This can be understood if one considers the equations of motion in (1) and (2) locally in the crust, neglecting differential rotation and electromagnetic spin down. From angular momentum conservation, we see that the size of the glitch \( \Delta \Omega_\text{G} \) will depend on the lag \( \Delta \Omega \) between the superfluid and the charged component via \( \Delta \Omega_\text{G} = \frac{2}{3} \Delta \Omega \), where \( I_c \) is the moment of inertia of the regions in which vortices unpin, while \( I_c \) is the moment of inertia of the region that is coupled fast enough to follow the rise of the glitch. The size of the region in which vortices unpin thus determines \( I_c \), and is crucial for the step size. The moment of inertia coupled during the glitch, \( I_c \), is essentially the moment of inertia of the whole core. The rest of the crust will be coupled on a longer time-scale compared to that of the rise, given that \( B_{\text{cr}} \ll B_{\text{gl}} \), and will thus decouple and only recouple slowly on a time-scale given by equation (3). If this time-scale is long compared to the time-scale on which the post-glitch relaxation is observed, the crust will be decoupled during the whole period and the increase in the spin-down rate will appear permanent.

The star will spin down faster by a fraction \( \approx I_{\text{cr}} / I_c \), with \( I_{\text{cr}} \) the moment of inertia of the crust. For a slow enough rise, this fraction is approximately constant. This can be seen in the middle panel of Fig. 2 in which we show that the quantity \( \Delta \nu / \nu \) varies little with increasing \( B \), until one gets to a value large enough that the rise is sufficiently fast to involve part of the core, giving rise to a visible relaxation. Note that in all figures we have assumed a ‘magnetar’ spin rate of \( v = 0.11 \) Hz, to illustrate that in this case the rise may be slow enough (\( \approx 1 \) d) to be detected (see e.g. Woods et al. 2004 for a possible detection of a slow rise). For a faster pulsar, the rise would be much faster and difficult to detect even in this ‘slow’ case (e.g. \( < 1 \) h for the Crab).

Finally, let us note that a small number of glitches show no observable increase in the spin-down rate and are consistent with being pure steps in frequency (Dib et al. 2008; Espinoza et al. 2011). A sudden release of vortices in a region in which vortices are creeping out will lead to decoupling of the rest of the crust and to

\[ \Delta \nu / \nu = 0.009 \]

\[ \Delta \nu / \nu = 0.01 \]
an increase in the spin-down rate after the glitch. If the increase in mobility were, however, to take place while most of the superfluid in the crust is still decoupled from the observed charged component (e.g. because it is strongly pinned), one would still have a step in frequency but there would be no change in the effective moment of inertia and thus in the spin-down rate. The region that is now coupled on a short time-scale will relax rapidly and give rise to the glitch, while the other crustal superfluid regions were decoupled before the glitch and remain decoupled after. The effective moment of inertia thus remains unaffected. We show an example of a glitch in this setup in the right-hand panel of Fig. 2 in which we assume a sudden release of vortices while the superfluid in the crust is decoupled. The result is a step in frequency, with no visible increase in the spin-down rate.

4 CONCLUSIONS

We have presented an analysis of different kinds of glitching behaviour in radio pulsars, and shown that glitches followed by a strong relaxation may have the same origin as the giant glitches of the Vela pulsar, but naturally scaled down in hotter, younger systems, such as the Crab or Magnetars. We have also shown that the slower hydrodynamical response to (possibly smaller) events due to random unpinning or crust quakes in the crust will lead to glitches that do not appear to relax, but appear as steps in frequency and frequency derivative. If the event takes place in a strongly pinned region it will appear only as a step in frequency.

We also argue that the same mechanisms that are at work in radio pulsars could naturally give rise to the sizes and recoveries observed in magnetar glitches. In particular, the longer periods of magnetars would naturally lead to a long-term strong increase in the spin-down rate, with no need for an additional mechanism to be involved. The slower time-scales associated with AXPs and SGRs make such events especially interesting as they would lead to long time-scales for the rise, possibly of days, that could be observed if one were to have better coverage of these objects. This would allow us to understand to what extent these events do, indeed, have the same origin as radio pulsar glitches or to which extent they could allow us to probe the physics of the magnetosphere, which is likely to play an important role (Lyutikov 2013) and could be the cause of phenomena such as ‘antiglitches’ (Archibald et al. 2013).

ACKNOWLEDGEMENTS

We thank B. Link and A. Watts for useful discussions. DA is supported by an NWO Vidi Grant (PI: A. Watts), BH by an ARC DECRA fellowship.

REFERENCES

Alpar M. A., 1977, ApJ, 213, 527
Alpar M. A., Baykal A., 2006, MNRAS, 372, 489
Alpar M. A., Pines D., Anderson P. W., Shaham J., 1984a, ApJ, 276, 325
Alpar M. A., Langer S. A., Sauls J. A., 1984b, ApJ, 282, 533
Andersson N., Comer G. L., 2006, Class. Quantum Gravity, 23, 5505
Anderson P. W., Itoh N., 1975, Nature, 256, 25
Andersson N., Sidery T., Comer G. L., 2006, MNRAS, 368, 162
Andersson N., Glimpotted K., Ho W. C. G., Espinoza C. M., 2012, Phys. Rev. Lett., 109, 1103
Archibald R. F. et al., 2013, Nature, 497, 591
Baym G., Pethick C., Pines D., 1969, Nature, 224, 673
Chamel N., 2013, Phys. Rev. Lett., 119, 011101
Cordes J. M., Downs G. S., Krause-Polstorf J., 1988, ApJ, 330, 847
Dall’Osso S., Israel G. L., Stella L., Possenti A., Perozzi E., 2004, in Kaaret P., Swank J. H., Lamb F. K., eds, AIP Conf. Proc. Vol. 714, X-ray timing 2003: Rossiie and Beyond. Am. Inst. Phys., New York, p. 289
Dib R., Kasvi V. M., Gavrii F. P., 2008, ApJ, 673, 1044
Dodson R. G., Lewis D. R., McCulloch P. M., 2007, Ap&SS, 308, 585
Epstein R. I., Baym G., 1992, ApJ, 387, 276
Espinoza C. M., Lyne A. G., Stappers B. W., Kramer M., 2011, MNRAS, 414, 1679
Gavrii F. P., Dib R., Kasvi V. M., 2011, ApJ, 736, 138
Glampedakis K., Andersson N., 2009, Phys. Rev. Lett., 102, 141101
Haskell B., Pizzochero P. M., Sidery T., 2012, MNRAS, 420, 658
Hooker J., Newton W. G., Li B.-A., 2013, preprint (arXiv:1308.0031)
Israel G. L., Götz D., Zane S., Dall’Osso S., Rea N., Stella L., 2007, A&A, 476, L9
Jahan-Miri M., 2006, ApJ, 650, 326
Jones P. B., 1992, MNRAS, 257, 501
Jones P. B., 1993, MNRAS, 263, 619
Link B., 2003, Phys. Rev. Lett., 91, 101101
Link B., 2012, preprint (arXiv:1211.2209)
Livingstone M. A., Kasvi V. M., Gavrii F. P., 2010, ApJ, 710, 1710
Lyutikov M., 2013, preprint (arXiv:1306.2264)
McCulloch P. M., Hamilton P. A., McConnell D., King E. A., 1990, Nature, 346, 822
Melatos A., Warszawski L., 2009, ApJ, 700, 1524
Melatos A., Peralta C., Wyithe J., 2008, Ap&SS, 319, 106, 081101
Page D., Prakash M., Lattimer J. M., Steiner A. W., 2011, Phys. Rev. Lett., 106, 081101
Pizzochero P. M., 2011, ApJ, 743, L20
Ruderman M., 1969, Nature, 223, 597
Seveso S., Pizzochero P., Haskell B., 2012, MNRAS, 427, 1089
Shetgrin P. S., Yakovlev D. G., Heinke C. O., Ho W. C. G., Pataunde D. J., 2011, MNRAS, 412, L108
Woods P. M. et al., 2004, ApJ, 605, 378
Yu M. et al., 2013, MNRAS, 429, 688

This paper has been typeset from a \TeX/\LaTeX file prepared by the author.