Glitches in Anomalous X-ray Pulsars

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Glitches in Anomalous X-ray Pulsars

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Abstract. After 10 years of RXTE monitoring of 5 Anomalous X-ray Pulsars, we report the detection of 10 glitches and 5 glitch candidates. Armed with sufficient data for a meaningful comparison of AXP and radio pulsar glitch properties, we show that in terms of fractional frequency change, AXPs are among the most actively glitching neutron stars, with glitch amplitudes in general larger than in radio pulsars. However, in terms of absolute glitch amplitude, AXP glitches are unremarkable. We show that three of the largest AXP glitches observed thus far have recoveries that are unusual among those of radio pulsar glitches, with the combination of recovery time scale and fraction yielding changes in spin-down rates following the glitch similar to, or larger than, the long-term average. We also observed a large long-term fractional increase in the magnitude of the spin-down rate of 1E 1841−045, following its largest glitch. These observations are challenging to interpret in standard glitch models, as is the frequent occurrence of large glitches given AXPs’ high measured temperatures. We speculate that the stellar core may be involved in the largest AXP glitches. Furthermore we show that unlike in radio pulsars, AXP glitches sometimes, but not necessarily always, involve major radiative events.

Keywords: anomalous X-ray pulsar, magnetar, neutron star

PACS: 97.60.Gb, 97.60.Jd, 95.85.Nv

INTRODUCTION

The past decade has seen significant progress in our knowledge of the observational properties of Anomalous X-ray Pulsars. From a timing point of view, their potential for great rotational stability was demonstrated [1], thereby allowing the discovery that AXPs can exhibit spin-up glitches [2, 3, 4], and large torque variations [5]. From a radiative point of view, AXPs are now known to show a variety of different variability phenomena [6], including long-lived flares, short bursts, large outbursts, and slow, low-level flux and pulse profile variability. At least some radiative variability has been seen to be correlated with timing behavior (e.g., 1E 2259+586 [7, 8]).

There are currently 8 known AXPs and two candidate AXPs. The evidence thus far argues that AXPs, like their close cousins, the Soft Gamma Repeaters, are magnetars – young, isolated neutron stars powered by a large magnetic energy reservoir [9]. To investigate these sources, we initiated an AXP monitoring program in 1997. This program has allowed us to perform phase-coherent timing of 5 of these AXPs and to discover 10 glitches and 5 candidate glitches, all listed in Table 1. In what follows, we will focus on the glitches discovered in AXPs RXS J170849.0−400910, 1E 1841−045, 1E 2259+586, and 1E 1048.1−5937. We will then compare AXP glitches to radio pulsar glitches.

OBSERVATIONS AND DATA ANALYSIS

The results presented here were obtained using the PCA on board RXTE. For each source, we analysed hundreds of observations obtained over several years of monitoring (see Table 1). For each observation, we extracted an average pulse time of arrival (TOA) corresponding to a fixed pulse phase. The pulse phase at any time can usually be expressed as a Taylor expansion polynomial. Ephemerides were extracted by fitting the TOAs to the polynomial using the pulsar timing software package TEMPO [10]. For more details see [10].

TIMING RESULTS

RXS J170849.0−400910 has a period of 11 s and P= 1.9×10−11. In 8.7 years of timing 3 glitches and 3 glitch candidates were discovered from this source (see Table 2, [2, 3, 4, 10, 11]). The timing history of RXS J170849.0−400910 is shown in the first two panels of Figure 1. The timing residuals around the glitch epochs are shown in Figure 2. The second glitch was fit to a model with an exponential recovery. The post-fit residuals were not featureless, indicating that the exponential model is not perfect. The candidate glitches were called candidates because a fourth degree polynomial provided as good a fit to the TOAs as a model involving a glitch.
TABLE 1. Timing history of the 5 AXPs monitored with RXTE.

<table>
<thead>
<tr>
<th>Source</th>
<th>Years of Phase-Coherent Timing with RXTE</th>
<th>Number of Observations</th>
<th>Number of Glitches</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>RXS J170849.0–400910</td>
<td>1998–2007</td>
<td>294</td>
<td>3 glitches</td>
<td>[2, 3, 4, 10, 11]</td>
</tr>
<tr>
<td>1E 2259+586</td>
<td>1997–2007</td>
<td>340</td>
<td>2</td>
<td>[7, 8], work in prep.</td>
</tr>
<tr>
<td>1E 1048.1–5937</td>
<td>2004–2007</td>
<td>410</td>
<td>1*</td>
<td>[12, 13, 14]</td>
</tr>
</tbody>
</table>

* Additional timing anomalies were detected at the onsets of the 2002 pulsed flux flares (work in prep.).

FIGURE 1. Spin and flux evolution in RXS J170849.0–400910. Top Solid curve: frequency evolution obtained from long-term phase-coherent timing after removal of a linear trend. Data points: measured frequencies in independent sub-intervals after subtraction of same linear trend. Next: Evolution of the frequency derivative in sub-intervals, when fitting locally for only \( \nu \) and \( \dot{\nu} \). Next: RMS Pulsed flux in the 2–10 keV range. Bottom: Unabsorbed phase-averaged 0.5–10 keV fluxes and photon indices from [18, 19] labelled by observing telescope. All Panels: Unambiguous glitch epochs are indicated with solid vertical lines. Candidate glitch epochs are indicated with dashed vertical lines. Figure from [10].

In addition to timing information, we report the RMS pulsed flux of this source (Fig. 1, Panel 3). Note the low-level variations. The total flux obtained from several imaging instruments [18, 19] is shown in the last Panel of Figure 1.

1E 1841–045 has a period of 11.8 s and \( \ddot{P} \approx 4.1 \times 10^{-11} \).

FIGURE 2. The three unambiguous glitches observed in RXS J170849.0–400910. Top panels: Frequency evolution around the glitch with the blow-up inset displaying glitch amplitude on a common scale for comparison. Middle panels: Residuals after subtraction of the best-fit pre-glitch ephemeris. Bottom panels: Residuals after subtraction of best-fit glitch models. All panels: Dashed vertical lines indicate assumed glitch epochs. Figure from [10].

In 7.6 years of timing, 4 glitches were discovered from this source (see Table 2), [10], (work in prep. for glitch 4). The timing history of 1E 1841–045 is shown in the first two panels of Figure 3. The first glitch was fit to an exponential recovery. The RMS pulsed flux is shown in Panel 3.

1E 2259+586 has a period of 7.0 s and \( \ddot{P} \approx 0.05 \times 10^{-11} \). In the past 10 years, 2 glitches were discovered from this source (see Table 2). The first glitch was fit to an exponential recovery and was accompanied by an outburst in which the pulsed and total fluxes were enhanced [7, 8]. The second glitch was not observed to be accompanied by a radiative event (work in prep). The RMS pulsed flux is presented in Figure 4. Note that the authors of [8] took
FIGURE 3. Spin and pulsed flux evolution in 1E 1841–045 up to one year before the 4th glitch. Top: Solid curve: frequency evolution obtained from long-term phase-coherent timing after removal of a linear trend. Dotted curve: alternate glitch recovery [10]. Filled circles: Measured frequencies in independent sub-intervals after subtraction of the same linear trend. Unfilled squares: Epochs of the two immediate post-glitch observations (too few for the measurement of an independent frequency but crucial for the phase-coherent analysis). Middle: Evolution of the frequency derivative in sub-intervals, when fitting locally for only v and v. Bottom: RMS pulsed flux in the 2–10 keV range. All panels: Glitch epochs are indicated with solid vertical lines. Figure from [10].

FIGURE 4. RMS Pulsed flux vs. time of 1E 2259+586. The vertical lines indicate the two glitch epochs. The apparent increase in the pulsed flux at the epoch of the second glitch is an artifact of the binning of the data points.

FIGURE 5. RMS Pulsed flux vs. time of AXP 1E 1048.1–5937. The vertical line indicates the epoch of the large glitch. Figure from [13].

TABLE 2. AXP glitches reported for 4 of the 5 monitored AXPs. The superscript (E) refers to glitches with an exponential recovery. The superscript (R) refers to glitches accompanied by an observed, confirmed radiative event.

<table>
<thead>
<tr>
<th>Glitch or Glitch Candidate</th>
<th>Glitch Amplitude (Hz)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>RXS J170849.0–400910 Glitch 1</td>
<td>5.1(3) × 10^{-8}</td>
</tr>
<tr>
<td>RXS J170849.0–400910 Glitch 2E</td>
<td>3.8(3) × 10^{-7}</td>
</tr>
<tr>
<td>RXS J170849.0–400910 Glitch 3</td>
<td>24.6(9) × 10^{-8}</td>
</tr>
<tr>
<td>RXS J170849.0–400910 Cand. 1</td>
<td>2.8(4) × 10^{-8}</td>
</tr>
<tr>
<td>RXS J170849.0–400910 Cand. 2</td>
<td>5.2(6) × 10^{-8}</td>
</tr>
<tr>
<td>RXS J170849.0–400910 Cand. 3</td>
<td>6.7(3) × 10^{-8}</td>
</tr>
<tr>
<td>1E 1841–045 Glitch 1E</td>
<td>12.9(6) × 10^{-7}†</td>
</tr>
<tr>
<td>1E 1841–045 Glitch 2</td>
<td>2.08(4) × 10^{-7}</td>
</tr>
<tr>
<td>1E 1841–045 Glitch 3</td>
<td>1.18(7) × 10^{-7}</td>
</tr>
<tr>
<td>1E 1841–045 Glitch 4</td>
<td>4.4(7) × 10^{-7}</td>
</tr>
<tr>
<td>1E 2259+586 Glitch 1E,R</td>
<td>6.08(8) × 10^{-7}</td>
</tr>
<tr>
<td>1E 2259+586 Glitch 2</td>
<td>1.22(3) × 10^{-7}</td>
</tr>
<tr>
<td>1E 1048.1–5937 Glitch 1R</td>
<td>2.63(19) × 10^{-6}</td>
</tr>
</tbody>
</table>

* For references, see Table 1.
† Less probable alternate glitch recovery predicts the glitch amplitude to be 2.20(3) × 10^{-7} Hz, see [10].

discovery of timing anomalies near the rise of each of the 2002 flares [14]. In mid-2004, the source became a lot less noisy, and phase coherent timing on a time-scale of years became possible. The source then exhibited a large glitch in 2007 (see Table 2) [12, 13, 14], coinciding with the onset of a fast-rising pulsed flux flare (Figure 5).

DISCUSSION

We have now observed a sufficiently large sample of AXP glitches (Table 2) that we can make meaningful comparisons with glitches in radio pulsars. Detection of systematic differences in AXP and radio pulsar glitch properties would be interesting as it could signal structural differences between magnetars and radio pulsars.
Glitch Amplitude Distribution: Figure 6 shows the fractional and non-fractional amplitude distributions of radio pulsar and AXP glitches. As is clear from the figure, although the fractional glitch amplitudes of AXPs are generally large by radio pulsar standards, the AXP absolute glitch amplitudes, more directly related to the angular momentum transfer during the glitch, are unremarkable.

Activity Parameters and Coupling Parameters: Fractional glitch activity has been defined as $a_g = \frac{1}{\Delta t} \sum \frac{\Delta \nu}{\nu}$, where $\Delta t$ is the total observing span and the sum is over all glitches, and includes decaying components [21]. The authors of [20] argued that $a_g$ provides a lower limit on the fraction of the moment of inertia of the neutron star that resides in the angular momentum reservoir (generally assumed to be the crustal superfluid) tapped during spin-up glitches, $I_{res}$. They showed that $I_{res}/I_c \geq \frac{\nu a_g}{|\dot{\nu}|} \equiv G$, where $I_c$ is the moment of inertia of the crust and all components strongly coupled to it, and $G$ is a “coupling parameter.” For radio pulsars, they argued for a universal $G$ that implies $I_{res}/I_c \geq 0.014$. Figure 7 shows $G$ plotted versus age for radio pulsars and AXPs. The relation derived in [20] holds for the radio pulsars and for AXPs RXS J170849.0−400910 and 1E 1841−045 but not for 1E 2259+586 which has has $G = 0.25$, much larger. Admittedly, for this AXP, $a_g$ is estimated from two glitches only. Still, the large $G$, if real, suggests that at least ~25% of the stellar moment of inertia is in the angular momentum reservoir (see also [8]).

Enhanced Spin-Down: For glitches that have exponential recoveries (see Table 2), the instantaneous spin-down rate $\dot{\nu}$ at the glitch epoch due to the recovery is $\Delta \nu/t$. Comparing this quantity for the AXP glitches that show recovery with the time-averaged $\dot{\nu}$, we find that for 1E 2259+586 $\Delta \nu/t = (8.2 \pm 0.6)\dot{\nu}$, $\Delta \nu/t = (0.64 \pm 0.6)\dot{\nu}$ for RXS J170849.0−400910, and $\Delta \nu/t = (0.75 \pm 0.08)\dot{\nu}$ for 1E 1841−045, all large by radio pulsar standards.

The increase in $|\dot{\nu}|$ post-glitch, at least for radio pulsars, is generally attributed to a decoupling of a small percentage of the moment of inertia of the star, usually presumed to be part of the crustal superfluid (e.g., [22]) with constant external torque. If the temporarily enhanced $|\dot{\nu}|$ observed in AXP recoveries were interpreted in the same way, it would imply that very large fractions (ranging from 0.4 to 0.9) of the moment of inertia of the star decoupled at the glitch, much larger than the crustal superfluid is reasonably expected to comprise, for any interior equation of state. To avoid this problem, [8] suggested a lag reversal between the crust and the superfluid before the glitch. However, for some glitches, there are problems with this scenario [10].

We also note that the large and long-term increase in $|\dot{\nu}|$ following the large glitch in 1E 1841−045 (Fig. 3) also implies a large $I_{res}/I_c$ [23, 10].

One possibility that can explain the large $G$ for
1E 2259+586, the large transient increases in $|\dot{v}|$ in three large AXP glitches, as well as the large extended $\dot{v}$ change in the first 1E 1841–045 glitch, is that core superfluid is somehow involved, as it is expected to carry the bulk of the moment of inertia.

**Temperature:** In glitches, the equilibrium angular velocity lag between the crust and more rapidly rotating crustal superfluid is thought to be the origin of glitches. This lag is proposed to develop because the superfluid’s angular momentum vortices become pinned to crustal nuclei and hence are hindered from moving outward as the star’s crust is slowed by the external torque.

As pointed out by [2], the high temperatures of AXP, as measured from their X-ray spectra, are at odds with the glitch observations. This is because in the crustal pinning models, the pinning force is highly temperature dependent, such that vortex lines can creep outward much more easily when the temperature is high (e.g., [24]). Hence, for example, the hotter Crab pulsar glitches less frequently and with smaller frequency jumps than the Vela pulsar because its vortex array can move outward more smoothly (e.g., [25]). If this were true, AXPs, having measured effective temperatures much higher than the Crab pulsar, should glitch less frequently and with smaller glitch amplitudes than the Crab pulsar, clearly not what is observed. If we abandon the crustal glitch model (at least in AXP glitches) the absence of the expected temperature dependence could be explained.

**Radiative Changes:** The approximate stabilities of the pulsed fluxes around the glitch epochs of RXS J170849.0–400910 and 1E 1841–045 (Panel 3 of Fig. 1 and 3, [10]) are in contrast to those seen near the first glitch of 1E 2259+586 and near the 1E 1048.1–5937 glitch, where large pulsed (and total) flux variations were seen (Fig. 4 and 5, Table 2, [7, 8, 5, 13]). Clearly, unlike radio pulsars, AXP glitches can be radiatively loud or radiatively quiet, at least in pulsed flux.

Although we did not see variations in the pulsed flux of RXS J170849.0–400910 (Fig. 1, Panel 3), the authors of [18, 19] reported the phase-averaged flux to be highly variable (Fig. 1, Panel 4). They also argued that the observed spectral and flux variations were correlated with glitch epochs although their sampling is comparable to the glitch rate. If the variations in the phase-averaged flux are real, the discrepancy between the flux and the pulsed flux suggests an anti-correlation between pulsed fraction and total flux, that acts to ensure that the pulsed flux is roughly constant. If so, pulsed flux is not a good indicator of energy output for this source. Regular monitoring with a single imaging instrument could settle this issue.

**SUMMARY**

In 10 years of RXTE monitoring of Anomalous X-ray Pulsars, we report the detection of 10 glitches and of 5 candidates. We compared these glitches to radio pulsar glitches and showed that a) the fractional glitch amplitudes of AXPs are large by radio pulsar standards, but their absolute amplitudes are not; b) the coupling parameter [20] which provides a lower limit on the fraction of stellar moment of inertia in the angular momentum reservoir is large for AXP 1E 2259+586 suggesting that core superfluid may be involved; c) the steep exponential recoveries of some AXP glitches may imply that a large fraction of the stellar moment of inertia decoupled at the glitch. This too may point to core superfluid involvement; d) in the crustal glitch model, the high AXP temperatures are at odds with the number of discovered glitches; e) AXP glitches are sometimes accompanied by radiative events while radio pulsar glitches are not.

Glitches of AXPs, their recoveries, and their accompanying radiative changes are manifestations of simultaneously internal and external neutron star events. They hold considerable information that, with the help of more detailed modelling, may help constrain the interior of AXPs in new ways.

**REFERENCES**