10 Years of RXTE Monitoring of Five Anomalous X-Ray Pulsars

Cite as: AIP Conference Proceedings 983, 262 (2008); https://doi.org/10.1063/1.2900157
Published Online: 04 March 2008

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10 Years of RXTE Monitoring of Five Anomalous X-Ray Pulsars

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Abstract. Anomalous X-ray Pulsars are believed to be magnetars: young, isolated neutron stars powered by a large magnetic energy reservoir. Here, we review recent observational progress on five anomalous X-ray pulsars based on a 10-year long monitoring project done using the Rossi X-Ray Timing Explorer (RXTE). In particular, we discuss timing behavior including glitches, radiative variability including bursts, pulsed flux changes, and pulse profile changes. We compare the timing properties to those of regular rotation-powered pulsars, and we consider the observed radiative phenomena in the context of the magnetar model.

Keywords: anomalous X-ray pulsar, magnetar, neutron star
PACS: 97.60.Gb, 97.60.Jd, 95.85.Nv

INTRODUCTION, OBSERVATIONS, AND RESULTS

Pulsars identified as AXPs are dubbed “anomalous” because their spin-down luminosity is too small to produce their observed (persistent and pulsed) X-ray emission. They typically exhibit X-ray luminosities \( \sim 10^{35} \text{ erg s}^{-1} \), spectra traditionally fit with an absorbed blackbody with a power-law tail, slow periods (2–12 s), and period derivatives \( P \) of \( \sim 10^{-12} \). These imply very large inferred magnetic fields of \((0.6–7) \times 10^{14} \text{ G}\). There are currently 8 known AXPs and two candidate AXPs. They are believed to be magnetars: young, isolated pulsars, powered by the decay of their large magnetic field [1]. An online summary of magnetar properties and references is maintained at McGill University by C. Tam (www.physics.mcgill.ca/pulsar/magnetar/main.html).

To investigate these sources, we initiated an AXP monitoring program in 1997. The program uses RXTE to look at each of the five brightest non-transient AXPs several times every month. The purposes of the program are to study the timing behavior of the sources including glitches, and to look for bursts, pulsed flux changes, and pulse profile changes.

Given the space limitation of this contribution, we summarize the phenomena observed from each of the monitored AXPs in Table 1 below.

DISCUSSION AND CONCLUSIONS

Timing: We have now detected 10 glitches and 5 candidates from 5 AXPs. Some of these glitches were accompanied by radiative changes (eg., 1E 2259+586 [14],

FIGURE 1. Example of a pulse profile change: the pulse profiles of 4U 0142+61 in 2001 (filled circles) and in 2006 (empty circles) in the 2–10 keV band are shown. Notice the difference in the height of the dip between the two peaks [3].

FIGURE 2. Bursts observed in the 2–20 keV lightcurve of AXP IE 2259+586 on 2002 June 18. The size of each time bin is 0.25 s [13].

FIGURE 3. Pulsed flux of 1E 1048.1–5937 in the 2–10 keV band. The first two peaks are the slow-rise pulsed flux flares. The enhancement in 2007 is the fast-rise flare associated with a large glitch.
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<td>1E 2259–586</td>
<td>Phase coherence maintained in 1998–2007.</td>
<td>• 2002 June 18: ~80 bursts [13, 14, 15] (Fig. 2).</td>
<td>• 2002 June: Outburst. The pulsed flux increased by an order of magnitude. It recovered in the following year [13, 14, 15].</td>
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<td>• 2001 Nov. 14: 1 burst [20].</td>
<td>• 2002 May: slow-rising flare [22] (Fig. 3).</td>
<td>• 2007 March: small but long-lasting profile changes [16, 18]</td>
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<td>• 2004 June 29: 1 burst with short-term (hours) flux enhancement [21]</td>
<td>• 2007 March: fast-rising flare [22] (Fig. 3).</td>
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<td>• 2007 April 28: 1 burst [16].</td>
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**TABLE 1.** Results of the RXTE AXP monitoring program.
and IE 1048.1−5937 [18]), while others were not (eg., 1E 1841−045 [11]). See [11] and Dib et al. (this volume) for a list of the glitch properties, and for a comparison of AXP and radio pulsar glitches.

**Bursts:** Bursts in AXPs have occurred: a) at the onset of outbursts (eg., 1E 2259+586), b) during pulsed flux flares (eg., 1E 1048.1−5937), and c) during short periods (weeks) of radiative variability (eg., 4U 0142+61). There also appears to be two kinds of bursts [23]. *Type A bursts* have extended tails, occur exclusively in AXPs, are near pulse maxima, and are accompanied by a short-term (hours) pulsed flux increase. Examples of these include the first three bursts from 1E 1048.1−5937 (although the first burst did not have a detectable extended tail) [20, 21], some of the bursts of 1E 2259+586 [15], and some of the bursts from 4U 0142+61 (although because of temporary pulse profile changes, the location of the pulse maximum in some of the observations containing bursts was different from the long-term location) [4]. These bursts may originate from crustal fractures [23, 21]. *Type B bursts* are without a tail and have no apparent phase dependence. They are SGR-like bursts and their origin is thought to be magnetospheric [23].

**Pulsed Flux Variability:** Pulsed flux variability is observed: a) as a slow increase over several years (eg., 4U 0142+61 [3]), b) as slow-rising and fast-rising flares (eg., 1E 1048.1−5937 [22, 18, 16]), c) as sudden outbursts (eg., 1E 2259+586 [14]), d) in burst tails (eg., 1E 1048.1−5937 [21] and 4U 0142+61 [4]). In an outburst, the sudden increase in the pulsed flux is likely due to a sudden reconfiguration of the surface following a crustal yield [14, 13]. The slower changes in the pulsed flux may be consequences of a twist in the magnetic field lines in the magnetosphere [22, 3]. In the magnetar model, increases in the luminosity and in the hardness are expected to accompany an increase in the twist angle. Indeed a flux/hardness correlation has been observed [18, 24, 25], but may also be purely thermal [26]. Note that a different correlation is also seen when comparing the data from the 2007 increase in the pulsed flux of 1E 1048.1−5937 to the data of the same AXPs in quiescence: the total flux and the pulsed fraction, both measured using *Chandra*, are tightly anti-correlated [27, 18] indicating that focusing instrument measurements are important for establishing the true energetics of these events. Finally, the post-burst short-timescale (minutes to hours) pulsed flux enhancement is interpreted as surface heating due to crustal cracking [21].

**Pulse Profile Changes:** Pulse profile changes seem to occur a) at the onsets of flares and outbursts (eg., 1E 2259+586 [14] and 1E 1048.1−5937 [16, 18]), b) during short periods (weeks) of radiative variability (eg., 4U 0142+61 [4]), c) at apparently random times (eg., RXS J170849−400910 and 1E 1841−045 [11]), d) around glitch times (eg., 1E 2259+586 [14], 1E 1048.1−5937 [16, 18], and RXS J170849−400910 [10]), e) as a slow evolving trend over several years (eg., 4U 0142+61 [3]). In some cases, the profile changes appear to be broadband [14], while in other cases they appear more prominent at certain energies [11]. This suggests crustal motions and surface activity, possibly coupled with magnetospheric activity, with the exact observational manifestation dependent on a variety of factors [28].

**Conclusions:** Recent observational progress on AXPs has been significant. Attempts have been made to interpret the observed timing and radiative variability in terms of the magnetar model. We have discussed some of them above. However, many issues still remain unexplained such as the connection between AXPs and SGRs, the large torque variations of AXP 1E 1048.1−5937 [22, 16], the spectral feature in the large burst from 4U 0142+61 [4], and the behavior of the pulsed fraction of RXS J170849−400910 (Dib et al. this volume, [11]) to name a few. Undoubtedly, much observational and theoretical work remains to be done before a complete picture of AXPs becomes clear.

**REFERENCES**