10 YEARS OF RXTE MONITORING OF THE ANOMALOUS X-RAY PULSAR 4U 0142+61: LONG-TERM VARIABILITY

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ABSTRACT

We report on 10 years of monitoring of the 8.7 s anomalous X-ray pulsar 4U 0142+61 using the Rossi X-Ray Timing Explorer (RXTE). This pulsar exhibited stable rotation from 2000 March until 2006 February; the rms phase residual for a spin-down model, which includes \( \dot{\nu}, \dot{\nu}_v \), and \( \dot{\nu}_s \) is 2.3%. We report a possible phase-coherent timing solution valid over a 10 yr span extending back to 1996 March. A glitch may have occurred between 1998 and 2000, but is not required by the existing timing data. The pulse profile has been evolving since 2000. In particular, the dip of emission between its two peaks got shallower between 2002 and 2006, as if the profile were evolving back to its pre-2000 morphology, following an earlier event, which possibly also included the glitch suggested by the timing data. These profile variations are seen in the 2–4 keV band, but not in 6–8 keV. We also detect a slow increase in the pulsed flux between 2002 May and 2004 December, such that it has risen by 36% ± 3% over 2.6 yr in the 2–10 keV band. The pulsed flux variability and the narrowband pulse profile changes present interesting challenges to aspects of the magnetar model.

Subject headings: pulsars: individual (4U 0142+61) — stars: neutron — X-rays: stars

1. INTRODUCTION

The existence of magnetars—young, isolated neutron stars powered by the decay of an ultrahigh magnetic field—is now well supported by many independent lines of evidence (Woods & Thompson 2006). This comes from the study of soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs), both of which classically exhibit X-ray pulsations having luminosity in the range of 10\(^{32}\)–10\(^{36}\) ergs s\(^{-1}\), periods \( P \) ranging from 5 to 12 s, \( P' \) of \( 10^{-13} \) to \( 10^{-11} \) s\(^{-1}\), and surface dipolar magnetic fields \( B \) in the range (0.6–7) \times 10\(^{14}\) G, assuming vacuum dipole magnetic braking. AXPs and SGRs, in the magnetar model, are ultimately powered by the internally decaying magnetic field. In the magnetar model, the pulsed X-rays are suggested to be the result of a combination of surface thermal emission and a nonthermal high-energy component from resonant scattering of thermal photons off magnetospheric currents (Thompson et al. 2002). Magnetar bursting, the hallmark of SGRs and also seen in AXPs, is believed to be a result of crustal yield and subsequent magnetospheric disturbances ultimately caused by stresses on the crust by the decaying internal field (see, for example, Woods et al. 2004).

Recently, thanks in large part to long-term monitoring campaigns, it has become clear that AXPs exhibit a variety of types of aperiodic X-ray variability that can in principle be useful for testing aspects of the magnetar model. This variability can be categorized into four types, some of which are seen contemporaneously with each other: very short duration SGR-like bursts, sudden outbursts and transient brightenings with decays lasting months or longer, slow-rise long-term flux variations, also with slow decays, and pulse profile changes.

Classic examples of SGR-like bursts and an outburst were seen in 2002 for AXP 1E 2259+586, which exhibited a sudden order-of-magnitude increase in the pulsed and total flux, followed by a one-year-long flux decay (Kaspi et al. 2003; Woods et al. 2004). The outburst was accompanied by over 80 short SGR-like bursts, a rotational glitch with interesting recovery on a timescale of 2 weeks, short-lived spectral changes, and dramatic broadband pulse morphology changes, which included the two profile peaks swapping heights and which lasted 2–3 weeks. The event was consistent with the picture of sudden crustal yield influencing both the interior and the exterior of the AXP, in analogy with large SGR bursts.

Several observations of this same source and others suggest similar outbursts in AXPs that went undetected. GINGA observations of 1E 2259+586 reported by Iwasawa et al. (1992) also showed a factor-of-2 pulsed flux change and pulse profile variations, both of which, in hindsight, could be explained by a contemporaneous but short-lived outburst that went unseen. In AXP 1RXS J170849.0–400910, two rotational glitches were discovered (Kaspi et al. 2000; Kaspi & Gavriil 2003; Dall’Osso et al. 2003). Dall’Osso et al. (2003) reported possible small pulse morphology changes associated with these glitches. Whether these glitches were accompanied by bursting that went unobserved is unknown, but plausible. The transient AXP XTE J1810–197 underwent a dramatic sudden brightening by nearly 2 orders of magnitude (Ibrahim et al. 2004) followed by a total flux decay that lasted years (Halpern & Gotthelf 2005); this may well have been an outburst similar to, although larger than, that in 1E 2259+586, but for which the brief main event went unobserved. Similarly, the transient candidate AXP AX J1845–0258 underwent a factor >100 decay in flux after an initial brightening that led to its discovery (Vasisht et al. 2000; Tam et al. 2006). This too could have been the result of an unseen outburst.

AXP outbursts appear to be fundamentally different from the slow-rise, long-term flux variations seen in AXP 1E 1048.1–5937. Gavriil & Kaspi (2004) discovered two long-lived, slow-rise X-ray—pulsed flux flares from this source. The first flare had peak pulsed flux a factor of ~2 greater than the quiescent level and lasted ~100 days. The second, larger flare had peak a factor of >4 higher than in quiescence and lasted over 1 year. The flares were accompanied by an increase in the phase-averaged flux of the source and a decrease in pulsed fraction, although the timescale and full dynamic range of the these changes have not been clearly established (Mereghetti et al. 2004; Tiengo et al. 2005). No simultaneous pulse morphology changes were detected, and
Although the source did exhibit some SGR-like bursts (Gavriil et al. 2004), they were not obviously correlated with pulsed flux. Large (factor of 10) torque changes were seen, especially during the large flare, but the correlation between torque and pulsed flux, at least on timescales smaller than the flare itself, was marginal. Overall, the slow-rise flares seen in 1E 1048.1–5937 are not thought to result from crustal cracking as in outbursts. They can, however, be explained by a spontaneous increase in the magnetic field twist in the magnetosphere. However, what might trigger such events is unclear. Nevertheless, Rea et al. (2004), they were not obviously correlated with pulsed flux, at least on timescales smaller than the flare itself, was marginal. Overall, the slow-rise flares seen in 1E 1048.1–5937 are not thought to result from crustal cracking as in outbursts. They can, however, be explained by a spontaneous increase in the magnetic field twist in the magnetosphere. However, what might trigger such events is unclear. Nevertheless, Rea et al. (2004), they were not obviously correlated with pulsed flux, at least on timescales smaller than the flare itself, was marginal. Overall, the slow-rise flares seen in 1E 1048.1–5937 are not thought to result from crustal cracking as in outbursts. They can, however, be explained by a spontaneous increase in the magnetic field twist in the magnetosphere.

2. Observations

The results presented here were obtained using the Proportional Counter Array (PCA) on board RXTE. The PCA consists of an array of five collimated xenon/methane multianode proportional counter units (PCUs) operating in the 2–10 keV range, with a total effective area of approximately 6500 cm² and a field of view of ~1° FWHM (Jahoda et al. 1996). Our 136 observations are of various lengths (see Table 1). Most were obtained over a period of several years as part of a long-term monitoring program, but some are isolated observations (see Fig. 1).

Table 1: Summary of RXTE Observations

| Observing Cycle | Typical Exposurea (ks) | Typical Separationb (weeks) | Number of Observationsb | Total Exposurec (ks) | First MJD–Last MJDd | First Date–Last Date |
|-----------------|------------------------|-----------------------------|------------------------|---------------------|---------------------|---------------------|
| 1               | 11                     | 0.1                         | 4                      | 45                  | 1996 Mar 29–1996 Mar 29 |
| 2               | 1                      | 4                           | 14                     | 16                  | 1996 Nov 24–1997 Dec 13 |
| 3               | 20                     | ...                         | 1                      | 20                  | 1998 Mar 21–1998 Mar 21 |
| 4               | ...                    | ...                         | 0                      | 0                   | ...                 | ...                 |
| 5               | 3                      | 4                           | 15                     | 46                  | 2000 Mar 7–2001 Feb 10 |
| 6               | 7                      | 6                           | 10                     | 54                  | 2001 Mar 18–2002 Jan 8 |
| 7               | 15                     | 6                           | 9                      | 100                 | 2002 Mar 6–2002 Dec 26 |
| 8               | 5                      | 2                           | 21                     | 124                 | 2003 Mar 28–2004 Feb 11 |
| 9               | 5                      | 2                           | 27                     | 86                  | 2004 Mar 2–2005 Feb 19 |
| 10              | 5                      | 2                           | 36                     | 120                 | 2005 Mar 9–2006 Feb 21 |

a The exposure and separation are only approximate.

b When the last digit of the observation ID of two successive data sets is different, the two data sets are considered separate observations.

c The total exposure does not include Earth occultation periods.

d First MJD and Last MJD are the epochs, in Modified Julian Days, of the first and the last observations in a cycle.

For the monitoring, we used the GoodXenon with Propane data mode, except during Cycle 10, when we used the GoodXenon mode. Both data modes record photon arrival times with 31.25 ms resolution and bin energies into one of 256 channels. To maximize the signal-to-noise ratio, we analyzed only those events from the top xenon layer of each PCU.

3. Analysis and Results

3.1. Phase-coherent Timing

Photon arrival times at each epoch were adjusted to the solar system barycenter using the position obtained by Patel et al. (2003) from Chandra data. They were then binned with 31.25 ms...
time resolution. In the timing analysis presented below, we included only the events in the energy range 2–10 keV (unless otherwise specified) to maximize the signal-to-noise ratio of the pulse. Each barycentric binned time series was epoch-folded using an ephemeris determined iteratively by maintaining phase coherence; see below. Resulting pulse profiles, with 64 phase bins, were cross-correlated in the Fourier domain with a high signal-to-noise ratio template created by adding phase-aligned profiles from all observations. The cross-correlation returned an average pulse time of arrival (TOA) for each observation corresponding to a fixed pulse phase. The pulse phase \( \phi \) at any time \( t \) can be expressed as a Taylor expansion,

\[
\phi(t) = \phi_0(t_0) + \nu_0(t - t_0) + \frac{1}{2} \nu_0(t - t_0)^2 + \frac{1}{6} \nu_0(t - t_0)^3 + \ldots,
\]

where \( \nu \equiv 1/P \) is the pulse frequency, \( \nu_0 \equiv d\nu/dt \), etc., and the subscript 0 denotes a parameter evaluated at the reference epoch \( t = t_0 \). The TOAs were fitted to the above polynomial using the pulsar timing software package TEMPO.5

We report an unambiguous phase-coherent timing solution that spans the postgap (i.e., after 2000 March, MJD 51,610) 6 yr period until 2006 February (MJD 53,787), including all data in RXTE Cycles 5–10. The parameters of our best-fit spin-down model, which includes \( \nu, \nu_0, \text{ and } \nu_2 \), are presented in Table 2. The corresponding phase residuals are shown in Figure 2. Note the unmodeled features in the residuals; these may be caused by a noise process similar to that commonly seen in radio pulsar timing (e.g., Livingstone et al. 2005).

The best-fit postgap ephemeris does not, however, fit the pregap TOAs well. Figure 3 shows a clear systematic deviation in the pregap residuals obtained after subtracting the postgap ephemeris. The best-fit frequency obtained from the postgap model at the reference epoch is larger than the frequency obtained from the best-fit model of the pregap TOAs at the same epoch (see Table 2).

\[ \text{Fig. 2.} \] Arrival time residuals for 4U 0142+61 for the postgap period, using the postgap ephemeris given in Table 2. The residuals have rms 2.3% of the pulse period.

\[ \text{Fig. 3.} \] Arrival time residuals for 4U 0142+61 for all RXTE cycles using the postgap ephemeris.

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**TABLE 2**

| Parameter                  | Pregap Ephemeris b Spanning Cycles 1–3 | Postgap Ephemeris Spanning Cycles 5–10 | Possible Ephemeris c Spanning All Cycles |
|----------------------------|----------------------------------------|----------------------------------------|----------------------------------------|
| MJD range                  | 50,170.693–50,893.288                  | 51,610.636–53,787.372                  | 50,170.693–53,787.372                  |
| TOAs                       | 19                                     | 118                                    | 137                                    |
| \( \nu \) (Hz)             | 0.115099566(3)                         | 0.1150969337(3)                        | 0.1150969304(2)                        |
| \( \dot{\nu} \) (Hz s\(^{-1}\)) | -2.659(3)                              | -2.6935(9)                            | -2.6514(7)                            |
| \( \ddot{\nu} \) (Hz s\(^{-2}\)) | ...                                    | 0.417(10)                             | -1.7(2)                                |
| \( \nu_0 \) (Hz s\(^{-3}\)) | ...                                    | ...                                    | 3.6(12)                                |
| \( \nu_2 \) (Hz s\(^{-4}\)) | ...                                    | ...                                    | 8.7(3)                                 |
| \( \nu_3 \) (Hz s\(^{-5}\)) | ...                                    | ...                                    | -5.01(13)                              |
| \( \nu_4 \) (Hz s\(^{-6}\)) | ...                                    | ...                                    | 6.6(4)                                 |
| \( \nu_5 \) (Hz s\(^{-7}\)) | ...                                    | ...                                    | ...                                    |
| Epoch (MJD)                | 50,530.000000                          | 51,704.000025                          | 51,704.000000                          |
| rms residual               | 0.019                                  | 0.023                                  | 0.019                                  |

\[ ^a \] Numbers in parentheses are TEMPO-reported 1σ uncertainties.

\[ ^b \] The pregap ephemeris reported here is slightly different from that reported in Gavriil & Kaspi (2002), because here we take into account Cycle 1 and 3 observations. Note that both ephemerides return the same number of pulsar rotation cycles between the first and last pregap observations used by Gavriil & Kaspi (2002).

\[ ^c \] It is possible to find a different overall ephemeris after adding an arbitrary but constant time jump to all postgap TOAs.

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5 See http://www.atnf.csiro.au/research/pulsar/tempo.
This, in principle, could indicate that a glitch occurred at some time during the gap. At MJD 51,250, midway between the pregap and the postgap ephemerides, the fractional change in frequency due to the possible glitch is $\Delta \nu/\nu = (7.11 \pm 0.15) \times 10^{-7}$. However, by using six frequency derivatives, we found a possible ephemeris that fits the entire Cycle 1–10 range (MJD 50,170–53,787; see Table 2). The rms phase residual for that ephemeris is 0.019 (see Fig. 4). Note that when finding an ephemeris that spans several years, it is not uncommon to require a large number of frequency derivatives in order to reduce the rms phase residuals to a number on the order of 5%. This is especially typical of young pulsars and is generally attributed to timing noise (e.g., Livingstone et al. 2005).

The possibility of a glitch in 4U 0142+61 during our gap was in fact examined by Morii et al. (2005). The authors showed that the frequency obtained from a 1998 August ASCA observation of 4U 0142+61 (MJD 51,046.699, 154 days after the start of our gap) differs from the frequency predicted at the epoch of the observation by the ephemerides previously reported for 4U 0142+61 in Gavriil & Kaspi (2002). Morii et al. reported a frequency $f = 0.1150972(6) \text{ Hz}$ at MJD 51,046.69875 for the ASCA observation. Our overall ephemeris (see Table 2) predicts $f = 0.115098404(3) \text{ Hz}$ at the same epoch. Their measurement is within 2 $\sigma$ of our prediction, indicating a $\sim$5% possibility that the two values are the same. Therefore, their measured $f$ can be explained by a gradual change of the spin-down rate without invoking a glitch.

However, the existence of our overall ephemeris cannot rule out the possibility of the glitch: in some rotational glitches, the frequency evolution, given some relaxation time after the glitch epoch, returns to what it was prior to the glitch (see, for example, the glitch reported in Kaspi & Gavriil 2003). If a glitch of this kind had happened during the 2 year gap and if the length of the gap was much greater than the relaxation time, the only long-term effect of the glitch that could still be observable with a timing analysis would be a random phase jump in the post-relaxation TOAs relative to the preglitch TOAs. To investigate this possibility, we added an arbitrary but constant time jump to all the postgap TOAs. We were still able to find a new ephemeris that connected the TOAs through the 2 year gap. This indicates that our overall ephemeris is not unique. Hence, we cannot rule out the possibility of a random phase jump between Cycles 3 and 5, and therefore a glitch cannot be ruled out.

It is important to note that our method for obtaining TOAs (cross-correlating the folded profiles of given observations with a high signal-to-noise ratio template obtained from all the observations combined) assumes a constant pulse profile. In §3.2 we show that the pulse profile is actually varying during our monitoring program. However, we performed simulations that showed that these changes do not result in timing offsets significantly larger than the reported TOA uncertainties. Hence the profile variations do not affect the above analysis.

### 3.2. Pulse Profile Changes

#### 3.2.1. Qualitative Observations

We performed a pulse profile analysis using FTOOLS version 5.3.1. We used the following steps: for each observation, we ran the FTOOLS `make_model` to combine the GoodXenon files. We then used the FTOOLS `fasebin` to make a phase-resolved spectrum of the entire observation with 64 phase bins across the profile. When we ran `fasebin`, we selected layer 1 of the detector, disregarded the propane photons, and included the photons from PCUs 1, 2, 3, and 4. We disregarded photons from PCU 0 because of the loss of its propane layer in 2000 (Jahoda et al. 2006) and because it gave results different from the other PCUs; `fasebin` also took care of barycentering the data. For each observation, we then used `seextract` to make a phase-averaged spectrum for the same set of detector layers and PCUs. The phase-averaged spectrum was then used by the perl script `pcarssr` to make a response matrix.

We loaded the phase-resolved spectra and the response matrices into the X-ray Spectral Fitting Package (XSPEC) and selected photons belonging to three energy bands: 2–10, 2–4, and 6–8 keV. Using XSPEC, we extracted an ASCII count rate spectrum of the entire energy bands. The profiles included XSPEC-obtained 1 $\sigma$ error bars on each of the phase bins in the profiles. To obtain a pulse profile in units of count rate per PCU, we divided the overall profile by a PCU coverage factor that took into account the amount of time each PCU was on.

We then aligned the 64 bin profiles with a high signal-to-noise ratio template using a cross-correlation procedure similar to the one described in the timing analysis. Then, for each RXTE cycle, we summed the aligned profiles, extracted the DC component from the summed profile, and scaled the resulting profile so that the value of the highest bin is unity and the lowest point is zero.

The average profiles in all three bands are presented in Figure 5 for comparison. In a given band, the different profile qualities are due to different net exposure times. It is important to note that the two narrow energy bands that we are using contain photons belonging to different spectral components: from the spectrum of 4U 0142+61 (see, for example, White et al. 1996), under the assumption that the spectrum is well described by a blackbody plus power-law tail, we know that the higher energy band (6–8 keV) contains negligible blackbody emission, while the lower energy band (2–4 keV) contains comparable amounts of blackbody and power-law emission.

Qualitatively, the evolution of the pulse profiles in the first two bands of Figure 5 is clear to the eye. In Cycles 1 and 2, the smaller peak, obvious in later cycles, is not very well defined. After the 2 year gap, in Cycle 5, the dip between the peaks is much more...
pronounced. The emission in the dip starts to rise most noticeably in cycles subsequent to Cycle 7. In the 6–8 keV band, the smaller peak appears to have lower amplitude in the normalized profiles than in 2–4 keV, indicating that it has a softer spectrum relative to the larger peak.

Another qualitative observation is that the ratio of the heights of the two peaks in the 2–10 keV and 2–4 keV bands appears to be closest to unity in the first cycle after the gap. The ratio starts to decrease in the cycles subsequent to Cycle 5. Note that from this figure alone we can compare the sizes of the two peaks, but we cannot track the evolution of the heights of each peak separately. In order to do that, we need to scale the pulse profile of each cycle by the average pulsed flux. This analysis is presented in § 3.4.

3.2.2. Fourier Analysis

To quantify the changes in the pulse profile, we computed the first six Fourier amplitudes of the average profiles of each cycle in each energy band. Harmonic numbers larger than 6 were
always consistent with zero. The results are shown in Figures 6, 7, and 8. In each of the three figures, the plots on the right show the power in each harmonic divided by the total power in all harmonics (not including the DC term). In the plots on the left, the observed pulse profiles are in the background (squares without error bars). The superimposed smooth curve in the foreground is made from the first six calculated Fourier components. The ratios of the first three Fourier harmonics relative to the fundamental are presented in Figure 9. Note that the ratios of the Fourier harmonics are not presented for Cycle 3 in Figures 6, 7, and 8, due to the very low signal-to-noise ratio.

Significant variations were seen in the pulse profile of 4U 0142+61 in the 2–10 keV band and in 2–4 keV; on the left side of both Figures 6 and 7, the most striking variable feature is the difference in the relative heights between the top of either peak and the bottom of the dip. On the right side, considering the first two Fourier components, the ratio of the second to first amplitudes ($A_2/A_1$) is significantly bigger than unity only in Cycle 5. It then falls steadily until, in Cycle 10, it reaches the same ratio as in Cycle 1. The evolution of the $A_2/A_1$ ratio in 2–4 keV is shown in Figure 9. In the pregap cycles, harmonics of order higher than 2 are only marginally significant. In the postgap cycles, harmonics 3 and 4 are most significant in Cycles 5 and 6, coinciding with the cycles where the dip in the time domain curve is sharpest. The evolution of the $A_3/A_1$ and $A_4/A_1$ ratios is also shown in Figure 9. Note the obvious rise in the harmonic ratios just postgap in the soft band, with apparent subsequent evolution to pregap values.

In the 6–8 keV band (see Fig. 8), statements about the behavior of the Fourier components are harder to make because of the poor signal-to-noise ratio; nevertheless, some trends are clear. Unlike in the lower energy band, the $A_2/A_1$ ratio does not appear to systematically increase or decrease. Also unlike in the lower band, harmonics 3 and 4 do not appear to vary systematically (see Fig. 9). Thus, in the band where all the emission is from the power-law component of the spectrum, the variations in the shape of the pulse profile, if any, are much less significant than the variation in the 2–4 keV band, which contains photons belonging to both components of the spectrum.

### 3.3. Pulsed Flux Time Series

To obtain a pulsed flux time series for 4U 0142+61, we did the following. First, for each PCU in each observation, we used a procedure similar to that described in § 3.2.1 to make a phase-resolved spectrum (with 16 phase bins across the profile) and a
response matrix. We then used the FTOOL `fmodtab` to correct
the exposure value in the phase-resolved spectrum of each PCU
in order to take into account the amount of time that each PCU
was on. Then, for each observation, we added the spectra ob-
tained from PCUs 1–4 using the FTOOL `fbadd` and added the
responses using the FTOOL `addrmf`. We used `fbadd` and `addrmf`
again to add the spectra and responses of all observations in a given
RXTE cycle. For each RXTE cycle, we loaded the phase-resolved
spectra into XSPEC and selected photons in the 2–10 keV range.
Using XSPEC, we extracted an ASCII count rate pulse profile for
each RXTE cycle. The profiles included XSPEC-determined 1/C27
error bars on each of the phase bins. We then smoothed each of
the profiles by eliminating the Fourier components corresponding
to harmonic numbers larger than 5. The pulsed flux for each of
the smoothed profiles was calculated using the following discrete area
formula:

\[ F = \frac{1}{N} \sum_{i=1}^{N} (p_i - p_{\text{min}}), \]

where \( i \) refers to the phase bin, \( N = 16 \) is the total number of
phase bins, \( p_i \) is the count rate in the \( i \)th phase bin of the smoothed
pulse profile, and \( p_{\text{min}} \) is the value of the minimum of the con-
tinuous smooth function that is made from the first five Fourier
components of the original profile.

The resulting pulsed flux history in counts s\(^{-1}\) per PCU is
shown in the top panel of Figure 10. Each point represents one
RXTE cycle. The pulsed flux has increased by \( 36\% \pm 3\% \) be-
tween Cycles 7 and 9. A quick rebinning of the observations
shows that the increase period lasted \( \sim 2.6 \) yr (between MJDs
52,400 and 53,350). We verified that the same trend is detected

![Fig. 8.—Same as Fig. 6, but for 6–8 keV.](image)

![Fig. 9.—Ratios of the Fourier amplitudes of the pulse profiles in two energy
bands. Top: Ratio of the Fourier amplitude of the second harmonic to that of
the fundamental. Middle: Ratio of the Fourier amplitude of the third harmonic to
that of the fundamental. Bottom: Ratio of the Fourier amplitude of the fourth
harmonic to that of the fundamental.](image)
We repeated the above procedure of finding the flux for narrower energy bands. There are hints that the long-term increase is present in the 2–4 keV band and not in 6–8 keV, but our statistics do not let us confirm this. If the pulsed flux increase is restricted to <6 keV, this could indicate that the spectrum of the pulsed emission is getting softer. Motivated by this possibility, we performed a detailed spectral analysis of four available archival *XMM-Newton* observations. We found that the spectrum is indeed getting softer (Gonzalez et al. 2007).

Note that the method that we used to calculate the pulsed flux, which consisted of calculating the pulsed area under the profile, is more sensitive to noise than are measurements of the rms pulsed flux like those used in Woods et al. (2004). Therefore, to reduce the effects of noise, it was necessary to combine the data from entire cycles in order to obtain each of the pulsed area points reported in the top panel of Figure 10, hence the large horizontal error bars. We report measurements of the pulsed area instead of reported in the top panel of Figure 10, hence the large horizontal error bars. We report measurements of the pulsed area instead of

The observed increase in the pulsed flux in the 2 keV band is comparable to the energy released in the second 9 937 flare (Gavriil & Kaspi 2004). It is also an order of magnitude smaller than the average energy release rate in the first 1E 1048–5937 flare (Gavriil & Kaspi 2004). The amount of energy released in the same 2.6 yr period due to the increase in the pulsed flux is ∼9 × 10⁴⁰ ergs in the 2–10 keV band. This is comparable to the energy released in the second 1E 1048–5937 flare (Gavriil & Kaspi 2004) and to the energy released in the in the year following the outburst in 1E 2259+586 (Woods et al. 2004).

### 3.4. Combined Pulse Morphology and Pulsed Flux Analysis

In § 3.2.2, we calculated the Fourier components of the average pulse profiles. This gave us the relative amplitude of the pulse profile harmonics in each *RXTE* cycle. In § 3.3, we calculated the pulsed flux for every observation. Here we compute a weighted average of the pulsed flux for each cycle using the flux points calculated in § 3.3. We then reconstruct the profiles for each of the cycles from the first six Fourier components (not including the DC), scale them by the average rms pulsed flux for that cycle, and add the necessary offset for the lowest point on each cycle to be zero. This means that the resulting scaled profiles return the correct pulsed flux. The advantage of this analysis is that
we can now trace the evolution of each of the peaks independently. The postgap scaled profiles in 2–10 keV and in 2–4 keV are presented in the top panels of Figures 11 and 12, respectively. We did not include a similar figure for 6–8 keV because of the poor signal-to-noise ratio in that band. The absolute heights of the peaks in the postgap cycles, as well as the absolute height of the dip in between, are plotted in the bottom panels of Figures 11 and 12. The error bars take into account both the errors on the Fourier components and the errors on the pulsed flux.

In both figures, there is a hint of increase in the height of the big peak between Cycles 7 and 9. The dip between the peaks appears to be getting shallower more rapidly between Cycles 7 and 9. The difference in the height of the dip over these 3 years is more significant than the difference in the height of either peak. This indicates that the biggest contribution to the change in the pulsed flux comes from an increase in the emission in the dip, which, in principle, could be caused by the widening of either peak around the dip.

4. DISCUSSION

4.1. Possible Event in the Gap?

Could a short-timescale energetic event (such as an outburst like that seen in 2002 for 1E 2259+586) have occurred sometime within the 2 year gap and triggered the pulsed flux and pulse profile changes that we are observing? As discussed above, the possibility of a glitch during the gap was examined by Morii et al. (2005). Here an examination of our timing, flux, and pulse profile analyses can provide further clues to help answer this question.
From our timing analysis (§ 3.1), there is some evidence for a glitch having occurred sometime during our gap. Hence, if an outburst did occur, it might have been accompanied by a glitch, as was the case for the 2002 outburst of 1E 2259+586 (Kaspi et al. 2003). If there was a glitch in 4U 0142+61, the unrecovered fractional change in frequency would have been $(7.11 \pm 0.15) \times 10^{-7}$, a factor of 6 smaller than the maximum fractional frequency change of $(4.24 \pm 0.11) \times 10^{-6}$ observed in 1E 2259+586. The fact that the pulsed flux in the first postgap observations is consistent with that in the last pregap observations could be consistent with an outburst in between if the initial flux increase during an outburst had time to die down (see Fig. 10). If we assume that the return of the pulse profile to its pregap shape is a recovery following an outburst, this would imply a much longer timescale for the pulse profile relaxation phase than for the pulsed flux relaxation, the opposite of what was seen following the 1E 2259+586 outburst (Woods et al. 2004). Alternatively, the postoutburst pulse profile relaxation could have been completed during the gap, and the slow return of the postgap profile to its pregap morphology could be attributed to a different phenomenon. This is further discussed in § 4.3. In either case, if there was an event during the gap, why the pulsed flux is currently rising is unclear. If the event associated with the putative glitch released energy deep in the neutron star crust, then the increase could be due to its slow release (e.g., Eichler & Cheng 1989; Hirano et al. 1997). Given the size of the observed flux increase and its timescale for release, the initial energy deposition would have had to have been large, $\sim 10^{49}$ ergs (Hirano et al. 1997). This is comparable to the observed energy release in giant SGR flares (Hurley et al. 2005).

If we assume that the pulse shape prior to the gap is the relaxed pulse shape, the evolution of the harmonic ratios shown in Figure 9 supports the possibility of relaxation of the profile following an event in the gap. To shed light on the events in the gap, we can compare our RXTE profiles with those observed with ASCA by Morii et al. (2005). In their Figure 4, pulse profiles in 0.5–10 keV for (1) September 1994, (2) August 1998, and (3) combined July and August 1999 profiles are presented. In the 1994 and 1998 observations, the profile consisted of two peaks, with the trailing peak being the smallest and the dip between the peaks being higher than the lowest bin in the profiles. The shape of the 1998 profile is in agreement with the RXTE pregap average pulse profiles for Cycle 2 (see Fig. 6). In the 1999 ASCA profile, the amplitude of the trailing peak was higher than that of the leading peak. In addition, the difference between the height of the dip and the lowest point in the profile decreased. Interestingly, the changes in the ASCA profiles appeared more significant at the lower end of the energy band, as we observe in our RXTE data. In 2000, the first RXTE cycle after the gap has a profile in which the trailing peak is once again smaller than the leading peak. The dip between the peaks, however, is still more pronounced than in the pregap observations.

Overall, the timing data and the pulse profile data are consistent with some sort of event, possibly a glitch with an accompanying sudden pulse profile change, having occurred between 1998 August and 1999 July, possibly with the latter’s long-term relaxation still ongoing as of early 2006. However, we suggest an alternate explanation for the latter point below.

4.2. Brief Review of the Magnetar Model

In the detailed magnetar model proposed by Thompson et al. (2002), the crust of a magnetar is deformed by internal magnetic stresses, thereby twisting the footpoints of the external magnetic field, driving powerful currents in the magnetosphere and twisting the magnetosphere relative to the standard dipolar geometry. These magnetospheric currents resonantly cyclotron-scatter seed surface thermal photons. The seed contribution to the thermal component of the spectrum is thought to arise from heat resulting from the active decay of a high internal magnetic field (Thompson & Duncan 1996; Thompson et al. 2002). The magnetospheric scattering is responsible for the nonthermal component of AXP spectra. In addition, the surface is back-heated by the currents, resulting in additional thermal emission. Indeed, the persistent emission in AXPs generally has a spectrum that is well described by a two-component model, consisting of a blackbody plus a hard power-law tail, as expected in this model.

Changes in pulsed and/or total X-ray luminosity, spectral hardness, and torque are predicted to have a common physical origin in the Thompson et al. (2002) model, and some correlations are expected. Changes in twist angle of the magnetic field cause, or may be caused by, changes in the magnetospheric current distribution (either due to sudden crustal deformation, as in AXP outbursts and SGR giant flares, or due to slower crustal deformations, as may be taking place in the AXP flares; Gavriil & Kaspi 2004). Larger twists generally correspond to harder persistent X-ray spectra and higher magnitudes of the spin-down rates, as is observed when comparing the harder SGR spectra to those of the softer AXPs (Marsden & White 2001). A similar trend might be expected for a single magnetar exhibiting luminosity variations. A higher luminosity should correspond to a larger twist, hence a harder spectrum, as has been reported for 1RXS J170849.0–400910 (Rea et al. 2005; Campana et al. 2007). A higher luminosity should also in general correspond to a larger magnitude of the spin-down rate. However, decoupling between the torque and the luminosity can occur because the torque is most sensitive to the current flowing on a relatively narrow bundle of field lines that are anchored close to the magnetic pole. For a single source, whether an X-ray luminosity change will be accompanied by a torque change depends on where in relation to the magnetic pole the source of the enhanced X-rays is located.

The Thompson et al. (2002) model can also explain properties of the pulse profiles of magnetars. According to the model, several effects can influence the pulse shape, generate subpulses, and/or increase the energy dependence of the pulse profile. In addition, an increase in the twisting angle of the magnetic field increases multiple scattering and increases the optical depth to resonant scattering, which can simplify the pulse shape. This is one of the two proposed explanations for the sudden simplification of the pulse profile of SGR 1900+14 after its dramatic giant flare (Woods et al. 2001), the other explanation being the sudden elimination of the nonaxiymmetric components of the magnetospheric currents (Thompson et al. 2002).

4.3. Possible Physical Interpretations for 4U 0142+61

In this paper, we have shown that the pulsed flux of 4U 0142+61 has increased on a timescale of a few years, and we have found simultaneous slow pulse profile evolution in the 2–4 keV band, which may be recovering from some event that occurred prior to 2000 but after 1997, possibly in the interval between 1998 August and 1999 July. We have also found evidence, as first suggested by Morii et al. (2005), that there was a timing glitch in that same interval, although we cannot confirm its existence. Can the magnetar model explain these observations?

The energy dependence of the pulse profile evolution is puzzling. As described above, in the twisted magnetosphere model of Thompson et al. (2002), the nonthermal emission in an AXP is the result of magnetospheric scattering of surface thermal photons. If the surface emission angular pattern were changing, the nonthermal angular pattern should as well. That we do not observe
comparable pulse profile changes in the 6–8 keV band for 4U 0142+61 is thus puzzling. One possibility is that the seed thermal emission is not changing appreciably, but the scattering currents in the outer regions of the magnetosphere, where the cyclotron energy is lower, are changing, while the inner currents are not. This could arise if there is evolution in the field configuration closer to the magnetic poles, with relatively little evolution closer to the magnetic equator. Why variations in the field configuration should be geographically localized, however, is unclear.

The increase in the pulsed flux over a timescale similar to that of the profile evolution is apparently accompanied by a softening of the spectrum (Gonzalez et al. 2007). As discussed above, the putative 1998/1999 glitch may have deposited a large amount of energy in the crust, which only started to be radiated away in 2002. The energy released would have had to have been large, ~10^{45} ergs (Hirano et al. 1997). Such a thermal energy release could be influencing the pulse profile as well, although some change in profile would be expected in the hard band too, which is not observed. Moreover, such an increase has not been observed following the glitches in 1E 2259+586 or 1RXS 170849.0–400910, although this could be a result of smaller total energy releases.

Alternatively, the increase in pulsed flux seen in 4U 0142+61 between 2002 and 2005 could be explained by the twisted magnetosphere model. In this framework, there are two possibilities: (1) a slow increase in the twist of the magnetic field lines in the magnetosphere or (2) a slow decrease in the twist angle.

In the first possibility, the observed increase in the pulsed flux could be an extreme case of the 1E 1048–5937 flares, i.e., a slow twisting of the magnetic field lines in the suggested interpretation of Gavriil & Kaspi (2004). This explanation is only valid if the total flux, which remains to be determined with an imaging telescope, is increasing as well. How this would be related to the putative 1998/1999 event is unclear; any flux enhancement that occurred then would have largely decayed away by 2000. In any case, for an increase in the twist angle, one expects a spectral hardening (Thompson et al. 2002). We do not observe this. Also for an increase in the twist angle, at least naively, the twisted magnetosphere model predicts an increase in torque as the flux rises (Thompson et al. 2002). From Table 2, the postglitch ephemeris \( \dot{\nu} \) is positive, meaning \( \dot{\nu} \) is increasing; i.e., the magnitude of the pulsar’s spin-down rate is decreasing, the opposite of what is expected for a flux increase, unless the magnetospheric currents causing the torque are flowing only in the small polar cap region. Finally, if the slow increase in pulsed flux were caused by a slow magnetospheric twisting, the decrease in the size of the Fourier components of order higher than unity in the low-energy band could be interpreted as a simplification of the pulse profile due to an increase in the scattering in the magnetosphere. However, the most extreme case of a pulse profile simplification, which was reported in SGR 1900+14, happened equally in all bands following a dramatic increase in the scattering after a giant flare (Woods et al. 2001; Thompson et al. 2002). The phenomenon that we have observed, by contrast, is restricted to the softer energies.

In the previous paragraph, we mentioned that the increase in the pulsed flux and the gradual changes in the pulse profile may indicate stress buildup caused by an increase in the twist angle in the magnetosphere. The pulse profiles of Cycles 2 and 10 are very similar, indicating that the pulse profile of Cycle 2 may also be showing signs of the same kind of stress buildup. Under these assumptions, if an event occurred in the gap following Cycle 2, it is reasonable to expect a similar event to follow Cycle 10. Indeed, in 2006 April, less than 2 months after the end of Cycle 10, the pulsar appears to have entered an extended active phase: a single burst accompanied by a pulse profile change was detected from the pulsar on April 6 (Kaspi et al. 2006). A series of four bursts was later detected on June 25 (Dib et al. 2006), and a larger burst was detected on 2007 February 7 (Gavriil et al. 2007). A detailed paper on these events is currently in preparation. If they are indeed due to a stress release following several years of slow magnetospheric twist, then the causes of the softening of the spectrum and of the decrease in the magnitude of the pulsar’s spin-down are unclear.

The second possibility in the framework of the twisted magnetosphere model is that the observed increase in the pulsed flux is accompanying a slow decrease in the twist angle of the magnetic field lines in the magnetosphere. This explanation is only valid if the total flux is decreasing. If the total flux were falling with the pulsed fraction rising, the observed spectral softening could be consistent with naive untwisting expectations, as would the decreasing spin-down rate. Indeed, an anticorrelation between total flux and pulsed fraction was observed by Tiengo et al. (2005) for 1E 1048.1–5937, supporting this possibility. However, the problem of why the pulse profile is evolving at low, but not high, energies remains.

### 4.4. Other Wavelengths

4U 0142+61 is truly a multiwavelength AXP. It is known to pulsate in the optical band (Kern & Martin 2002; Dhillon et al. 2005), and it has been detected in the near-IR (Hulleman et al. 2004), in the mid-IR using Spitzer (Wang et al. 2006), and in hard X-rays (Kuiper et al. 2006; den Hartog et al. 2006).

The origin of the emission at these other wavelengths remains unclear, although some models have been proposed. In hard X-rays, Thompson & Beloborodov (2005) argue that the emission either is due to bremsstrahlung photons emitted by a thin surface layer or is due to synchrotron emission originating from the region in the magnetosphere where the electron cyclotron energy is in the keV range. The near-IR and optical emission is thought to be magnetospheric (Eichler et al. 2002), while the mid-IR emission is suggested to be due to a passive fallback disk (Wang et al. 2006).

Looking for correlations between the X-rays and the emission in other wavelengths may serve as tests of emission models, as correlations between X-ray and near-IR fluxes have sometimes been observed. For example, a correlation in the decays of the X-ray and near-IR fluxes in 1E 2259+586 was observed following the 2002 outburst (Tam et al. 2004); a similar correlation was reported for XTE J1810–197 (Rea et al. 2004). However, in other instances, the two fluxes were not correlated, as for 1E 1048–5937 (Gavriil & Kaspi 2004; Mereghetti et al. 2004; Durant et al. 2004). In 4U 0142+61, reported variations in the IR are not seen contemporaneously in our X-ray data and are on timescales much shorter than that of the X-ray variation reported here (Hulleman et al. 2004; Durant & van Kerkwijk 2006).

Wang et al. (2006) observed mid-IR emission from 4U 0142+61, which they argue is associated with a passive fallback disk irradiated by the central X-ray pulsar. If this is the case, then if 4U 0142+61’s X-ray flux is increasing, one expects a corresponding increase in the disk emission. It is thus important to establish the behavior of the total flux, in addition to that of the pulsed flux reported on here.

The possible presence of a disk suggests that if a sudden, impulsive outburst occurred in the gap, the energy released must have been significantly smaller than the disk binding energy, after accounting for the disk thickness. For a central pulsar mass of \( M_{\text{psr}} \approx 1.4 M_{\odot} \), a uniform disk of mass \( M \approx 3 M_{\odot} \), and inner and outer radii \( R_1 \approx 3 R_{\odot} \) and \( R_2 \approx 10 R_{\odot} \) (Wang et al. 2006),
the disk binding energy is \(\sim 4 \times 10^{42}\) ergs. Since the X-ray luminosity of the source (\(\sim 10^{35}\) ergs s\(^{-1}\)) integrated over a period >5000 yr is much larger than the binding energy of the observed disk, one must assume that when the source is not undergoing an outburst, the disk is in an equilibrium state where the rate of energy absorption is balanced by the rate of disk emission. Assuming this equilibrium cannot hold on the timescale of a sudden outburst, then IR observations of the disk provide an upper limit of \(4 \times 10^{42}/f\) ergs on the energy released in a possible outburst in the gap, where \(f\) is the fraction of the solid angle occupied by the thickness of the disk. For \(f = 0.01\), this upper limit is 3 orders of magnitude larger than the total energy released during the flares of 1E 1048–5937 (Gavriil & Kaspi 2004). It is also 5 orders of magnitude larger than the energy released during the first day of the 1E 2259+586 outburst (Wood et al. 2004). Thus, an event in the gap of the magnitude of either the flares or the outburst occurring could have affected the disk, but seems unlikely to have disrupted it. For \(f = 0.01\), the upper limit is also of the same magnitude as the energy released in either the SGR 1900+14 or the SGR 0526-66 giant flares (Mazets et al. 1999). This suggests that there have been no events of the magnitude of the giant SGR flares since the putative disk’s formation. Given that we have witnessed three giant SGR flares, each from a different source since 1979, and none from AXPs, this suggests that AXPs do not exhibit giant flares. This would suggest an interesting distinction between SGRs and AXPs: if there is an evolutionary link between the two, the AXP phase must come first, unless a debris disk can re-form following a giant flare.

The mid-IR emission has also been interpreted as an active fallback disk in which the pulsar is accreting in a propeller mode. In this case, the dipole field strength of the pulsar is typical of conventional radio pulsars, i.e., \(\sim 10^{12}\) G (Ertan et al. 2007), although the surface field strength is in the magnetar range, because of higher order multipoles. In this model, the X-rays arise from propeller accretion. Without detailed models of the spectra and of the pulse shapes expected in this model, we cannot interpret our observations in this framework. Nevertheless, one might expect a torque change with luminosity in this model. For 4U 0142+61, as noted in § 4.3, the magnitude of the torque is decreasing while the pulsed flux is increasing. If propeller accretion is occurring, then the total flux should be decreasing; this can be checked (Gonzalez et al. 2007). We note that evidence against such a torque/luminosity correlation has been presented by Gavriil & Kaspi (2004) for a different AXP.

5. SUMMARY

Our continuing RXTE monitoring program has revealed a possibly new AXP variability phenomenon: 4U 0142+61 exhibited a slow but steady increase in its pulsed flux between 2002 May and 2004 December, such that it has risen 36% ± 3% over 2.6 yr in the 2–10 keV band. This is accompanied by a softening of the spectrum (Gonzalez et al. 2007). Quasi-simultaneously, the pulse profile, which comprises two peaks with different spectra, has been evolving since 2000. In particular, the dip of emission between the two peaks has been rising since 2002, as if it is returning to its pre-2000 morphology, in which there was no clear distinction between the peaks. The profile evolution translates to a reduction of the power in the Fourier harmonics of order higher than 1 since 2000. This is in contrast with the pulsed flux, which seems to be moving away from the pre-2000 value. The evolution in the pulse profile is seen in the 2–4 keV band, but not in the 6–8 keV band, presenting an interesting puzzle for the twisted magnetosphere model for magnetars. Intriguingly, Morii et al. (2005) have suggested the pulsar suffered a glitch just before 2000, on the basis of a single discrepant ASCA period measurement. Our phase-coherent timing using RXTE demonstrates that a glitch is plausible but not necessary to explain the data, but our pulse profile evolution analysis provides new evidence that such an event occurred.

Physical interpretations that described well other observed long-term changes in AXP emission (such as outburst afterglow or flux changes caused by an increased twist in the magnetosphere) do not explain all the phenomena that we have observed. Most of our observations could be explained by the twisted magnetosphere model if the total flux of 4U 0142+61 is actually decreasing. This would indicate a slow untwisting in the magnetosphere. Alternatively, if the total flux is increasing, a slow increase in the twist angle in the magnetosphere can account for the pulse profile simplification and for the post–Cycle 10 events, but the changes in the spin-down rate and the softening of the spectrum would remain unexplained. Finally, the data could be explained by energy release following an energy deposition, perhaps due to a glitch that occurred in the crust of the star sometime during the post–Cycle 2 gap, although the energy deposited would have had to have been large. No matter what, the absence of profile evolution at high energies remains a puzzle.

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