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Do magnetars glitch? Timing irregularities in anomalous X-ray pulsars

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ABSTRACT

We examine the timing history of several anomalous X-ray pulsars (AXPs), and find that they exhibit spin-down irregularities that are statistically similar to those of radio pulsars. We propose that these irregularities are simply glitches like those of radio pulsars, and fit glitching spin-down solutions to the data available for 1E 2259+586, 1E 1048.1−5937 and 4U 0142+61. The inferred magnitude of the glitches ($\Delta\Omega$) is comparable to that exhibited in radio pulsar glitching. With these results, we argue that the three AXPs that we have studied are isolated neutron stars spinning down by magnetic dipole radiation and powered by a combination of cooling, magnetic field decay and magnetospheric particle bombardment.

Key words: radiative transfer – stars: magnetic fields – stars: neutron – X-rays: stars.

1 INTRODUCTION

Over the past decade, several X-ray pulsars with unusually long periods ($P \sim 10\,\mathrm{s}$) and unusually small luminosities ($L \sim 10^{35}$–$10^{36}\,\mathrm{erg\,s^{-1}}$) have been discovered in or near young supernova remnants (SNRs) (e.g. Vasisht & Gotthelf 1997). Mereghetti & Stella (1995) group these objects as a class; they are known as braking (White et al. 1996) or 'anomalous' (Van Paradijs, Taam & van den Heuvel 1995) X-ray pulsars (AXPs). Thompson & Duncan (1996) suggest that these objects are isolated neutron stars spinning down by magnetic dipole radiation with B_p (the strength of the dipole at the surface) $\gtrsim 10^{14}$ G, i.e. 'magnetars' (Duncan & Thompson 1992), and that the decay of their intense magnetic fields powers their X-ray emission. Heyl & Kulkarni (1998) examine this issue further in the context of the cooling evolution of these objects. Heyl & Hernquist (1997b, 1998) argue that their emission may be powered by the cooling of the neutron star core through a strongly magnetized or light-element envelope without any appreciable field decay. The observations by Kouveliotou et al. (1998) of SGR 1806–20 indicate that SGRs soft-gamma repeaters and AXPs may be related, which further connects the AXPs with models of SGRs that invoke magnetars (Thompson & Duncan 1995, 1996). For several AXPs, the spin-down age of the neutron star and the age of the surrounding remnant are similar, bolstering these arguments.

Several contrasting models for AXPs have been proposed in which a neutron star is slowly accreting from the interstellar medium (Wang 1997), from a very low-mass companion (Mereghetti & Stellar 1995; Baykal & Swank 1996) or from the remains of a high-mass X-ray binary (Van Paradijs et al. 1995; White et al. 1996; Ghosh, Angelini & White 1997). In these models, irregularities in the accretion flow explain the irregular nature of the spin-down or torque noise (Baykal & Swank 1996) as found in observations of accreting pulsars (e.g. Bildsten et al. 1997; Chakrabarty et al. 1997; Nelson et al. 1997). However, it is difficult to reconcile the ages of the supernova remnants with the low rotation rates of the pulsars, unless these neutron stars were born rotating unusually slowly.

In this Letter, motivated by the coincidences between the characteristic spin-down ages of some AXPs and the ages of the SNRs surrounding them, we examine a model in which AXPs are isolated pulsars rather than accreting sources. Specifically, we focus on the spin-down irregularities of three anomalous X-ray pulsars, and compare their timing behaviour with that of isolated radio pulsars having a range of periods from 1.6 ms to 3.7 s.

2 TIMING IRREGULARITIES IN AXPs AND RADIO PULSARS

Arzoumanian et al. (1994) have studied the timing behaviour of a large sample of radio pulsars over a wide range of periods and period derivatives. To characterize the timing irregularities of these objects, they fit the observed rotational phase (ϕ) as a function of time (t) of each pulsar with a function of the form

$$\phi = \phi_0 + \nu t + \frac{1}{2}\dot{\nu} t^2 + \frac{1}{6}\ddot{\nu} t^3 \dots \quad . \tag{1}$$

Further, they define a stability parameter

$$\Delta(t) = \log\left(\frac{1}{6\nu}|\ddot{\nu}|t^3\right) \tag{2}$$

if $|\ddot{\nu}| > 2\sigma_{\ddot{\nu}}$; otherwise they adopt an upper limit

$$\Delta(t) < \log\left(\frac{2\sigma_{\ddot{\nu}} t^3}{6\nu}\right). \tag{3}$$

Since the observations were taken over several years, they use a characteristic time of 10^8 s so that $\Delta_8 \equiv \Delta(10^8\,\mathrm{s})$ is approximately the logarithm of the clock error of the pulsar in seconds over the span of the observations.

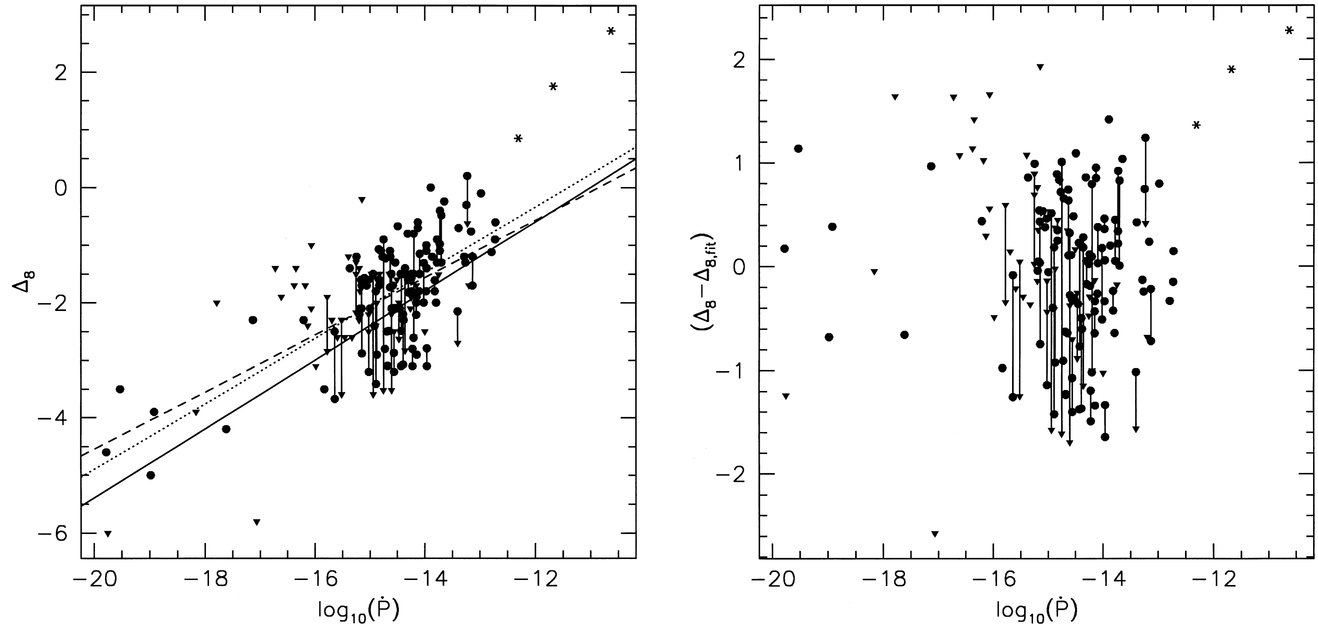

Figure 1. The left-hand panel depicts the timing noise parameter, Δ_8, plotted against the period derivative for 139 radio pulsars (triangles and circles from Arzoumanian et al. 1994) and three anomalous X-ray pulsars (asterisks). Inverted triangles represent upper limits. When two or more estimates of Δ_8 are available, the corresponding points are connected by a vertical line. The right-hand panel shows the residuals of the data relative to the best-fitting linear relation (the dotted line of the left-hand panel). The other lines are explained in the text.

For the AXPs, we use the first derivative of equation (1) to determine the value of Δ_8 for the pulsars 1E 2259+586 (Baykal & Swank 1996), 1E 1048.1−5937 (Oosterbroek et al. 1998) and 4U 0142+61 (Hellier 1994; White et al. 1996; and the 1984 August observation analysed by Israel, Mereghetti & Stella 1994). Israel et al. (1994) present several marginal results for other observations of 4U 0142+61, which we omit from our analysis.

Fig. 1 presents the results for 139 radio pulsars from Arzoumanian et al. (1994), along with the three AXPs studied here. In the left-hand panel, the solid line traces the relation $\Delta_8 = 6.6 + 0.6 \log \dot{P}$ given by Arzoumanian et al. (1994) for the set of radio pulsars. The dotted line gives the best-fitting relation for the complete sample, $\Delta_8 = 6.5 + 0.57 \log \dot{P}$, and the long-dashed line traces the relation $\Delta_8 = 5.4 + 0.50 \log \dot{P}$, which is the best-fitting relationship for the radio pulsars alone.

The right-hand panel shows the residuals of the data relative to the best-fitting linear relation for the entire data set. Although the AXPs (asterisks) have significantly larger values of $\dot{P}$ and activity parameters, they follow well the relationship for the pulsar population as a whole.

2.1 Glitch fitting

For two of the AXPs there are sufficient observations that we can fit glitches to the timing solution to determine a lower limit on the frequency of glitching in these objects and an upper limit on the magnitude of the glitches themselves. We fit a spin-down relationship that is linear in time with the possibility of several discontinuous jumps in period between the observations. Since the data are sparsely sampled, we assume that the period can jump immediately before any observation. The best-fitting glitch models are found by minimizing the value of χ^2 with respect to the slope and intercepts of the model while varying the positions of the discontinuities. Fig. 2 gives two glitch models for the AXPs 1E 1048.1−5937 and 1E 2259+586.

Although both pulsars have periods between 6 and 7 s, their period derivatives differ by nearly a factor of 30. When the timing data for these pulsars are fitted with glitch solutions, we find that the characteristic size of the glitches also varies by a factor of approximately 30. The typical size of the glitches for 1E 1048.1−5937 is $\Delta\Omega \approx 2 \times 10^{-4}\,\mathrm{s}^{-1}$, while the more slowly decelerating pulsar, 1E 2259+586, glitches more weakly with $\Delta\Omega \approx 5 \times 10^{-6}\,\mathrm{s}^{-1}$, comparable to the value found by Usov (1994). The strengths of these glitches are comparable to those of the glitches in the Vela and Crab pulsars respectively (e.g. Shapiro & Teukolsky 1983).

3 DISCUSSION

We have found that AXPs follow an extension of the relation between pulsar clock error and period derivative proposed by Arzoumanian et al. (1994) for millisecond and ordinary radio pulsars. Furthermore, by fitting discontinuities on a linear relationship, $P(t)$, we find that AXPs exhibit glitches with values of $\Delta\Omega$ similar to those of radio pulsars. For example, if glitches occur when vortex lines pinned to nuclei in the crust are freed and angular momentum is suddenly transferred to the crust (e.g. Alpar et al. 1984; Pines & Alpar 1985), $\Delta\Omega$ is simply proportional to the number of vortex lines that become unpinned during the event. In this scenario, the value of $\Delta\Omega$ may depend on the properties of the outer core and inner crust of the neutron star, and will not be strongly affected by the presence of a strong magnetic field. Thompson & Duncan (1996) argue that the evolution of magnetic field in a strongly magnetized neutron star may encourage glitching with an amplitude $\Delta\Omega \sim 10^{-5}$, similar to the values inferred here.

In this Letter, we have described similarities between the AXPs and ordinary radio pulsars in the context of timing irregularities. This begs the question why AXPs are not observed as radio pulsars. A simple possibility is that the solid angle subtended by the open-field lines in a pulsar magnetosphere decreases as the period increases. Both models and observations of the radio pulsars indicate that the radio emission is limited to the open-field lines; consequently, it becomes less likely that the pulse beam crosses our line of sight as the period of the pulsar increases.

Mészáros (1992) summarizes several models for the emission beams from radio pulsars in the context of observations and theory. In general, the half-opening angle of the pulse beam is $\sim 5°$ for a period of 1 s and decreases as $P^{-\gamma}$, where $\gamma = 1/3$–$1/2$. To be conservative, we compare two cone-type pulsars for which

$$\rho \sim 6\overset{\circ}{.}5\left(\frac{P}{1\,\mathrm{s}}\right)^{-1/3}. \qquad (4)$$

The probability of observing a given pulsar will be proportional to the solid angle subtended by its rotating beam or beams,

$$\mathcal{P} \sim \sin\rho$$

For a 7-s pulsar, $\mathcal{P} \sim 6$ per cent; consequently, if the AXPs do emit radio waves like cone pulsars, about a dozen of these objects would need to be found before we should expect to have a fifty-fifty chance of detecting radio emission from any one of them.

In preceding paragraphs, we argued why one might be unlikely to observe the radio emission from AXPs. Most pulsar emission models rely on the formation of an electron–positron cascade through one-photon pair production to power the radio emission (e.g. Mészáros 1992). Several studies have argued that if $B \gtrsim B_c$, where $B_c \approx 4.414 \times 10^{13}$ G, a gamma-ray photon will preferentially decay into a bound electron–positron pair (Usov & Melrose 1996).

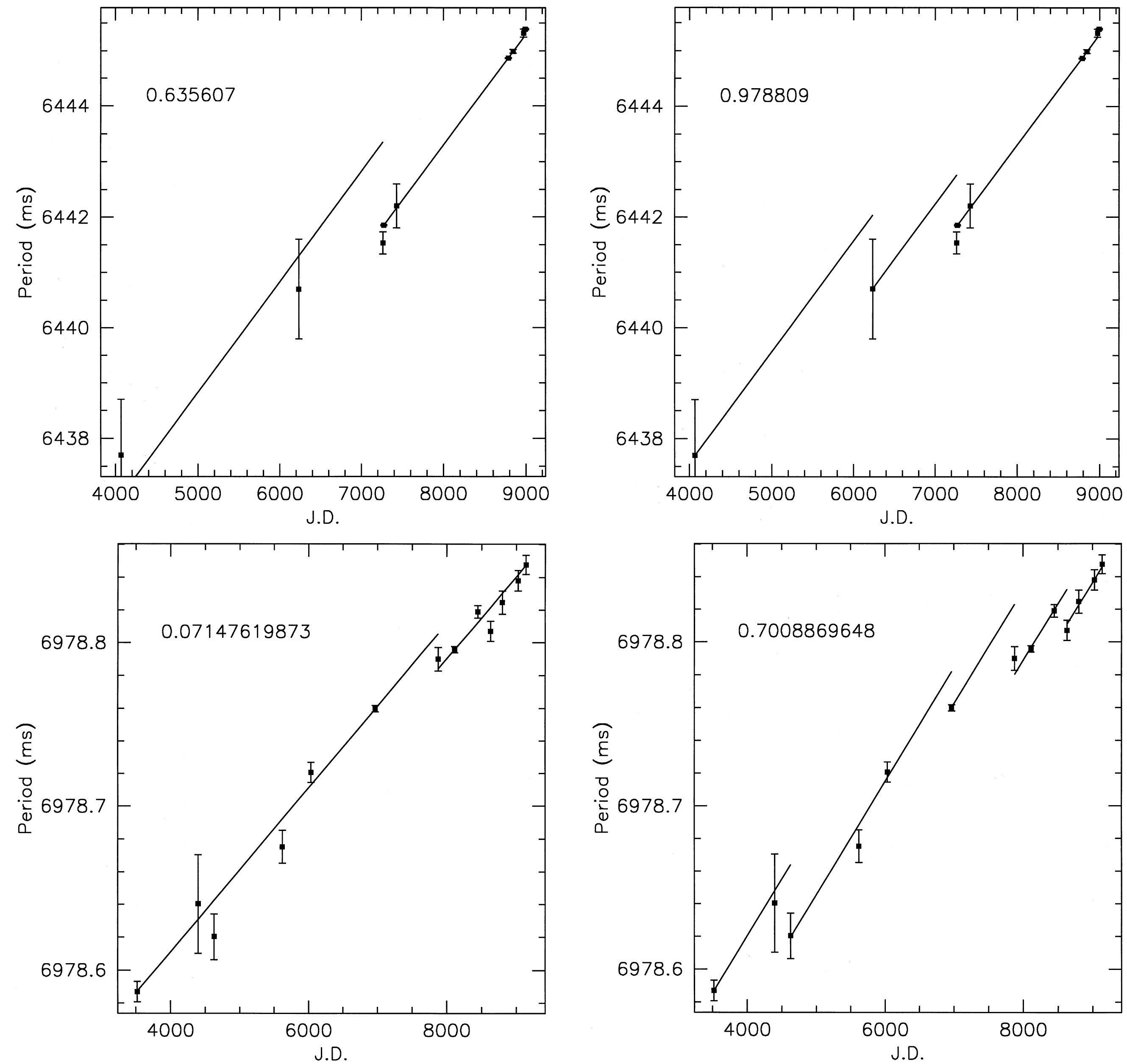

Figure 2. Glitch models for the AXPs 1E 1048.1–5937 and 1E 2259+586. The upper two panels depict one- and two-glitch models for the spin-down of 1E 1048.1–5937, and the lower two panels depict one- and five-glitch models for the period evolution of 1E 2259+586. The χ^2 likelihood that each model fits the data is given in the upper left quadrant of each panel.

This creates a relativistically outflowing neutral gas which is unable to produce radio emission collectively (Arons 1998). As the gas flows into more weakly magnetized regions, the positronium becomes more weakly bound and eventually photoionizes. Depending on where the pair plasma forms, the outflow may power a plerion. The AXPs may therefore be connected with the plerions that appear to be driven by a strong field but lack a radiative signature of a central compact source (Helfand, Becker & White 1995). Because of the formation of bound e^+e^- pairs in strong fields, it is natural that AXPs with $B > B_c$ are unobserved in the radio; however, like other young isolated pulsars, they may exhibit plerionic emission.

Alternatively, Baring & Harding (1997) argue that in sufficiently strong fields ($B \gtrsim B_c$) the quantum electrodynamic process of photon splitting (Adler 1971; Heyl & Hernquist 1997a) can dominate one-photon pair production. This will effectively quench the pair cascade, making coherent pulsed radio emission impossible.

4 CONCLUSION

Because the AXPs studied in this paper exhibit spin-down variations like neutron stars which we know to be isolated, our results suggest that they are isolated as well. This implies that these objects do indeed have $B \sim 10^{14-15}$ G, and that their X-ray emission is powered either by the cooling of the core of the neutron star or by the decay of its field, since these are the two largest sources of free energy available to these objects. The possibility of distinguishing between this scenario and alternative models in which variations in AXP periods are driven primarily by accretion from a disc may soon be realized when detailed spectra of AXPs are obtained with the *AXAF* satellite.

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REFERENCES

Adler S. L., 1971, Ann. Phys., 67, 599
Alpar M. A., Anderson P. W., Pines D., Shaham J., 1984, ApJ, 276, 325
Arons J., 1998, in Shibata S., Sata M., eds, Neutron Stars and Pulsars. Universal Academy Press, Tokyo, in press (astro-ph/9802198)
Arzoumanian Z., Nice D. J., Taylor J. H., Thorsett S. E., 1994, ApJ, 422, 671
Baring M. G., Harding A. K., 1997, in Dermer C. D., Strickman M. S., Kurfess J. D., eds, Proc. Fourth Compton Symp. AIP Conf. Proc. 410, Am. Inst. Phys., New York, p. 638
Baykal A., Swank J., 1996, ApJ, 460, 470
Bildsten L. et al., 1997, ApJS, 113, 367
Chakrabarty D. et al., 1997, ApJ, 474, 414
Duncan R. C., Thompson C., 1992, ApJ, 392, L9
Ghosh P., Angelini L., White N. E., 1997, ApJ, 478, 713
Helfand D. J., Becker R. H., White R. L., 1995, ApJ, 453, 741
Hellier C., 1994, MNRAS, 271, L21
Heyl J. S., Hernquist L., 1997a, Phys. Rev. D, 55, 2449
Heyl J. S., Hernquist L., 1997b, ApJ, 489, L67
Heyl J. S., Hernquist L., 1998, MNRAS, 297, L69
Heyl J. S., Kulkarni S. R., 1998, ApJ, 506, L61
Israel G. L., Mereghetti S., Stella L., 1994, ApJ, 433, 25
Kouveliotou C. et al., 1998, Nat, 393, 235
Mereghetti S., Stella L., 1995, ApJ, 442, L17
Mészáros P., 1992, High-Energy Radiation from Magnetized Neutron Stars. Univ. Chicago Press, Chicago
Nelson R. W. et al., 1997, ApJ, 488, L117
Oosterbroek T., Parmar A. N., Mereghetti S., Israel G. L., 1998, A&A, 334, 925 (astro-ph/9803226)
Pines D., Alpar M. A., 1985, Nat, 316, 27
Shapiro S. L., Teukolsky S. A., 1983, Black Holes, White Dwarfs, and Neutron Stars. Wiley-Interscience, New York
Thompson C., Duncan R. C., 1995, MNRAS, 275, 255
Thompson C., Duncan R. C., 1996, ApJ, 473, 322
Usov V. V., 1994, ApJ, 427, 984
Usov V. V., Melrose D. B., 1996, ApJ, 464, 306
Van Paradijs J., Taam R. E., van den Heuvel E. P. J., 1995, A&A, 299, 41
Vasisht G., Gotthelf E. V., 1997, ApJ, 486, L129
Wang J. C. L., 1997, ApJ, 486, L119
White N. E., Angelini L., Ebisawa K., Tanaka Y., Ghosh P., 1996, ApJ, 463, L83