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 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 (∆Ω) is comparable to that exhibited in radio pulsar glitching. With these results we argue that the three AXPs that we 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.

Subject headings: stars: neutron — stars: magnetic fields — radiative transfer — X-rays: stars

1. Introduction

Over the past decade, several X-ray pulsars with unusually long periods (P ∼ 10 s) and unusually small luminosities (L ∼ 10^{35} − 10^{36} erg/s) have been discovered in or near young supernova remnants (e.g. Vasisht & Gotthelf 1997). Mereghetti & Stella (1995) grouped this objects as a class. These objects 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 \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) and Heyl & Hernquist (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 and AXPs may be related, which further connects the AXPs with models of SGRs that invoke magnetars (Thompson & Duncan 1993; Thompson & Duncan 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 ISM (Wang 1997), from a very low mass companion (Mereghetti & Stella 1993; Baykal & Swank 1999) or from the remains of a high-mass X-ray binary (Van Paradijs, Taam & van den Heuvel 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; Nelson et al. 1997; Chakrabarty et al. 1997). However, it is difficult to reconcile the ages of the supernova remnants with the slow 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 will focus on the spin-down irregularities of three anomalous X-ray pulsars and compare their timing behavior 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) study the timing behavior of 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 of each pulsar with a function of the form

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

(1)

Further, they define a stability parameter

$$\Delta(t) = \log \left( \frac{1}{6 \nu} |\dddot{\nu} t^3| \right),$$

(2)

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

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

(3)

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

For the AXPs, we use the first derivative of Equation 1 to determine the value of $\Delta_8$ 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 August 1984 observation analyzed by Israel, Mereghetti & Stella 1994). Israel, Mereghetti & Stella (1994) present several marginal results for other observations of 4U 0142+61 which we omit from our analysis.

Figure 1 presents the results for 139 radio pulsars from Arzoumanian et al. (1994) along with the three AXPs studied here. In the left panel, the lower 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 upper dotted line gives the best fit 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-fit relationship for the radio pulsars alone.

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

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 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 fit glitch models are found by
minimizing the value of $\chi^2$ with respect to the slope and intercepts of the model while varying the positions
of the discontinuities. Figure 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 seconds, their period derivatives differ by nearly
a factor of thirty. 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 thirty. The typical size of
the glitches for 1E 1048.1-5937 is $\Delta \Omega \approx 2 \times 10^{-4}$ s$^{-1}$, while the more slowly decelerating pulsar, 1E 2259+586,
glitches more weakly with $\Delta \Omega \approx 5 \times 10^{-6}$ s$^{-1}$, comparable to the value found by Usov (1994). The strengths
of these glitches are comparable to 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 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 which 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 of 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 $\sim 5^\circ$ for a period of 1 s and
decreases as $P^{-\gamma}$ where $\gamma = 1/3 - 1/2$. To be conservative we will compare two cone-type pulsars for which

$$\rho \sim 6.5^\circ \left(\frac{P}{1 \text{ s}}\right)^{-1/3}. \tag{4}$$

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

$$P \sim \sin \rho \tag{5}$$

For a seven-second pulsar, $P \sim 6\%$; consequently, if the AXPs do emit radio waves like cone pulsars,
about 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 it 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). 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 which 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 QED 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 possibility and alternative models in which variations in AXP periods are driven primarily by accretion from a disk may soon be possible when detailed spectra of AXPs are obtained with the AXAF satellite.

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Fig. 1.— The left panel depicts the timing noise parameter, $\Delta_8$, plotted against the period derivative for 139 radio pulsars (triangles and disks from Arzoumanian et al. 1994) and 3 anomalous X-ray pulsars (asterisks). Inverted triangles represent upper limits. When two or more estimates of $\Delta_8$ are available, the corresponding points are connected by a vertical line. The right panel shows the residuals of the data relative to the best-fit linear relation (the dotted line).
Fig. 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 panels depict one- and five-glitch models for the period evolution of 1E 2259+586. The $\chi^2$ likelihood that each model fits the data is given in the upper left quadrant of each panel.