Activity From Magnetar Candidate 4U 0142+61: Bursts and Emission Lines

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Abstract. After 6 years of quiescence, Anomalous X-ray Pulsar (AXP) 4U 0142+61 entered an active phase in 2006 March that lasted several months. During the active phase, several bursts were detected, and many aspects of the X-ray emission changed. We report on the discovery of six X-ray bursts, the first ever seen from this AXP in ~10 years of Rossi X-ray Timing Explorer monitoring. All the bursts occurred in the interval between 2006 April 6 and 2007 February 7. The burst durations ranged from $8 - 3 \times 10^3$ s as characterized by $T_{90}$. These are very long durations even when compared to the broad $T_{90}$ distributions of other bursts from AXPs and Soft Gamma Repeaters (SGRs). The first five burst spectra are well modeled by simple blackbodies, with temperature $kT \sim 2 - 6$ keV. However, the sixth and most energetic burst had a complicated spectrum consisting of at least three emission lines with possible additional emission and absorption lines. The most significant feature was at $\sim 14$ keV. Similar 14-keV spectral features were seen in bursts from AXPs 1E 1048.1–5937 and XTE J1810–197. If this feature is interpreted as a proton cyclotron line, then it supports the existence of a magnetar-strength field for these AXPs.

INTRODUCTION

Anomalous X-ray Pulsars (AXPs) are isolated neutron stars that show pulsations in the narrow range of 2–12 s. Their observed 2-10 keV X-ray luminosities ($\sim 10^{33} - 10^{35}$ erg s$^{-1}$) cannot be accounted for by their available spin-down energy. It is widely accepted that AXPs are magnetars – young isolated neutron stars powered by their high magnetic fields [1, 2]. The inferred surface dipolar magnetic fields of AXPs are all above $9.9 \times 10^{13}$ G. The magnetar model was first proposed to explain Soft Gamma Repeaters (SGRs). SGRs show persistent properties similar to AXPs, but they were first discovered by their enormous bursts of soft gamma rays ($> 10^{44}$ erg) and their much more frequent, shorter, and thus less energetic bursts of hard X-rays. To date, SGR-like X-ray bursts have been observed from four AXPs, thus solidifying the connection between the two source classes [3, 4, 5, 6]. For a review of magnetar candidates see Woods and Thompson [7].

Thus far, only the magnetar model can explain the bursts observed from SGRs and AXPs [1]. The internal magnetic field exerts stresses on the crust which can lead to large scale rearrangements of the external field, which we observe as giant flares. If the stress is more localized, then it can fracture the crust and displace the footpoints of the external magnetic field which results in short X-ray bursts. The highly twisted internal magnetic field also slowly twists up the external field and it is believed that the magnetospheres of magnetars are globally twisted [8]. Reconnection in this globally twisted magnetosphere has also been proposed as an additional mechanism for the short bursts [9].

In addition to bursts, AXPs and SGRs exhibit pulsed and persistent flux variations on several timescales. An hours-long increase in the pulsed flux has been seen to follow a burst in AXP 1E 1048.1–5937 [10]. On longer timescales, AXPs can exhibit abrupt increases in flux which decay on ~week-month timescales. These occur in conjunction with bursts and are thought to be due to thermal radiation from the stellar surface after the deposition of heat from bursts. Such flux enhancements have been observed in SGRs (see Woods et al. [11] for example). The flux enhancement of AXP 1E 2259+586 during its 2002 outburst was also interpreted as burst afterglow [12], however, a magnetospheric interpretation has also been proposed [13]. AXP 1E 1048.1–5937 exhibited three unusual flux flares. In the first two, the pulsed flux rose on week-long timescales and subsequently decayed back on time scales of months [14, 15]. Although small bursts sometimes occur during these events [10], burst afterglow cannot explain the flaring, thus these variations have been attributed to twists implanted in the external magnetosphere from stresses on the crust imposed by the internal magnetic field. AXPs XTE J1810–197 and the AXP candidate AX J1845–0258 have also exhibited flux...
variations, however it is not clear whether these were of the abrupt rise type as in 1E 2259+586 or the slow-rise type as in 1E 1048.1–5937. Finally, AXP 4U 0142+61 has exhibited the longest timescale flux variations, in which the pulsed flux increased by 19±9% over a period of 2.6 years [16].

**ANALYSIS AND RESULTS**

All data presented here are from the Proportional Counter Array (PCA) aboard the *Rossi X-ray Timing Explorer (RXTE)*. The PCA is made up of five identical and independent proportional counter units (PCUs). Each PCU is a Xenon/methane proportional counter with a propane veto layer. The data were collected in either GoodXenonWithPropane or GoodXenon mode which record photon arrival times with ~1-µs resolution and bins them with 256 spectral channels in the ~2-60 keV band.

**Burst Analysis**

We have been monitoring 4U 0142+61 with the PCA for nearly a decade. Currently, it is observed bi-monthly with a typical observation length of 5 ks. For each monitoring observation of 4U 0142+61, using software that can handle the raw telemetry data, we generated 31.25 ms lightcurves using all Xenon layers and only events in the 2–20 keV band. These lightcurves were searched for bursts using our automated burst search algorithm introduced in Gavriil et al. [3] and discussed further in Gavriil et al. [17]. In an observation on 2006 April 6, we detected a significant burst, and four more bursts were detected in a single observation on 2006 June 25. The sixth and most energetic burst was detected on 2007 February 7. There were 3, 3, and 2 PCUs on at the times of the bursts for the April, June and February observations, respectively. The bursts were significant in each active PCU.

To further analyze these bursts we created event lists in FITS format using the standard FTOOLS. For consistency with previous analysis of SGR/AXP bursts we extracted events in the 2–60 keV band. These events were barycentered using the position found by Patel et al. [18] for the source. The burst lightcurves are displayed in Fig. 1.

Before measuring any burst parameters we determined the instrumental background using the FTOOLS pcabackest. We extracted a background model lightcurve using the appropriate energy band and number of PCUs. pcabackest only determines the background on 16 s time intervals, so we interpolated these values by fitting a polynomial of order 6 to the entire observation, which yielded a good fit for each observation.

The burst peak time, rise time and peak flux were determined using the methods described in Gavriil et al. [17]. Usually, to measure the fluence for SGR and AXP bursts, we subtract the instrumental background for the entire observation, which yielded a good fit for each observation. The fluence in this case is the height of the step function. Although this technique worked well for the first burst, which was a short isolated event, it was not appropriate for bursts 2, 3, and 4 because they had overlapping tails, and bursts 5 and 6 had tails that extended beyond the end of the observation. Thus, we opted to fit the bursts to exponential rises with decaying tails. Our model fits are overplotted on the bursts in Fig. 1. As is done for γ-ray bursts and SGR and AXP bursts, we characterized the burst duration by $T_{90}$, the time from when 5% to 95% of the total burst counts have been collected. To determine the $T_{90}$ duration we integrated our burst model and numerically determined the 5% and 95% time crossings. All burst temporal parameters are presented in Table 1.

1. http://fits.gsfc.nasa.gov
2. http://heasarc.gsfc.nasa.gov/docs/software/ftools/

Burst spectra were extracted using all the counts...
| Parameter | April 2006 | June 2006 | February 2007 |
|-----------|-----------|-----------|--------------|
| Burst day (MJD UTC) | 53831 | 53911 | 54138 |
| Burst start time (UT) | 07:09.55.544(7) | 01:15:54.555(11) | 01:20:0.131(3) |
| Burst rise time, $t_{+11}$ | $7^{+4}_{-3}$ | $11^{+4}_{-2}$ | $3^{+3}_{-1}$ |
| Burst duration, $T_{90}$ (s) | $8^{+0.7}_{-0.6}$ | $562.2^{+0.2}_{-0.3}$ | $92.5^{+0.2}_{-0.3}$ |
| $T_{90}$ Fluence (counts PCU$^{-1}$) | 65.6 | 1847±4 | 14377±41 |
| $T_{90}$ Fluence ($\times 10^{-10}$ erg cm$^{-2}$) | 16±3 | 229±11 | 1455±53 |
| Peak Flux (counts s$^{-1}$ PCU$^{-1}$) | 299±59 | 367±65 | 551±97 |
| Peak Flux ($\times 10^{-10}$ erg s$^{-1}$ cm$^{-2}$) | 75±19 | 46±8 | 253±22 |
| Blackbody Temperature, ($kT_{bb}$) | $6.2^{+4.4}_{-1.9}$ | $2.67^{+0.10}_{-0.09}$ | $2.12^{+0.08}_{-0.04}$ |

* All quoted errors represent 1-σ uncertainties.
† For burst 6, the temperature is that of the blackbody component after accounting for the emission lines.

For each of the three observations containing bursts, we made two binned time series in count rate per PCU, one for the 2–4 keV band and the other for 4–20 keV. We only included the photons detected by the PCU that was on for the entire duration of the observation. The time resolution was 1/32 s. We removed the 4 s centered on each burst from each time series. Then, we broke each time series into segments of length ~500 s. For each segment, we calculated the pulsed flux using the $PF_{i} = \frac{1}{N_{i}} \sum_{i} \frac{N}{N_{p}}$, where $N_{i}$ is the total number of counts in each time segment, $N$ is the total number of counts in the entire time series, $p$ is the count rate in the phase bin of the pulsed flux, and $P_{i}$ is the average count rate in the off-pulse bin. This allowed us to calculate the pulsed flux, $PF_{i}$, using the Fourier decomposition method described by Woods et al. [12], only incorporating the contribution of the first 5 harmonics for consistency with [14] and [20]. While least sensitive to noise, the RMS method returns a pulsed flux number that is affected by pulse profile changes. Therefore, we used the FTOOL pulsed flux number that is affected by pulse profile changes. Therefore, we used the FTOOL pulsed flux number.

For burst 6, however, we found that the blackbody model provided an adequate fit for the 4–20 keV data. This was also the case for the background continuum model, which was well modeled by a single power law. Therefore, we used this model for the background continuum. We then tested our results against the predictions of the blackbody model for the 2–4 keV data. The results were consistent with the predictions of the blackbody model.

**Pulsed Flux Analysis**

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Woods et al. [5] first argued that there appear to be two classes of magnetar bursts. Type A bursts are short, symmetric, and occur uniformly in pulse phase. Type B bursts have long tails, thermal spectra, and occur prefer-

following the large 2007 February burst.

**DISCUSSION**

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The magnetic field strength is given by

$$E = B \frac{mc}{\hbar e}. \tag{1}$$

Setting $m$ equal to the proton mass we obtain $B = 2.2 \times 10^{13} (E/14 \text{ keV})$ G. This field estimate is much greater than that derived from the spin down of the source, however the burst spectroscopic method measures the field at the surface which can be multipolar, while the spin down measurement is sensitive to the dipolar component.

The feature also could be an electron cyclotron feature from a burst which occurred higher up in the magnetosphere. Although these features can, in principle, be proton/electron cyclotron features there are many problems with interpreting them as such. First, it is not clear why three different sources, with different magnetic field strengths would exhibit features with similar energies. Moreover, it is unclear why these features are seldom seen and have not been seen in other high signal-to-noise bursts. Detailed modeling of burst spectra is definitely warranted. The fact that these features occur at similar energies, despite having different magnetic field strengths, may suggest that they are actually atomic lines, and could possibly provide new insights into the composition of the crust and atmosphere of these enigmatic objects.

REFERENCES

1. C. Thompson, and R. C. Duncan, *MNRAS* 275, 255–300 (1995).
2. C. Thompson, and R. C. Duncan, *ApJ* 473, 322–342 (1996).
3. F. P. Gavriil, V. M. Kaspi, and P. M. Woods, *Nature* 419, 142–144 (2002).
4. V. M. Kaspi, F. P. Gavriil, P. M. Woods, J. B. Jensen, M. S. E. Roberts, and D. Chakrabarty, *ApJ* 588, L93 (2003).
5. P. M. Woods, C. Kouveliotou, F. P. Gavriil, Kaspi, V. M., M. S. E. Roberts, A. Ibrahim, C. B. Markwardt, J. H. Swank, and M. H. Finger, *ApJ* 629, 985–997 (2005).
6. H. Krimm, S. Barthelmy, S. Campana, J. Cummings, G. Israel, D. Palmer, and A. Parsons, *The Astronomer’s Telegram* 894, 1–+ (2006).
7. P. M. Woods, and C. Thompson, “Soft Gamma Repeaters and Anomalous X-ray Pulsars: Magnetar Candidates,” in *Compact Stellar X-ray Sources*, edited by W. H. G. Lewin, and M. van der Klis, Cambridge University Press, UK, 2006.
8. C. Thompson, M. Lyutikov, and S. R. Kulkarni, *ApJ* 574, 332–355 (2002).
9. M. Lyutikov, *ApJ* 580, L65 (2002).
10. F. P. Gavriil, V. M. Kaspi, and P. M. Woods, *ApJ* 641, 418–426 (2006).
11. P. M. Woods, C. Kouveliotou, E. Göğüş, M. H. Finger, J. Swank, D. A. Smith, K. Hurley, C. Thompson, *ApJ* 552, 748–755 (2001).
12. P. M. Woods, V. M. Kaspi, C. Thompson, F. P. Gavriil, H. L. Marshall, D. Chakrabarty, K. Flanagan, J. Heyl, and L. Hernquist, *ApJ* 605, 378–399 (2004).
13. W. Zhu, V. M. Kaspi, P. M. Woods, F. P. Gavriil, R. Dib, *ApJ* (2007), arXiv:0710.1896 (astro-ph).
14. F. P. Gavriil, and V. M. Kaspi, *ApJ* 609, L67–L70 (2004).
15. C. R. Tam, F. P. Gavriil, R. Dib, V. M. Kaspi, P. M. Woods, and C. Bassa, *ApJ* (2007), arXiv:0707.2093 (astro-ph).
16. R. Dib, V. M. Kaspi, and F. P. Gavriil, *ApJ* 666, 1152–1164 (2007).
17. F. P. Gavriil, V. M. Kaspi, and P. M. Woods, *ApJ* 607, 959–969 (2004).
18. S. K. Patel, C. Kouveliotou, P. M. Woods, A. F. Tennant, M. C. Weisskopf, M. H. Finger, C. A. Wilson, E. Göğüş, M. van der Klis, and T. Belloni, *ApJ* 587, 367–372 (2003).
19. M. Durant, and M. H. van Kerkwijk, *ApJ* 650, 1082–1090 (2006).
20. M. E. Gonzalez, R. Dib, V. M. Kaspi, P. M. Woods, C. R. Tam, and F. P. Gavriil, *ApJ* (2007), arXiv:0708.2756 (astro-ph).