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A simple mechanism for the anti-glitch observed in AXP 1E 2259+586

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ABSTRACT

In this letter, we develop a simple internal mechanism that can account for the recent 'anti-glitch' observed for AXP 1E 2259+586 ($|\Delta\nu/\nu| \gtrsim 10^{-7}$). We propose that the cumulative decay of the internal toroidal magnetic field component will eventually become large enough to turn an originally stable prolate stellar configuration into an unstable one. The subsequent rearrangement of the stellar structure will result in a sudden spin-down of the whole star. We present order-of-magnitude calculations to give confidence to this scenario, using a simple, but physically reasonable, analytical stellar model. We estimate the energy released by the proposed mechanism and show that it is in agreement with the observations. Based on this model, we predict that to achieve the observed sudden spin-down, a minimum magnetar-like value for the magnetic field strength is needed. Consequently, we do not expect this kind of anti-glitch activity to occur in normal pulsars.

Key words: magnetic fields – stars: neutron – X-rays: individual: 1E 2259+586.

1 INTRODUCTION

Magnetars are neutron stars powered by their strong internal magnetic fields (Duncan & Thompson 1992). A detailed study of the temporal behaviour of a magnetar's emission could constrain both the external dipolar magnetic field and internal structure (Kouveliotou et al. 1998; Chamel & Haensel 2008). Even though all neutron stars suffer a long-term spin-down, many sudden spin-ups, known as glitches in the literature, have been observed for pulsars and magnetars (Espinoza et al. 2011; Yu et al. 2013). Recently, clear evidence of the first sudden spin-down was observed for a magnetar, anomalous X-ray pulsar (AXP) 1E 2259+586 (Archibald et al. 2013), which was a so-called anti-glitch. The authors propose two different interpretations for the observational evidence: (i) an anti-glitch event followed by a normal glitch (after ∼100 d) or (ii) a sequence of two anti-glitches (separated by ∼50 d). Spin-down events have also been observed for magnetars SGR 1900+14 (Woods et al. 1999) and 4U 0142+61 (Gavriil, Dib & Kaspi 2011), and for the high-magnetic-field pulsar PSR J1846–0258 (Livingstone, Kaspi & Gavriil 2010), but none of these is considered strictly as an anti-glitch, because of the long timescales (17–127 d).

AXP 1E 2259+586 has a ∼7 s period, a characteristic age of $\sim 10^6$ yr and a spin-inferred surface dipolar magnetic field of $B_{\rm d} \sim 5.9 \times 10^{13}$ G.[1] This values gives a minimum strength for the internal magnetic field. AXP 1E 2259+586 has been monitored with *Rossi X-ray Timing Explorer* and *Swift X-ray Telescope* over the last two decades, showing a stable spin-down rate, with the exception of two spin-up glitches in 2002 (Kaspi et al. 2003) and 2007 (Içdem, Baykal & Inam 2012), a timing event in 2009 (Içdem et al. 2012) and this anti-glitch in 2012.

To explain this anti-glitch, one of the observational facts that has to be adjusted by any model is a change in frequency of $\sim -5 \times 10^{-7}$ Hz in ∼100 d (Archibald et al. 2013). This spin-down can be interpreted as two instantaneous changes in spin frequency ($|\Delta\nu/\nu| \gtrsim 10^{-7}$). To adjust the timing data from *Swift*, in Archibald et al. (2013) the authors propose two models: (i) an anti-glitch in which $\Delta\nu/\nu = -3.1(4) \times 10^{-7}$ followed by a spin-up event of amplitude $\Delta\nu/\nu = 2.6(5) \times 10^{-7}$ or (ii) an anti-glitch in which $\Delta\nu/\nu = -6.3(7) \times 10^{-7}$ followed by a second anti-glitch in which $\Delta\nu/\nu = -4.8(5) \times 10^{-7}$. Based on a Bayesian analysis, model (ii) is favoured (Hu et al. 2014).

The second aspect that has to be addressed is the energetic one. On 2012 April 21, *Fermi*/GBM detected a hard X-ray burst with a duration of 36 ms (Foley et al. 2012) completely consistent with the epoch of the anti-glitch event. The observed fluence in the 10–1000 keV band corresponds to an energy release of $E_\gamma \sim 10^{38}$ erg. Moreover, an increase by a factor 2 in the 2–10 keV flux was also

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observed (Archibald et al. 2013), resulting in a $E_X \sim 10^{41}$ erg energy release (Huang & Geng 2014).

Several explanations for this anti-glitch event have been proposed, based both on external (Lyuticov 2013; Tong 2014; Huang & Geng 2014; Ouyed, Leahy & Koning 2014) and internal (Duncan 2013) origins. Despite searches at radio and X-ray wavelengths, no surrounding afterglow was detected (Archibald et al. 2013), arguing against a sudden particle outflow or wind-driven scenario. Thus, the most promising approach seems to be an internal rearrangement of the star. In this letter, we aim to provide a simple mechanism for the observed sudden spin-down of the star. We propose that as a consequence of the natural long-term decay of the internal magnetic field, an initially prolate-shaped stable stellar configuration becomes unstable enough to crack the crystallized stellar crust. Then, the re-accommodation of the star into a stable more spherical shape, leads to the anti-glitch. A similar scenario was also suggested to account for the SGR 1900+14 event (Ioka 2001).

Magnetically deformed compact stars were studied by Wentzel (1961), Ostriker & Hartwick (1968) and Katz (1989). More recently, in Cutler (2002) and Haskell et al. (2008), the authors developed a formalism to model magnetically deformed neutron stars in a more realistic manner. In their work, deformations are calculated for a rotating uniform-density star with a mixed poloidal–toroidal magnetic field configuration. A similar study with more realistic equations of state was performed by Frieben & Rezzolla (2012), who obtained quadrupolar distortions of the same order. This is the main reason why we used a simple uniform-density star for our analytical calculations. For magnetars, like AXP 1E 2259+586, deformations due to rotation effects are completely irrelevant, because of their long periods. Their main result is that while for strong poloidal magnetic fields, as for rapid rotation, stars tend to become oblate to keep mechanically stable, when internal toroidal fields dominate the magnetic field configuration, prolate stars are favoured.

For the volume-preserving $l = 2$ mode and a mixed toroidal–poloidal magnetic field, the quadrupolar distortion of equilibrium configurations for incompressible stars of uniform density is given by

$$\epsilon = \frac{I_{zz} - I_{xx}}{I_{zz}} = -\frac{25R^4}{24G_N M^2}\left(\langle B_t^2\rangle - \frac{21}{10}\langle B_p^2\rangle\right), \tag{1}$$

where $\langle B_t^2\rangle$ is the mean value of the square of the toroidal magnetic field strength, $\langle B_p^2\rangle$ the mean value of the poloidal component, R the radius of the undeformed star, G_N the gravitational constant and M the mass of the neutron star.

Even though a purely toroidal magnetic field is unstable (Braithwaite 2009), an additional poloidal component with energy $E_p/E_t = B_p^2/B_t^2 \sim 1$–$5$ per cent stabilizes the magnetic field configuration (Reisenegger 2013), allowing us to neglect the poloidal contribution to equation (1) as $\langle B_p^2\rangle \ll \langle B_t^2\rangle$.

Horowitz & Kadau (2009) found that neutron star crusts are strong enough to support an ellipticity up to a critical value of $\epsilon_c \lesssim 4 \times 10^{-6}$ before cracking.

2 THE MODEL

The theoretical picture that we want to explore is the following: given a certain initial mostly toroidal magnetic field of strength $\langle B_t^i\rangle$, the neutron star crust crystallizes in a prolate equilibrium configuration, with constant ellipticity ϵ^- given by equation (1). The magnetic field decays due to the combination of Ohmic and Hall effects in the neutron star interior with timescale $\sim 10^5$ yr (see for instance Pons, Miralles & Geppert 2009; Viganò et al. 2013). As a consequence, this prolate configuration with ϵ^- departs more and more from equilibrium until it reaches a critical strain, becoming unstable enough to crack the stellar crust. Then, the stellar structure achieves a new stable and less prolate configuration, with ellipticity ϵ^+, associated with the present magnetic field strength, which we call the final magnetic field strength, $\langle B_t^f\rangle$. Because the more spherical configuration, ϵ^+, has a greater moment of inertia with respect to the spin axis, chosen to be z in our case, with respect to the previous ϵ^- configuration, and considering that in the absence of an external torque then angular momentum is conserved, this sudden change in the stellar structure can easily account for the observed sudden frequency spin-down.

A change in the oblateness of a uniform-density star induces a spin frequency shift given by:

$$\frac{\Delta\nu}{\nu} \equiv \frac{\nu^+ - \nu^-}{\nu^-} = \frac{I_{zz}^-}{I_{zz}^+} - 1 = \left(\frac{R_e^-}{R_e^+}\right)^2 - 1, \tag{2}$$

where $R_e^{\mp}$ and $\nu^{\mp}$ are the equatorial radii and spin frequencies before and after the anti-glitch. In this case, R_e is related to the ellipticity of the star by:

$$R_e = R(1 - 2\epsilon)^{-1/6}. \tag{3}$$

Thus, we can write equation (2) as a function of the quadrupolar distortions before and after the anti-glitch, $\epsilon^{\mp}$:

$$\frac{\Delta\nu}{\nu} = \frac{(1 - 2\epsilon^+)^{1/3}}{(1 - 2\epsilon^-)^{1/3}} - 1 \approx \frac{2}{3}(\epsilon^- - \epsilon^+), \tag{4}$$

where, in the last approximation, we used that, in the cases we are interested in, both $|\epsilon^{\mp}| \sim 10^{-6} \ll 1$.

Substituting equation (1) into equation (4), and assuming that the magnetic field is aligned with the rotation axis of the star, we obtain $\Delta\nu/\nu$ as a function of $\langle B_t^{i,f}\rangle^2$:

$$\frac{\Delta\nu}{\nu} \approx \frac{2}{3}\frac{25R^4}{24G_N M^2}\left(\langle B_t^f\rangle^2 - \langle B_t^i\rangle^2\right), \tag{5}$$

from which follows

$$\langle B_t^f\rangle \approx \sqrt{\langle B_t^i\rangle^2 - B_0^2} \tag{6}$$

where

$$B_0^2 = -\left(8.7 \times 10^{14}\,\mathrm{G}\right)^2 \left(\frac{\Delta\nu}{\nu}\right)_6 \left(\frac{M}{1.4\,\mathrm{M}_\odot}\right)^2 \left(\frac{R}{10\,\mathrm{km}}\right)^{-4},$$

which would change for a more complete treatment. Here

$$\left(\frac{\Delta\nu}{\nu}\right)_6 = \left(\frac{\Delta\nu}{\nu}\right)/10^{-6}$$

and

$$\left(\frac{\Delta\nu}{\nu}\right) < 0$$

for anti-glitches.

Note that a more thorough model considering a neutron star with a solid crust surrounding a liquid core, as the one proposed by Franco, Link & Epstein (2000) for studying starquakes in rotation-powered pulsars, would be useful. However, we stress that in this letter we present order of magnitude calculations to give confidence to the scenario that we are suggesting.

To estimate the energy released by this mechanism during the anti-glitch event, we use the model from Baym & Pines (1971) developed for pulsar glitches. In this classic work, the authors consider three energy contributions: gravitational, coming from the global change in the stellar shape; rotational, associated with the spin frequency shift, $\Delta\nu/\nu$ and strain tensions released by the crust. This strain energy is accumulated because, even though the magnetic field decays from $\langle B_t^i\rangle^2$ to $\langle B_t^f\rangle^2$ in $\sim 10^5$ yr, the crystallized crust keeps its original shape of ϵ^- by increasing its internal tension, and thus departing from equilibrium. Once the critical strain is achieved, the crust cracks and the star re-accommodates into an ϵ^+ equilibrium configuration, releasing this stored energy. Moreover, as we are considering a magnetar instead of a pulsar, we also consider the magnetic energy released due to the displacement of magnetic field footpoints. However, because the length scale, ℓ, associated with the change in shape in our model is small, $\ell/R \sim \epsilon$, we assume that magnetic field reconnection does not take place, as in the standard soft gamma repeater (SGR) theory (Thompson & Duncan 1995, 1996).

3 RESULTS

Following our model, for a constant-density neutron star, which is deformed to a prolate shape by a mostly toroidal magnetic field (Cutler 2002), we calculate the long-term decay in the magnetic field strength, $\Delta\langle B_t\rangle$ needed to account for the $\Delta\nu/\nu$ observed in the anti-glitch of AXP 1E 2259+586.

In Fig. 1, we plot the physical solutions, $\Delta\langle B_t\rangle < 0$, to equation (6), as a function of the mean initial toroidal magnetic field strength $\langle B_t^i\rangle$, for three different neutron star configurations, assuming a jump in frequency $\Delta\nu/\nu = -6.3 \times 10^{-7}$ equal to the first of the two events of model (ii). In grey, we plot the identity as a reference.

For a typical neutron star of radius R = 10 km and mass $M = 1.4\,M_\odot$, with a mean toroidal magnetic field of $\langle B_t\rangle = 2 \times 10^{15}$ G, which corresponds to a maximum value for the magnetic field strength $B_M \gtrsim 10^{16}$ G (Reisenegger 2013), we estimate that a decay in the magnetic field of about $\sim$10 per cent can be responsible for the observed spin-down. This qualitative result is almost insensitive to other acceptable values for the mass, radius and magnetic field strength of magnetars (see Fig. 1). Detailed studies of the magnetic field evolution in neutron stars show that a magnetic field decay of $\sim$10 per cent is easily achieved after $t \lesssim 10^6$ yr for a magnetar like AXP 1E 2259+586 (Viganò et al. 2013).

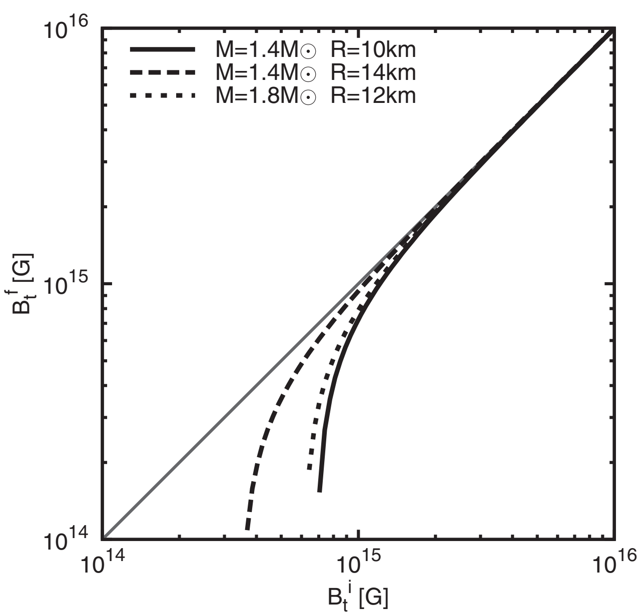

Figure 1. Physical solutions to equation (6) for $\Delta\nu/\nu = -6.3 \times 10^{-7}$ as a function of $\langle B_t^i\rangle$, for three different neutron star configurations (see the legend). In grey we plot the identity function as a reference.

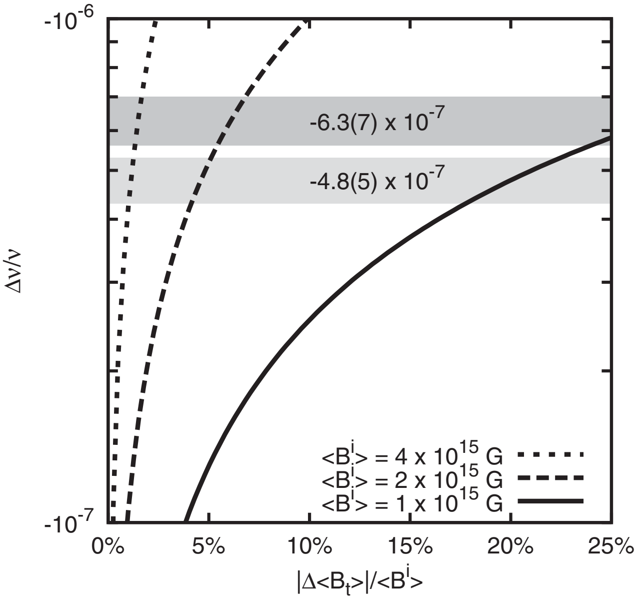

Figure 2. $\Delta\nu/\nu$ values obtained from equation (5) as a function of the relative change $|\Delta\langle B_t\rangle|/\langle B_t^i\rangle$ in the mean toroidal magnetic field strength. As a reference, we also show the $\Delta\nu/\nu$ values in shaded rectangles with their corresponding error bars for the anti-glitch/anti-glitch pair observed for AXP 1E 2259+586.

For each of the adopted neutron star configurations, we find that a minimum value for $\langle B_t^i\rangle$ is needed for a solution to equation (4) for the observed $\Delta\nu/\nu$. This critical value is, in any case, several times 10^{14} G, which avoids anti-glitches in normal pulsars, and this phenomenon can occur only in strongly magnetized neutron stars, i.e. magnetars. This result explains why even though many pulsars have been thoroughly monitored for several decades, no sudden spin-down event of this kind has been detected at all.

In Fig. 2, we present $\Delta\nu/\nu$ from equation (4) as a function of the change $|\Delta\langle B_t\rangle|/\langle B_t^i\rangle$ in the mean toroidal magnetic field strength. The shaded rectangles account for the values of $\Delta\nu/\nu$ from model (ii) with their corresponding error bars.

In this way we show how our simple model can take into account the observed sudden frequency change observed in magnetar AXP 1E 2259+586. Let us now focus on analysing the energetics.

For a typical neutron star, following Baym & Pines (1971) and assuming a normal neutron star crust, we estimate a gravitational energy release of $\sim 10^{42}$ erg, while the rotational and crustal strain contributions are several orders of magnitude smaller. Assuming a typical SGR, the magnetic energy released is $\sim 10^{41}$ erg. Hence, the total energy emitted after the anti-glitch in gravitational waves, particles and electromagnetic radiation should be of the order of 10^{42} erg, which is compatible with *Fermi*/GBM and *Swift* observations.

4 DISCUSSION

A very simple model to explain the anti-glitch observed in magnetar AXP 1E 2259+586 is presented here. We propose that a natural decay of the toroidal magnetic field component, of approximately $\sim$10 per cent, from an initial $\langle B_t^i\rangle \gtrsim 10^{15}$ G, would be enough to destabilize an originally prolate configuration of the stellar structure and crack the neutron star crust, reducing it to a more spherical one. As a result, the sudden change in the moments of inertia of the star produces a net spin-down, as the one observed in Archibald et al. (2013). Moreover, under this scenario, by considering a typical neutron star, we estimate an energy release of $\sim 10^{42}$ erg, in agreement with the emission detected by *Fermi* and *Swift* observatories in the epoch when the anti-glitch occurred.

Our model predicts that an anti-glitch, such as the one detected by Archibald et al. (2013) for AXP 1E 2259+586, can only be achieved if the mean internal toroidal magnetic field of the neutron star is several times 10^{14} G, as in magnetars. This critical value avoids this kind of anti-glitch in the very vast population of rotation-powered pulsars, which might be the reason why this event is the first of its kind to be detected, since the known magnetar population is rather low (10–20 members) and it has been observed for ∼20 yr.

As an extension of our simple model, the second event reported by Archibald et al. (2013) could be explained in the context of a more complex scenario where the first sudden anti-glitch is followed by aftershocks, as is normally observed with terrestrial earthquakes. Assuming $\langle B_{\rm t}^{\rm i} \rangle = 2 \times 10^{15}$ G, using equation (6), we estimate $\langle B_{\rm t}^{\rm f} \rangle \approx 1.87 \times 10^{15}$ G ($\Delta B \sim 6.5$ per cent) for the first anti-glitch and $\langle B_{\rm t}^{\rm f} \rangle \approx 1.78 \times 10^{15}$ G ($\Delta B \sim 11$ per cent) for both anti-glitches considered as a composite event. As we cannot go deeper than the temporal resolution of two consecutive observations, we cannot be sure of how anti-glitches develop in shorter timescales. Actually, from the data presented in Archibald et al. (2013), it is not clear if the second event is an anti-glitch or a normal glitch. Modelling the dynamics in detail is beyond the scope of this letter.

It is also worth noticing that gravitational waves, potentially observed by advanced LIGO, should be emitted under this scenario due to oscillations induced by the changes in the stellar structure.

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