LONG-TERM X-RAY CHANGES IN THE EMISSION FROM THE ANOMALOUS X-RAY PULSAR 4U 0142+61

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ABSTRACT

We present results obtained from X-ray observations of the anomalous X-ray pulsar (AXP) 4U 0142+61 taken between 2000 and 2008 using XMM-Newton, Chandra, and Swift. These observations coincide with periods of long-term changes and burst epochs previously reported using the Rossi X-ray Timing Explorer (RXTE). In observations taken before 2006, we find that the pulse profile became more sinusoidal and the pulsed fraction increased with time. These results confirm those derived using RXTE and expand the observed evolution to energies below 2 keV. The total flux in the 0.5–10 keV band determined with XMM-Newton is observed to be nearly constant in observations taken before 2006, while an increase of ~10% is seen afterwards and coincides with the burst activity detected from the source in 2006–2007. After these bursts, the evolution toward more sinusoidal pulse profiles ceased while the flux and pulsed fraction returned to pre-bursts levels. No evidence for large-scale, long-term changes in the emission as a result of the bursts is seen. We also report on observations taken with the Gemini telescope after two bursts which show source magnitudes consistent with previous measurements. Our results demonstrate the wide range of X-ray variability characteristics seen in AXPs and we discuss them in light of current emission models for these sources.

Key words: pulsars; general – pulsars: individual (4U 0142+61) – stars: neutron

Online-only material: color figure

1. INTRODUCTION

Recent observations of neutron stars have uncovered the wide variety of observational manifestations they appear to have, from rotation-powered pulsars and isolated thermally cooling objects to the so-called magnetars (see Kaspi 2010 for a review). The latter class includes anomalous X-ray pulsars (AXPs) and soft gamma repeaters (SGRs; see, e.g., Woods & Thompson 2006). Observationally, magnetars exhibit long spin periods of several seconds, have persistent X-ray luminosities of \( \sim 10^{34} - 10^{36} \) erg s\(^{-1}\), and have estimated surface dipolar magnetic fields of \((0.6–7) \times 10^{14} \) G (see, e.g., Kaspi 2007; Mereghetti 2008 for recent reviews of AXPs). Optical and infrared (IR) counterparts have been found for many of these objects (e.g., Israel et al. 2003; Kaspi et al. 2003; Kaplan et al. 2009). Despite their soft spectrum at low X-ray energies, they have also been shown to produce copious amounts of hard X-ray emission (e.g., Molkov et al. 2004; Kuiper et al. 2006).

Magnetars are thought to be neutron stars whose X-ray emission is powered by the decay of an ultra-high magnetic field \((B > 10^{15} \) G; Thompson & Duncan 1995, 1996, but see Bhattacharya & Soni 2007). The sudden bursts of high-energy emission seen from some of these sources are believed to be powered by the rearrangement of their magnetic field, while the nature of the optical/IR emission in this model is currently under study (e.g., Beloborodov & Thompson 2007). On the other hand, the active fallback disk model argues that the persistent emission at low X-ray energies arises from accretion onto the neutron star, while the optical/IR emission is thought to originate from the disk itself (e.g., Alpar 2001; Ertan et al. 2007). If only a passive (i.e., non-accreting) disk is present, it could then be responsible for part of the emission at optical/IR wavelengths (Wang et al. 2006). However, a magnetar origin for the high-energy bursts is still needed in all disk models, as well as a magnetospheric origin for any pulsed emission at optical wavelengths.

4U 0142+61 has the highest observed X-ray flux of all known AXPs. It has a period \( \dot{P} = 8.7 \) s, period derivative \( P = 2.0 \times 10^{-11} \), inferred surface dipolar magnetic field strength of \( B = 3.2 \times 10^{14} \sqrt{P/P_G} \) G = \( 1.3 \times 10^{14} \) G, and has been detected from the mid-IR to hard X-rays (Israel et al. 1994; Gavriil & Kaspi 2002; den Hartog et al. 2007). In the mid-IR, it is unclear whether the emission found by Wang et al. (2006) arises from the disk or from the magnetosphere (e.g., Ertan et al. 2007b; Beloborodov & Thompson 2007). The optical emission was found to be pulsed with a peak-to-peak pulsed fraction of \( \sim 29\% \) (Kern & Martin 2002; Dhillon et al. 2005). A distance to the source of 3.5–4.2 kpc has been derived through various methods (Durant & van Kerkwijk 2006; Rivera-Ingraham & van Kerkwijk 2010). In addition, 4U 0142+61 has a soft X-ray spectrum that has been fitted traditionally with a blackbody plus power-law model with temperature \( kT \sim 0.4 \) keV and photon index \( \Gamma \sim 3.3 \) (e.g., Juett et al. 2002; Patel et al. 2003). However, the extrapolation of this soft X-ray model to the optical/IR overpredicts the observed emission if associated with the power-law component, while it underpredicts this emission if it is associated with the blackbody component. Recently, the emission from 4U 0142+61 in the 1–250 keV range has been fit with more diverse models (see, e.g., Rea et al. 2007a, 2007b; den Hartog et al. 2008; Güver et al. 2008).

A long-term monitoring campaign for 4U 0142+61 has been carried out with the Rossi X-ray Timing Explorer (RXTE) for the past 10 yr. Using these data, Dib et al. (2007) reported a slow evolution of the pulse profile between 2000 and 2006, as well as a slow increase in the pulsed flux between 2002 and 2006. These changes may be associated with a possible glitch, or an-
other event, that may have occurred between 1998 and 2000. Given the low amplitude of the reported variations, it is important to verify their presence with an independent instrument. In addition, the source entered an active phase showing six pulses with high precision. The data were reduced using CIAO version 3.4 and standard techniques. Source events were extracted from a region 4 pixels wide around the peak of the emission, with background regions taken far from the source.

2.3. Swift

4U 0142+61 has been observed numerous times with Swift. For the purposes of our work, we chose the X-ray Telescope (XRT) observations with the highest number of counts and sufficiently high time resolution to allow for a study of the timing properties of the pulsar (see Table 1). The data were reduced applying standard screening criteria and using Swift software version 3.3 under HEASoft version 6.6.3. Source counts were extracted in regions 4 pixels wide (~2′) around the peak of the emission, with background regions taken far from the source.

3. X-RAY PULSE RESULTS

3.1. Pulse Profiles

The XMM-Newton, Chandra, and Swift data were used to study the long-term evolution of the X-ray pulse profile. The data were transformed to the solar system barycenter and folded at the predicted periods for each observation using ephemerides derived from Dib et al. (2007). The data were divided into different energy ranges: 0.5–10, 0.5–2, and 2–10 keV. Sample background-subtracted, normalized pulse profiles for these bands are shown in Figure 1. Prior to 2006, an evolution of the pulse profile in the 2–10 keV band is clearly visible and confirms the results obtained using RXTE by Dib et al. (2007). In addition, the sensitivity to lower energies allows us to further constrain the evolution and conclude that it is also present in the 0.5–2 keV band.

More specifically, before 2006 we find that the relative height of the two peaks increased with time, while the depth of the

Table 1. X-ray Observations of 4U 0142+61

| Date         | MJD   | CCD Mode/Exp. Time | Counts \(a\) |
|--------------|-------|--------------------|--------------|
| XMM-Newton   |       |                    |              |
| 2002 Feb 13  | 52318.3 | Small-Window/2.9 ks | 1.29 × 10^5  |
| 2003 Jan 24  | 52663.9 | Small-Window/3.8 ks | 1.62 × 10^5  |
| 2004 Mar 1   | 53065.5 | Timing/29.4 ks     | 1.47 × 10^6  |
| 2004 Jul 24  | 53211.3 | Timing/21.2 ks     | 1.07 × 10^6  |
| 2006 Jul 28  | 53944.8 | Small-Window/3.7 ks | 1.71 × 10^5  |
| 2007 Jan 13  | 54113.8 | Small-Window/4.4 ks | 1.95 × 10^5  |
| 2007 Feb 10  | 54141.1 | Timing/8.6 ks      | 4.24 × 10^5  |
| 2008 Jan 27  | 54492.0 | Small-Window/5.5 ks | 2.39 × 10^5  |
| 2008 Mar 6   | 54532.1 | Small-Window/4.5 ks | 2.09 × 10^5  |
| Chandra      |       |                    |              |
| 2000 May 21  | 51685.8 | Continuous Clocking/5.9 ks | 1.23 × 10^5 |
| 2006 May 29  | 53915.4 | Continuous Clocking/18.6 ks | 3.86 × 10^5 |
| 2007 Feb 10  | 54141.3 | Continuous Clocking/20.1 ks | 3.99 × 10^5 |
| Swift        |       |                    |              |
| 2005 Feb 13  | 53414.8 | Windowed-Timing/6.6 ks | 2.8 × 10^4  |
| 2007 Feb 10  | 54141.2 | Windowed-Timing/3.5 ks | 1.6 × 10^4  |
| 2008 Apr 5   | 54561.2 | Windowed-Timing/5.0 ks | 2.2 × 10^4  |

Notes. \(a\) Net counts in the 0.5–10 keV range. Uncertainties smaller than last digit shown.
...dip between them became less pronounced. This caused the profiles to become more sinusoidal, as can be seen from a Fourier analysis, in which the ratio of the power in the first harmonic to the total power increased while this same ratio for the second harmonic stays fairly constant. The ratio of power in the higher harmonics then decreases during this time. Figure 2 (right) shows these ratios for the profiles in the 2–10 keV range obtained from both XMM-Newton and RXTE and for 0.5–2 keV profiles obtained from XMM-Newton9 (see Dib et al. 2007 for details.) Given that RXTE profiles before the bursts were derived by averaging many observations to increase the signal-to-noise ratio, the fact that a similar evolution is seen in the individual XMM-Newton observations confirms the long-term nature of the observed changes. The ratio of the powers in the 0.5–2 keV band for these observations shows more scatter and suggests that the trend is stronger at higher energies during the time covered by the XMM-Newton and RXTE observations. After the bursts were detected in 2006, the profiles fluctuated more (with more power going to higher harmonics around the time of the bursts; see also Gavriil et al. 2010) and the overall evolution toward more sinusoidal profiles seems to have ceased. The latest data taken in 2008, more than a year after the last recorded bursts, show further deviations from sinusoidal profiles and similarities to earlier data in 2002–2004, particularly for the latest observation on 2008 March.

3.2. Pulsed Fractions

The fact that the pulse profile evolves with time makes it difficult to determine the pulsed fractions (and thus pulsed fluxes) of the source accurately. A few different methods are commonly used in the literature to calculate these values; each has advantages and caveats. Here, we compare the results obtained from two of these methods: the rms and area methods.

We calculate the rms pulsed fraction using

\[ PF_{\text{rms}} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left( \frac{a_k^2 + b_k^2}{\sigma_a^2 + \sigma_b^2} \right)} \]

where \( a_k \) is the kth even Fourier component defined as \( a_k = \frac{1}{N} \sum_{i=1}^{N} p_i \cos(2\pi ki/N) \), \( \sigma_{a_k}^2 \) is the uncertainty of \( a_k \), \( b_k \) is the odd kth Fourier component defined as \( b_k = \frac{1}{N} \sum_{i=1}^{N} p_i \sin(2\pi ki/N) \), \( \sigma_{b_k}^2 \) is the uncertainty of \( b_k \), \( i \) refers to the phase bin, \( N \) is the total number of phase bins, \( p_i \) is the count rate in the ith phase bin of the pulse profile, and \( N \) is the maximum number of Fourier harmonics to be taken into account (we have used 5 harmonics for 4U 0142+61; see also Dib et al. 2007). On the other hand, the area pulsed fraction is obtained using

\[ PF_{\text{area}} = \frac{a_0 - p_{\text{min}}}{a_0} \]

where \( a_0 = \frac{1}{N} \sum_{i=1}^{N} p_i \) and \( p_{\text{min}} \) is the average count rate in the off-pulse phase bins of the profile, determined by cross-correlating with a high signal-to-noise template, and calculated in the Fourier domain after truncating the Fourier series to 5 harmonics.

While less sensitive to noise, the rms method returns a pulsed flux number that is affected by pulse profile changes. On the other hand, while the area method is more physically meaningful, problems in locating the true minimum and its error because of noise and binning tend to bias these values upward. The resulting values for all the observations of 4U 0142+61 are shown in Figure 3. We note that the Chandra values appear to be consistently lower than those found using XMM-Newton and Swift and could reflect the calibration uncertainties present in these data (see Section 4).

A significant change in the pulsed fraction over time is seen for both methods. Overall, the pulsed fraction increased with time, reaching an apparent maximum in the observations taken after the 2006 burst activity from the source. For example, using
the values from the rms (area) method, the pulsed fraction measured with XMM-Newton between 2002 and 2006 increased by 40% ± 3%, 31% ± 8%, and 37% ± 7% (66% ± 10%) in the 0.5–10, 0.5–2, and 2–10 keV bands, respectively. The pulsed fraction also increased significantly in the pre-burst observations (2002–2004) and between bursts, the pulsed fraction appears to be relaxing toward pre-burst levels.

In addition, we used the two longest XMM-Newton observations to study the behavior of the pulsed fraction with energy. In this case, we find evidence for an increase in pulsed fraction with energy. In the 0.5–1, 1–6, and 6–10 keV ranges we find average rms values of 5.1% ± 0.3%, 6.1% ± 0.2%, and 14% ± 2%, respectively. When using the area method we find values of 7.9% ± 0.6%, 9.7% ± 0.4%, and 18% ± 5% at 0.5–1, 1–6, and 6–10 keV, respectively. Given that the pulse profile changes significantly with energy and the area method gives less significant changes, we view this suggested increase in pulsed fraction with energy with caution.

### 4. X-RAY SPECTRAL RESULTS

The spectra were binned to contain a minimum of 50 counts per spectral channel and oversampling the energy resolution by a factor of 3. For the XMM-Newton PN data, due to the large number of counts collected from these observations, the statistical errors are very small and a systematic error of 2% was added to each spectrum (consistent with current calibration uncertainties in the PN; Kirsch et al. 2004). The phase-averaged PN spectrum for each observation was fitted in the 0.6–10 keV range using the XSPEC package version 11.3.0. Unfortunately, we cannot make use of the Chandra observations taken in CC mode to study the spectral characteristics of 4U 0142+61. While the XMM-Newton observations confirm that spectral changes are present in the source at the ~10% level (as will be shown below), the CC data show variations at levels higher than this, which cannot be corrected for at present due to calibration uncertainties. The lower signal-to-noise Swift XRT data do not contribute to constraining the evolution of the spectrum, other than to suggest that changes are present. Therefore, the XMM-Newton PN was used as the prime instrument to study the long-term spectral evolution of 4U 0142+61.

The XMM-Newton PN spectra were fitted simultaneously assuming a common value for the column density $N_H$, which was then held constant at its best-fit value. As previously reported, single-component models do not describe the emission well and we tried various multi-component models, a sample of them are listed in Table 2 and shown in Figure 4. Rea et al. (2007a, 2007b) and den Hartog et al. (2008) used various models to fit the emission from 4U 0142+61 in the 1–250 keV range, some based on Comptonized emission as expected from current magnetar models. Güver et al. (2008) have also used a spectral model based on a variant of the magnetar model to fit the XMM-Newton data from 4U 0142+61. Since our main focus is to report on model-independent, long-term changes in the emission from 4U 0142+61, we tried various multi-component models using blackbody and power-law components here. Our best-fit models (see Section 4.1) are as statistically acceptable as those presented by the above authors. While the specific values for temperature, emitting area, unabsorbed flux, etc., depend on the model that is used to fit the data (see Table 2 and Figures 5 and 6; see also

![Figure 3.](image-url)

**Figure 3.** rms (left) and area (right) pulsed fractions in the 0.5–10 keV (top), 0.5–2 keV (center) and 2–10 keV (bottom) ranges. Values shown correspond to those measured with XMM-Newton (filled circles), Chandra (open diamonds) and Swift (crosses). The dashed lines indicate the three burst epochs. (A color version of this figure is available in the online journal.)

### Table 2

| Parameter | Range of values |
|-----------|----------------|
| $N_H$ ($10^{21}$ cm$^{-2}$) | $9.8(2) \times 10^{21}$ |
| $kT$ (keV) | $0.39(3) - 0.44(4)$ |
| $R$ (km) | $4.6(5) - 7.3(8)$ |
| $\Gamma$ | $3.55(2) - 3.79(2)$ |
| $\chi^2$/dof | $3609/2368$ |

| Parameter | Range of values |
|-----------|----------------|
| $N_H$ ($10^{21}$ cm$^{-2}$) | $7.0(2) \times 10^{21}$ |
| $kT_{cool}$ (keV) | $0.27(1) - 0.31(1)$ |
| $R_{cool}$ (km) | $14.4(1.9) - 17.4(2.8)$ |
| $kT_{hot}$ (keV) | $0.50(1) - 0.60(4)$ |
| $R_{hot}$ (km) | $2.6(7) - 4.4(7)$ |
| $\Gamma$ | $2.6(1) - 3.0(1)$ |
| $\chi^2$/dof | $2609/2350$ |

**Notes.**

- $kT$ and $R$ represent the observed blackbody temperature and radius, respectively, while $\Gamma$ is the power-law photon index.
- Errors quoted are 1σ confidence level. Radii calculated using a distance of 3.8 ± 0.4 kpc. Values shown do not represent a monotonic change with time but the range of values over the observation epochs.

10 The flux uncertainties in the CC mode are not well calibrated due to various issues, such as the lack of coordinate information, uncertainties in the location of the source with respect to bad pixels and columns on the chip, and unknown PSF/pileup profiles. See CXC Helpdesk ticket 9114 for more details.
Figure 4. Best-fit spectral models and residuals obtained for the representative 2004 March XMM-Newton observation of 4U 0142+61. The models shown are BB+PL (top, $\chi^2$/dof = 570/263), 2BB+PL (middle, $\chi^2$/dof = 320/261), and 2BB+BknPL (bottom, $\chi^2$/dof = 418/261). See Table 2 for general fit values. The individual components for each model are also shown.

Figure 5. Phase-averaged fluxes and hardness ratios derived for the BB+PL model. The hardness is derived using $(H - S)/(H + S)$, where $H$ is the flux in the 0.5–2 keV range and $S$ is the flux in the 2–10 keV range. Absorbed (left) and unabsorbed (right) values are shown. The dashed lines indicate the three burst epochs.

Figure 6. Phase-averaged fluxes and hardness ratios derived for the 2BB+PL model. Absorbed (left) and unabsorbed (right) values are shown. The dashed lines indicate the three burst epochs. Note the similar long-term behavior to the flux derived from the BB+PL model and the different $y$-axis range for the unabsorbed flux.

below), we concentrate here on long-term flux and hardness changes that are model independent.

4.1. Phase-averaged Spectrum

The traditional blackbody plus power-law model used for AXPs (BB+PL) give results consistent with those previously reported for the source (e.g., Juett et al. 2002; Patel et al. 2003). However, the derived $\chi^2$ values are large and many features are evident in the residuals (see Figure 4). In addition, the derived value for the column density of interstellar absorption for this model is inconsistent with that estimated by Durant & van Kirkwijk (2006b) based on the analysis of the high-resolution RGS spectra available from the longer XMM-Newton observations listed in Table 1 ($N_H = (6.4 \pm 0.7) \times 10^{21}$ cm$^{-2}$). We found that a two-blackbody model does not fit the observed spectrum well. Instead, a two-blackbody plus power-law model (2BB+PL) produces the best statistical fit to the data from our sample of models (for the entire data set we have $\chi^2/\nu = 1.11$; see Table 1). The cooler blackbody component is consistent with arising from the entire surface of the star while the hot component arises from a smaller area. Similar multi-component models have been used to fit the emission from various magnetars (e.g., Rea et al. 2009; Bernardini et al. 2009). Plots of these models to the spectrum for the 2004 March observation are shown as an example in Figure 4.11

A summary of the range of values for all the observations obtained from our BB+PL and 2BB+PL fits is shown in Table 2. The high quality data used here expand on what has already been pointed out by other authors: in addition to the dubious physical nature of the standard blackbody plus power-law model used to fit AXP spectra, the data suggest that statistically speaking,

11 Due to the high statistics, the data show residuals at $\sim$1.8 keV that coincide with a silicon edge in the PN effective area calibration (http://xmm.vilspa.esa.es/docs/documents/CAL-TN-0018.pdf)
it does not reproduce the observed spectra well, at least for 4U 0142+61. While we cannot claim that the models used here are better physical representations of the observed emission than those presented by, e.g., Güver et al. (2008), they describe the observed spectral shape better than a BB+PL and produce reasonable spectral parameters.

Independent of the model used to fit the data, we find significant changes in the spectral characteristics of 4U 0142+61 during the span of the observations. Figure 5 shows the absorbed and unabsorbed fluxes, as well as the hardness of the spectrum, derived using the BB+PL fit. The hardness is calculated using \((H - S)/(H + S)\), where \(S\) is the flux in the 0.5–2 keV range and \(H\) is the flux in the 2–10 keV range. The values as given by the 2BB+PL fit are shown in Figure 6. The reported fluxes include a 2% error due to calibration uncertainties, which greatly dominates over statistical errors due to the large number of counts detected.

Overall, before the recent burst activity, the total flux was fairly constant, with a possible decrease in flux being present and accompanied by an overall softening. After the 2006 burst activity, the flux increased significantly with higher energies showing a larger increase. Therefore, the spectra for the two observations carried out close to burst epochs show evidence of hardening, while the one in between shows a softer spectrum. The recent observations in 2008 are consistent with a continued decay after the burst activity, especially for the 0.5–2 keV range. However, an increase in the 2–10 keV flux is seen in the last observation of 2008 March. These results are independent of the spectral model used to fit the data.

An almost identical long-term behavior in the count rate and flux is measured with MOS1,\(^{12}\) albeit with large cross-calibration offsets with respect to the PN instrument and smaller number of counts. The MOS2 chips were operated in three different modes during seven of these observations (it was turned off on 2002 February and had a very short exposure time on 2008 March), with two imaging observations also showing an increase in the flux. Thus, we argue that the observed spectral changes are intrinsic to 4U 0142+61 and not dominated by calibration uncertainties.

We find that, in general, most spectral changes are dominated by flux changes above 2 keV and not necessarily accompanied by significant changes in model parameters such as temperature and photon index. This is shown in Figure 7 using the values derived from the 2BB+PL model (as it is the most statistically favored model) and similar results are obtained for the other models in Table 2. The hardness versus 2–10 keV flux data shown in Figure 7 (top panel) deviate from a constant value at more than the 3\(\sigma\) level. In contrast, the 0.5–2 keV flux does not show a significant correlation to any measured parameter. The observed hardness changes are also present with higher significance when looking at the count rates detected from the source, supporting the results obtained through spectral analysis.

The largest change in spectral parameters are seen in the last XMM-Newton observation on 2008 March (MJD 54532.1) where we also find a significant increase in the 2–10 total flux of (17 \pm 1)\% from pre-burst levels while the 0.5–2 keV flux remains consistent with previous measurements. Here, a hardening of the spectrum is accompanied by a flattening of the power-law index while the blackbody temperatures decreased (see Figures 6 and 7). Our measured 2–10 keV pulsed flux increased significantly for this observation, though not as much as during the burst epochs since the pulsed fraction is consistent with pre-burst levels (see Figure 7). The 2–10 keV pulse profile also shows a distinct change from the previous observation on 2008 January and similarities to earlier profiles from 2002 to 2004 (see Figures 1 and 2). No usable data were obtained from the MOS1 and MOS2 instruments on this epoch. However, RXTE did observe 4U 0142+61 at various times close to this XMM-Newton observation. While the RXTE observations around this epoch are short and the derived emission characteristics have large uncertainties, the observation immediately preceding the XMM-Newton observation (taken 3.7 days before, on MJD 54528.4) shows a hint of change in the 2–10 keV pulse profile similar to that seen by XMM-Newton and a 1.5\(\sigma\) increase in the 2–10 keV pulsed flux of (40 \pm 26)\% above the long-term average. The rest of the RXTE observations were taken more than 17 days before and 14 days after the XMM-Newton observation and show no changes to the observed emission.

4.2. Pulsed Flux

We also studied the changes in pulsed flux during the observations, the values of which can be compared to those derived from the RXTE observations presented by Dib et al. (2007). We have estimated the pulsed flux for each observation by taking the phase-averaged flux calculated above (Section 4.1) and multiplying it by the pulsed fraction derived in Section 3.2 using the rms and area methods. The pulsed flux for each observation derived from the 2BB+PL model is shown in Figure 8 (using the absorbed flux, as strictly speaking only an “absorbed pulsed fraction” can be measured). The increase in pulsed flux around the time of the bursts is very significant due to the higher flux and higher pulsed fraction. However, the 2008 March observation with higher total flux does not have a significantly higher pulsed flux since the pulsed fraction remains lower than its maximum value around the burst epochs.

\(^{12}\) The EPIC MOS1 instrument was operated in timing mode in all but the 2007 February observation. No usable data were obtained on three epochs due to high radiation and short exposure times.
Figure 8. Pulsed fluxes for 4U 0142+61 obtained from the absorbed fluxes for the 2BB+PL model and the pulsed fraction derived using the rms (left) and area (right) method. The dashed lines indicate the three burst epochs.

Figure 9 shows the absorbed pulsed flux in the 2–10 keV range derived from RXTE observations; it is an updated version of that found in Dib et al. (2007) and is extended to include the most recent observations of 4U 0142+61. The flux in counts and energy are both shown, as the former allows for higher time resolution (the observations where bursts were seen are denoted with stars), while the latter combines multiple observations and allows for direct comparison with the lower panel of Figure 8 (see Dib et al. 2007; Gavriil et al. 2010 for details). As can be seen from both figures, the same long-term trend is present in both data sets, albeit XMM-Newton has larger uncertainties at 2–10 keV due to its lower sensitivity in this energy range and the smaller number of observations available. The apparent offset between the RXTE and XMM-Newton fluxes at 2–10 keV is likely caused by cross-calibration uncertainties.

5. INFRARED OBSERVATIONS

5.1. Gemini

Two Director’s Discretionary Time (DDT) observations of 4U 0142+61 were obtained with the Gemini North Telescope, on 2006 June 30 and 2007 February 13. Both observations were taken 5–6 days after an X-ray burst (Dib et al. 2006; Gavriil et al. 2007). Ky-band images were made with the Near-Infrared Imager (NIRI), an ALADDIN InSb 1024 × 1024 pixel detector array which, with the f/6 camera, provided a 119.9 × 119.9 arcsec² field of view and plate scale of 0.117 pixels. The standard reduction procedures were performed using the Gemini package (version 1.6) for IRAF (version 2.12.2). Each frame was a 2 × 30 s integration; seventeen dithered frames in 2006 June and 20 in 2007 February, were averaged to make one combined image for each observation.

5.2. Results

The point source 4U 0142+61 was clearly identified in both Gemini observations. We used DAOPHOT in IRAF for point-spread function (PSF) photometry; the FWHM of the PSF was approximately 0.5 on 2006 June 30 and 0.6 on 2007 February 13. Using the results of Hulleman et al. (2004), we calibrated our photometry relatively by measuring the $K_S$-band magnitude offsets of 10 nearby field stars and applying that offset to the 4U 0142+61 counterpart, incorporating the offset scatter into the final uncertainties. The final calibrated magnitudes are $K_S = 19.70 \pm 0.05$ and $K'_S = 19.86 \pm 0.05$ mag in 2006 June and 2007 February, respectively. The uncertainties are DAOPHOT-determined and include the calibration uncertainties.

Observations of 4U 0142+61 before the bursts have encompassed a large magnitude range, from $K = 19.68 \pm 0.05$ to $K' = 20.78 \pm 0.08$ mag (Hulleman et al. 2004; Durant & van Kerkwijk 2006c), consistent with the above values measured after the bursts. Therefore, we find no evidence to suggest that the AXP had brightened significantly in the near-IR several days after the X-ray bursts.

6. DISCUSSION

We have found that the X-ray emission from 4U 0142+61 changed significantly from 2000–2008. Here, we attempt to
summarize this complex behavior, highlighting the features we believe are most important for constraining models of magnetar emission. In Figure 10, we summarize the main 2–10 keV emission characteristics for easy reference and comparison with other work (see also Figures 1, 2, and 6). Before the 2006 burst activity, the pulse profile became more sinusoidal and the pulsed fraction (and pulsed flux) increased. Our results agree with those that Dib et al. (2007) and Gavriil et al. (2010) reported in the 2–10 keV range using RXTE data and we find that these changes are also present in the 0.5–2 keV band. During this time, the total flux was approximately constant with time (although a slight decrease is suggested by the data, especially in the 2–10 keV range). The emission also showed an overall softening independent of the assumed spectral model. After 2006, the 0.5–10 keV flux increased by (10 ± 3)% and the spectrum hardened for those observations close to the detected bursts (the spectrum softened to pre-burst levels in between these observations). The increase in flux is thus energy dependent, with the 0.5–2 and 2–10 keV ranges showing increases of (7 ± 3)% and (15 ± 3)%, respectively. During this time, the pulse profile evolution toward more sinusoidal shapes stopped and the pulsed fraction increased.

The latest observations in 2008 show a decrease toward pre-burst levels for the pulsed fraction and flux. However, the 2008 March observation shows a larger 2–10 keV flux than thus far observed for 4U 0142+61 accompanied by a harder spectrum and a distinct change in pulse profile. No bursts or changes in flux were seen within this XMM-Newton observation. In addition, one RXTE observation close to this epoch shows a hint of pulse profile change and increased pulsed flux. Given how fast the source appears to recover after burst episodes (see Section 6.1), it is possible that an unseen burst occurred around this epoch.

In general, changes in flux and hardness of the spectrum appear to be correlated, with observations having a higher flux also showing a harder spectrum (see Figure 7). This correlation appears to hold at least for the small range of flux phase-space that is covered by the current observations. In addition, the softening of the spectrum before 2006 agrees with the results presented by Dib et al. (2007) and the spectral hardening for observations close to detected bursts (in addition to a softening in between) agrees with the behavior observed by Gavriil et al. (2010). Our pre-burst absorbed fluxes also agree with those of Rea et al. (2007a) reporting a BB+PL model.

Anomalous X-ray pulsars exhibit a wide range of behavior in their variability, from sudden energetic bursts to long-term changes. The AXP 1E 1048–5937 was shown to have large, long-term flares of its pulsed flux (one of them lasting about a year; Gavriil & Kaspi 2004) and variations by a factor of ~2 to its phase-averaged flux (Tiengo et al. 2005). In its most recent active period, prolonged changes to its observed emission have been seen as well as a correlation between hardness and flux as seen here for 4U 0142+61 (Tam et al. 2008; Dib et al. 2009). Changes in the phase-averaged flux of 1RXS J170849.0–400910 of ~60% on a timescale of years have also been reported (Campana et al. 2007) with a correlation between hardness and flux as well. 1RXS J170849.0–400910 was shown to have pulse profile changes possibly associated with glitches and low-level pulsed flux variations at various epochs, while 1E 1841–045 was shown to have possible long-term pulse profile changes and glitches with no obvious radiative changes (Dib et al. 2008; Zhu & Kaspi 2010). On the other hand, a large outburst accompanied by long-term changes in almost all emission characteristics was seen in 1E 2259+586; this source also shows a hardness-intensity correlation (Kaspi et al. 2003; Woods et al. 2004; Zhu et al. 2008). We briefly note that a BB+PL model to the observed emission from the above sources results in large temperatures and steep power-law indices. As such, the power-law component may in fact dominate the observed emission below ~1–2 keV, as shown in Figure 4 for 4U 0142+61. Therefore, the hardness–intensity correlations that are measured in terms of the value of the power-law index may be dominated by the evolution of the low-energy emission from these sources.

The very low-level, long-term spectral changes seen here for 4U 0142+61 have not been observed thus far in other sources and were detected thanks to the high quality of the available data. The fact that the largest changes are suggested to be accompanied by bursting activity points to an origin in a common event (see Section 6.1). The overall changes in pulse and spectral properties of 4U 0142+61 support the view of magnetars as very active sources with a wide range of variability characteristics. We now discuss the observed changes in light of the commonly cited models for AXP emission: the magnetar and disk models.

6.1. The Magnetar Model

6.1.1. X-ray emission characteristics

In the magnetar model, thermal X-ray emission from the surface provides seed photons which are resonantly Compton-scattered (RCS) to higher energies by the enhanced currents in a twisted magnetosphere (Thompson et al. 2002; Lyutikov & Gavriil 2006; Fernández & Thompson 2007; Nobili et al. 2008; Rea et al. 2008). Bursts of emission are explained as sudden, small-scale reconfigurations of the surface following a crustal yield due to a magnetospheric twist. Large outbursts are explained as global reconfigurations and/or reconnections of the magnetic field after a large twist. Long-term variability, assuming constant underlying thermal emission, is viewed as increases (or decreases) in the twisting of the magnetosphere by...
currents from the stressed crust. The optical depth to scattering increases as the twist angle of the magnetosphere increases and in this case we expect a hardening of the spectrum to accompany an increase of the emitted flux. This scenario has been used to explain the hardness–intensity correlation observed in magnetars. The fact that the predicted correlation between flux and hardness is seen for 4U 0142+61 (with the brighter observations having a harder spectra) and that the largest changes are observed to coincide with a period of increased burst activity support this interpretation.

Estimates for the post-burst luminosity and its decay timescale expected from the decay of a magnetospheric twist have been worked out by Thompson et al. (2002), Beloborodov & Thompson (2007), and Beloborodov (2009). Here, the non-thermal RCS radiation is created by the ohmic dissipation of electric currents as the twist decays. Beloborodov (2009) found that a localized twist model is in overall agreement with the properties of the burst from the transient AXE XTE 1810–197 (L ∼ 2 × 10^34 erg s^{-1} and τ ∼ 0.6 yr). However, Rea et al. (2009) found that for the outburst from the new magnetar candidate SGR 0501+4516, the observed decay timescale of τ ∼ 1 month implies a twist luminosity of only ∼10^{33} erg s^{-1}, short of the observed luminosity of ∼2.5 × 10^{34} erg s^{-1}. In the case of 4U 0142+61, the discrepancy is even larger, as the largest of the observed bursts (on MJD 54138) had a luminosity of ∼10^{36} erg s^{-1} (Gavriil et al. 2010; about a factor of 10 higher than the long-term flux of ∼10^{35} erg s^{-1}) while we show here that the flux completely recovered within days. In order to explain such emission, unusual twist characteristics are required. For example, the threshold self-induction voltage of the decaying twist needed to maintain the necessary currents would have to be much larger than the canonical ~1 GeV expected to apply for these sources. Whether such voltages are possible is not currently known (see Beloborodov & Thompson 2007; Beloborodov 2009).

On the other hand, Özel & Güver (2007) have proposed that the afterglow emission from magnetars arises mainly from the cooling crust of the star and less so from changes in the magnetospheric currents. For example, most of the burst emission (arising from a large twist in the magnetosphere) can be deposited deep in the crust, heating it; its subsequent cooling dominates the spectral evolution of the star. In this case, the observed temperature and total flux would be directly correlated and would also explain the hardness–intensity correlation. However, this does not seem to be the case for 4U 0142+61. Again, although the latest burst observed from this source was the longest and among the most energetic detected from AXPs thus far (Gavriil et al. 2007, 2010), all observations taken after the burst show a rapid return to the previous state without additional changes. This suggests that long-term recovery regions (e.g., the inner crust) have not been significantly affected, or that they were slightly affected and recovered very quickly.

The long-term evolution of the pulsed fraction in 4U 0142+61 does not show a clear correlation with the total flux. This is different from what is observed in other sources. For 1E 1048.1–5937, higher phase-averaged fluxes correspond to lower pulsed fractions (Tiengo et al. 2005; Tam et al. 2008), a behavior that can be interpreted (at least in principle) as a growing hot spot on the surface. On the other hand, the AXP 1E 2259+586 shows a general increase in pulsed fraction for higher phase-averaged fluxes (Woods et al. 2004; Zhu et al. 2008). In the transient AXE XTE 1810–197, as the source slowly faded after a large (undetected) burst around the end of 2002, the pulsed fraction and flux both decreased with time. This behavior may be interpreted as a fading hot spot against the background of a large-area cool blackbody (Gotthelf & Halpern 2007; Bernardini et al. 2009). However, in the case of 4U 0142+61, we see a complex behavior of the pulsed fraction as a function of flux with no clear correlations (see the lower panel of Figure 7). The continuous increase in the pulsed fraction independent of the total flux suggests that different mechanisms might contribute to the observed emission with varying strengths over time. The twisted magnetosphere model generally predicts that pulsed fraction and flux should correlate positively with twist angle (for details, see, e.g., Fernández & Thompson 2007); this mechanism could be responsible for the bulk of the pulsed fraction and total flux increase for 4U 0142+61 close to the bursting period and their subsequent decay afterwards as the twist relaxed.

We note that so far, timing and radiative events in AXPs have shown some correlation. While some timing glitches have not been accompanied by radiative events, the converse is not generally true, and all radiative outbursts are consistent with being accompanied by timing anomalies (Dib et al. 2008; Zhu & Kaspi 2010). However, our single 2008 March observation raises the interesting possibility that some radiative events might in fact be timing “quiet” (possibly if they are not major, long-lived events but shorter bursts; which in turn begs the question of how large of an event is required to be accompanied by a timing anomaly). We also note that Dib et al. (2009) reported an epoch of similarly high pulsed flux from AXP 1E 1048.1–5937 with no other timing irregularities (this occurred at MJD 53682; see their Figure 10). In the case of 4U 0142+61, its low pulsed fraction might conspire to make such events undetected with RXTE. For other sources, it is possible that decreases in pulsed fraction during such events might also make them harder to detect using RXTE and call for further monitoring of these sources with imaging telescopes to capture the whole range of their behavior.

We thus find that the emission from 4U 0142+61 shows characteristics that are distinct from those of other AXPs, and while it generally agrees with magnetar models, the details of the evolution are too complex to be explained currently. We also note that the changes observed here are some of the smallest measured with high precision for any magnetar.

6.1.2. Emission at Other wavelengths

The hard X-ray emission observed in AXPs has also been proposed to arise from the twisted magnetosphere, which is thought to act as an accelerator and create a hot corona close to the surface of the star (Thompson & Beloborodov 2005; Beloborodov & Thompson 2007). In this case, we would expect the changes seen here (mainly those associated with the onset of bursts) to have corresponding changes at hard X-rays. However, very long integrations are required by hard X-ray telescopes in order to detect the source and measure its flux with any interesting significance (see, e.g., den Hartog et al. 2008). Given the short-lived nature of the events observed here, it is unlikely that changes in the hard X-rays would be detectable.

The origin of the optical and IR emission in the magnetar model is not well understood, with the proposed mechanisms not studied in detail and thus having uncertain correlation with the X-ray flux (see Thompson & Beloborodov 2005).
no significant change in the near-IR flux after the bursts that could be correlated with the overall increase in the X-ray flux during this time. However, given the large variability seen from 4U 0142+61 in the optical/IR (e.g., Hulleman et al. 2004) and the subtle nature of the changes in X-rays, we cannot test for a possible correlation between the emission at these wavelengths.

6.2. The Disk Models

The discovery of mid-IR emission from 4U 0142+61 has prompted a significant debate on whether it arises from a possible disk and, additionally, whether it is a passive (Wang et al. 2006; Kaplan et al. 2009) or an active disk (Ertan et al. 2007b). In the case of a passive disk the magnetar mechanism is still needed to explain the X-ray emission from the star, while an active disk accretes onto a star with a dipole field of \( \sim 10^{12}-10^{13} \) G (a magnetar field in the quadrupole or higher components in then needed to explain the bursting behavior; Ertan et al. 2007a, 2007b). The (un)possible optical/IR/UV emission results from the disk as it radiates through viscous energy dissipation and by irradiation from the star. Most of the disk radiation, which peaks in the IR, comes from the outer regions.

The fact that the main X-ray spectral changes are seen to correlate with an increased burst activity argue against a disk origin. Although an increased X-ray flux from the star can affect the irradiation emission from the putative disk around 4U 0142+61, these X-ray changes might or might not be accompanied by changes at longer wavelengths depending on the reprocessing efficiency of the disk. Therefore, the fact that no significant change in the near-IR emission is seen does not constrain these models. In addition, the large range and associated uncertainties of previously reported IR detections do not allow for intrinsic changes in the emission of several percent, as observed in the X-ray range, to be readily identified.

7. CONCLUSION

The observations presented here further demonstrate that variability in AXPs is common. The variability can take many forms and can proceed on a wide range of time scales. The radiative properties of these objects are seen to vary by orders of magnitude in the case of outbursts and by a few percent as seen here. The pulse profile, pulsed fraction, and flux of 4U 0142+61 have undergone evident changes during the span of the our observations (2000–2008). Before the bursts were detected, the pulse profile became more sinusoidal, while more complicated changes were seen afterwards. On the other hand, the pulsed fraction increased throughout the observations, reached a maximum during the burst epochs and has since decreased. The total flux is observed to have been nearly constant in the observations taken before the bursts, while an increase of \( \sim 10\% \) is seen afterwards in the 0.5–10 keV range. The flux increase is energy dependent, with higher energies showing a larger increase. No evidence for further long-term changes as a direct consequence of the bursting activity is seen. The data also suggest a correlation between flux and hardness of the spectrum, with larger fluxes on average having harder spectra. In general, the spectral behavior of the source supports a magnetar origin, in which current models predict that larger twists in the magnetosphere produce brighter, harder emission which can coincide with increased burst activity. However, the detailed evolution of the spectrum and pulse characteristics throughout the observations suggests a more complicated scenario, with unusual twist characteristics needed to explain the emission. No significant variations close to the burst epochs in the near-IR are detected from 4U 0142+61; however, this is not constraining on models.

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