VARIATION OF SPECTRAL AND TIMING PROPERTIES IN THE EXTENDED BURST TAILS FROM THE MAGNETAR 4U 0142+61

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ABSTRACT

Extended emission episodes with an intensity above the preburst level are observed following magnetar bursts from a number of soft gamma repeaters and anomalous X-ray pulsars (AXPs). Such extended tail emissions were observed following two events detected from AXP 4U 0142+61. We investigated in detail the evolution of spectral and temporal properties during these two tail segments using Rossi X-ray Timing Explorer/Proportional Counter Array observations, and report distinct variations in the spectral and temporal behavior throughout the tails. In particular, in both cases we observed a sudden enhancement of the pulsation amplitude in conjunction with bursts and a slow decline of X-ray emission (cooling) during the tail. We suggest that an inefficiently radiating trapped fireball formed during the burst, which can heat up the stellar surface, is able to explain the tail properties and its energetics. We also present the episodic detection of absorption and emission features during tails. One possible mechanism that has been proposed to give rise to such spectral lines is the proton/ion cyclotron resonance process, which has been suggested as offering a valuable tool in probing the complex magnetic field of magnetars.

Key words: pulsars: individual (4U 0142+61) – stars: magnetars – stars: neutron – X-rays: stars

1. INTRODUCTION

Magnetars are a small group of isolated neutron stars possessing exceptionally strong surface magnetic fields in the range \(10^{15} - 10^{18}\) G (Duncan & Thompson 1992). These systems have relatively long spin periods ranging between 0.3 and 12 s, and emit X-rays in the luminosity range of \(10^{33} - 10^{36}\) erg s\(^{-1}\). Soft gamma repeaters (SGRs) are a sub-class of magnetars and are characterized by emitting high intensity and repeating bursts in the soft gamma-ray band. Such bursts have peak luminosities of \(10^{37} - 10^{39}\) erg s\(^{-1}\), lasting typically for a duration of \(\sim 0.1\) s (Göğüş et al. 2001). In their active phases, SGRs can emit a few to sometimes thousands of bursts. From energetics and morphological perspectives, SGR bursts are broadly divided into three categories. The typical short bursts have isotropic energies up to \(10^{43}\) erg and last for a small fraction of a second (Göğüş et al. 2001). The intermediate events are more energetic, having isotropic energies of \(10^{31} - 10^{33}\) erg and lasting for few seconds (Ibrahim et al. 2001; Mereghetti et al. 2009; Göğüş et al. 2011). The giant flares are extremely energetic events emitting isotropic energies of \(10^{44} - 10^{46}\) erg and lasting for hundreds of seconds (Mazets et al. 1979; Hurley et al. 1999, 2005). Magnetar bursts at all scales are generally explained by the magnetar model (Duncan & Thompson 1992), which suggests that the fracturing of the neutron star crust at a rather localized or global scale releases a build-up of magnetic stress in the solid crust and gives rise to these sudden flashes of energy release (Thompson & Duncan 1995). Alternatively, such bursts can also be explained by magnetic reconnection events in the highly magnetized neutron star environments (Lyutikov 2003, 2015).

Anomalous X-ray pulsars (AXPs) are also members of the magnetar family and exhibit SGR-like bursts (see for e.g., Gavriil et al. 2002; Kaspi et al. 2003). The AXP bursts usually occur less frequently, and are energetically similar to or a bit weaker than the typical short SGR bursts (Gavriil et al. 2004). Of the twelve confirmed AXPs, six sources have shown SGR-like bursts (see Olausen & Kaspi 2014 and the online list of magnetars\(^1\) for their bursting behavior). 1E 2259+586 is currently the most prolific AXP in bursting; 80 bursts were detected in a single Rossi X-ray Timing Explorer (RXTE) observation in 2002 (Gavriil et al. 2004). Although these bursts resemble SGR bursts in many respects, there were some notable differences; for example, the more energetic AXP bursts have the harder spectra whereas SGR burst spectra tend to get softer with increasing energy (Gavriil et al. 2004).

The group of intermediate energy events emerged with leading bursts, followed by prolonged emission episodes with intensities that were clearly above the preburst emission level. These so-called bursts with extended tails have been detected in a number of magnetars: SGR 1900+14 (Ibrahim et al. 2001; Lenters et al. 2003), SGR 1806–20 (Göğüş et al. 2011), and SGR J1550–5418 (Kuiper et al. 2012; Şaşma Muş et al. 2015). The extended tails last for about a few tens of seconds to thousands of seconds. The energy emitted during such extended tails is a small fraction of the total energy of the leading bursts (Lenters et al. 2003; Göğüş et al. 2011). However, recent investigations of SGR 1550–5418 bursts with extended tails indicate that the energetics of the tails are not always linked; many bright bursts do not exhibit extended tails, whereas those observed tails were preceded by much lower intensity bursts (Şaşma Muş et al. 2015). Detailed studies of the extended tails from all these sources yield distinct timing and spectral evolution properties during these phases (Ibrahim et al. 2001; Lenters et al. 2003; Şaşma Muş et al. 2015). The tail spectra are generally described with a thermal shape (using a black-body function with temperature, 1.5–4 keV) and exhibit a cooling trend. This can be explained by the cooling of the thermal component on the neutron star surface, which was heated up by the preceding burst.

4U 0142+61 is currently the brightest persistent AXP source (see Table 2 of the online magnetar catalog (see footnote 1) and references therein; Patel et al. 2003). This source is spinning with a period of 8.7 s and has a period derivative of

\(^{1}\) http://www.physics.mcgill.ca/~pulsar/magnetar/main.html
0.2 × 10^{-11} \text{s}^{-1}, which implies a surface dipole magnetic field of strength 1.3 × 10^{14} \text{G}. RXTE monitored this source for more than a decade. Its spin frequency generally showed a high degree of stability (Gavriil et al. 2002; Dib et al. 2007), although there are some indications of a glitch (Mori et al. 2005). This source entered an active phase in 2006 March, when remarkable changes in temporal and spectral properties were observed, including, for the first time, several bursts from this particular AXP (Gavriil et al. 2011). Gavriil et al. (2011) studied the spectral and temporal characteristics of these bursts and found that their \(T_{90}\) durations (Kouveliotou et al. 1993) spanned a very wide range, from 0.4 to 1757 s. For each burst, they extracted a single X-ray spectrum considering its entire \(T_{90}\) interval. They found that the spectra of five bursts were well represented with a single black-body model, but reported unusual signatures of spectral emission features on top of the single component black-body model for the sixth burst. The authors concluded that a broad spectral feature at \(\sim 14\) keV, along with a narrow feature at \(\sim 8\) keV, were required to explain the spectrum well, and suggested time-dependent spectral variations by employing an unusual time-resolved spectral investigation technique (see Figure 4 in Gavriil et al. 2011). They showed that the pulse profiles of the source in the observations comprising the bursts exhibit significant changes, with additional pulse peaks. Following the bursts, the 4–20 keV pulse flux during the decay of the bursts increased (Gavriil et al. 2011). The authors also performed a long-term timing investigation, provided a phase coherent timing solution, and uncovered a likely anti-glitch (sudden spin-down event) in conjunction with active phase.

Motivated by the indications of the spectral and temporal variations during the tails of these bursts, and to better understand the nature of reported spectral features, we investigated the bursts from 4U 0142+61, particularly focusing on the extended tail emission episodes. We describe the RXTE data used in Section 2 and explain the method of analyzing the extended tails in Section 3. In Section 3, we also present the results of our time-resolved spectral and timing analyses during the tails. The physical implications of our results and the comparison with previous observations are then discussed in the final section.

2. OBSERVATION

The RXTE routinely monitored 4U 0142+61 starting from 2000 until the end of the mission at the end of 2011. Here, we only focused on the observations comprising the bursts reported by Gavriil et al. (2011), with data collected using the Proportional Counter Array (PCA; Jahoda et al. 2006) on board RXTE. The PCA consisted of five proportional counter units (PCUs), each of which was made up of one Propane veto, three Xenon, and one Xenon veto layer. The PCA operated in the energy range 2–60 keV and had a large effective area of \(\sim 6500 \text{cm}^2\), which made it a highly sensitive instrument. For our analysis, we used data in Good-Xenon mode because it offers an excellent time resolution of 1 \(\mu\text{s}\) and 256 channel spectral capability. The data was analyzed using the relevant HEASOFT v6.16 tools and the CALDB version 20120110. For timing analysis, we converted the photon arrival times to that at the solar system barycenter. IDL version 8.5 was used extensively for the purposes of timing analyses and plotting. For this analysis, we concentrated on the bursts on 2006 June 25 (bursts 2, 3, 4, 5 in Gavriil et al. 2011), which we refer to as event A, and the burst on 2007 February 07 (burst 6 in Gavriil et al. 2011), referred to as event B hereafter.

3. ANALYSIS OF EXTENDED TAILS

We identified the extended tail as the interval following a burst during which the emission is clearly greater than the preburst level. The extended tails following the bursts in event A and event B continue until the end of the observing window and correspond to a duration of 463 and 1600 s, respectively. Figures 1 and 2 show the light curves for the events A and B, respectively. The bottom four panels of each of the two plots show the energy-resolved light curves for the energy ranges 2.0–5.0, 5.0–10.0, 10.0–20.0, and 20.0–30.0 keV. These light curves are binned with a 2 s time resolution for illustration purposes. However, burst identifications and tail segmentations were done with much finer time resolution, as we discuss later. The top panels of each plot show the zoomed-in lightcurve of the bursts spanning an interval between 0.5 s before the burst and 100 s after. Periodic modulations at the spin period can be
observed during the tail of both events, especially in the zoomed-in panels. We investigated the spectral evolution of events with extended emission by separating them into different time segments: We inspected the light curves of these events using different time resolutions and have seen clear distinct features in 31.25 ms binned light curves. We used these features and pulse amplitude variations as a guideline to separate them into different segments. Finally, we fine-tuned the borders between the regions, especially during the first ∼100 s of the events, by inspecting the variations in the spectra and divided event A in 10 different regions and event B in 13 different regions. The events start with a significantly high intensity peak, which we call a burst, followed by a gradually decaying enhanced emission region. We do not exclude any possible weak burst features observed at 31.25 ms time resolution during the extended tail because they could not be significantly distinguished from noise and did not perceptibly affect the properties of the tail segments. Although the light curve of event A is fairly simple (a distinct burst + segments with enhanced emission), the light curve of event B consists of morphologically and spectrally different regions that we call gray and oscillation regions. Gray regions are the transition interval between the burst and oscillation phases; the oscillation region follows the gray zone and has clearly seen oscillations at the spin frequency of the source (see the top panel of Figure 2). The durations and corresponding counts of each segment during these two events are exhibited in Table 1. The total count given in each segment is background subtracted.

### 3.1. Spectral Analysis

We extensively investigated the variation of spectral properties throughout the extended tail emission episodes, particularly on short timescales, to probe any changes in its continuum and the presence of line features. The spectrum for each segment during the tail was extracted and spectral fits were performed in the energy range of 2.5–30 keV using XSPEC software version 12.9. We used an interstellar neutral hydrogen column density of $7.3 \times 10^{21}$ cm$^{-2}$ (Weng et al. 2015), which was kept constant in spectral fits. The background spectra were extracted from 350 and 438 s long data segments in the preburst data of events A and B, respectively. Each spectrum was accumulated from all layers of operating PCUs, and then grouped so that each spectral bin would include at least 20 counts. We fitted the continuum

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### Table 1

| Event | Observation Date | Segment | Total\(^a\) Count | Segment\(^b\) Duration (s) | Active PCUs |
|-------|------------------|---------|-------------------|--------------------------|-------------|
| A     | 2006 Jun 25      | Burst   | 191.29            | 1.0                      | 0, 2, 3     |
|       |                  | Tail 1  | 1780.57           | 50.0                     |             |
|       |                  | Tail 2  | 947.57            | 50.0                     |             |
|       |                  | Tail 3  | 737.57            | 50.0                     |             |
|       |                  | Tail 4  | 509.57            | 50.0                     |             |
|       |                  | Tail 5  | 469.82            | 50.0                     |             |
|       |                  | Tail 6  | 1035.57           | 50.0                     |             |
|       |                  | Tail 7  | 530.57            | 50.0                     |             |
|       |                  | Tail 8  | 754.57            | 50.0                     |             |
|       |                  | Tail 9  | 791.82            | 50.0                     |             |
| B     | 2007 Feb 07      | Burst   | 254.15            | 0.125                    | 0, 2        |
|       |                  | Gray 1  | 535.91            | 0.75                     |             |
|       |                  | Gray 2  | 789.37            | 2.16                     |             |
|       |                  | Gray 3  | 360.62            | 2.56                     |             |
|       |                  | Osc     | 3201.84           | 42.06                    |             |
|       |                  | Tail 1  | 4993.12           | 200.0                    |             |
|       |                  | Tail 2  | 3069.12           | 200.0                    |             |
|       |                  | Tail 3  | 2161.12           | 200.0                    |             |
|       |                  | Tail 4  | 2147.12           | 200.0                    |             |
|       |                  | Tail 5  | 2544.12           | 200.0                    |             |
|       |                  | Tail 6  | 2396.12           | 200.0                    |             |
|       |                  | Tail 7  | 1985.12           | 200.0                    |             |
|       |                  | Tail 8  | 1748.12           | 200.0                    |             |

**Notes.**

\(^a\) Background subtracted total count obtained for each spectrum.

\(^b\) Duration as considered for spectral and timing analysis (see text).
spectra using a variety of thermal and non-thermal models, as well as their combinations. We now present the details of our investigations for both events A and B.

3.1.1. Event A

We divided the ~460 s long extended tail emission into 50 s segments to perform time-resolved spectral analysis. We provide the details of the spectral analysis results in Table 2 and present the time evolution of model parameters in Figure 3. The burst spectrum was fit well with a single black-body model (Figure 4), temperature $kT = 5.64^{+0.83}_{-0.65}$ keV ($\chi^2 = 0.53$ for 10 degrees of freedom, dof). A single non-thermal model (power law) yielded a worse fit, giving a $\chi^2 = 1.10$ for the same dof. Using the black-body fit results, we obtained the unabsorbed burst flux in the 2.5–30 keV as $1.6 \pm 0.2 \times 10^{-9}$ erg s$^{-1}$ cm$^{-2}$, which corresponds to a total burst luminosity of $2.3 \times 10^{36}$ erg s$^{-1}$ (assuming the distance to the source as 3.5 kpc; Durant & van Kerkwijk 2006). The tail spectra (except for the second tail segment) were also best described by a single black body with the temperature showing a smooth decline trend: The black-body temperature was $3.87^{+0.16}_{-0.15}$ keV just following the burst and decreased to $1.83^{+0.13}_{-0.12}$ keV at the end of the extended emission phase. We also estimated the radii of the black-body emitting region, which varied from 0.11 ± 0.01 to 0.23 ± 0.03 km during the extended tail in an irregular manner (see Figure 3). The spectral best fits to the different time segments are shown in Figure 4. Adding a power law to the black body does not provide any improvement to the reduced chi-square of the fits. We tested the temporal evolution of the flux and black-body temperature using the power law model. This model resembles the general decline trend, even though it yields poor fit statistics (reduced chi-square values greater than three). The power law indices for the flux and temperature decay were $-0.568 \pm 0.018$ and $-0.182 \pm 0.014$, respectively. Note that these indices matched closely with the reported values for other bursts from various sources (Ibrahim et al. 2001; Feroci et al. 2003; Lenters et al. 2003) and also with the theoretical expectations (Thompson et al. 2002; Lenters et al. 2003).

It is important to emphasize the fact that the spectrum of the second segment after the burst (Tail 2) was fitted with a single black-body model with a statistically acceptable $\chi^2 = 0.99$ for 60 dof. However, there were clear signatures of spectral intensity deficits around 4.5 and 6.5 keV (see Figure 4). We modeled the spectrum of this segment with a combined model of a black-body function and two (Gaussian) absorption lines. This model improves the fit statistics, $\chi^2 = 0.66$ for 56 dof, and yields the centroid energies of $4.56 \pm 0.13$ and $6.70^{+0.15}_{-0.17}$ keV for the two absorption features.

Next, we needed to check whether the addition of Gaussian absorption lines was statistically significant. In general, the F-test is employed to test the statistical significance of the addition of parameters to an existing model. However, in the

| Segment | $kT$ (keV) | Radius (km) | $E$ (keV) | Norm | $E$ (keV) | Norm | $10^{-9}$ erg s$^{-1}$ cm$^{-2}$ | $\chi^2$ (dof) |
|---------|-----------|------------|----------|------|----------|------|-------------------------------|--------------|
| Burst   | $5.64^{+0.83}_{-0.65}$ | $0.15^{+0.02}_{-0.01}$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | $1.550^{+0.209}_{-0.199}$ | 0.53 (10) |
| Tail 1  | $3.87^{+0.16}_{-0.15}$ | $0.11^{+0.01}_{-0.01}$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | $0.218^{+0.012}_{-0.011}$ | 1.31 (58) |
| Tail 2  | $2.17^{+0.13}_{-0.12}$ | $0.23^{+0.03}_{-0.01}$ | $4.56^{+0.13}_{-0.13}$ | $-0.00139^{+0.00016}_{-0.00037}$ | $6.70^{+0.15}_{-0.17}$ | $-0.00089^{+0.00022}_{-0.00022}$ | $0.082^{+0.005}_{-0.005}$ | 0.66 (56) |
| Tail 3  | $2.55^{+0.20}_{-0.18}$ | $0.13^{+0.02}_{-0.01}$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | $0.061^{+0.006}_{-0.006}$ | 1.21 (61) |
| Tail 4  | $1.96^{+0.15}_{-0.14}$ | $0.18^{+0.03}_{-0.02}$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | $0.040^{+0.004}_{-0.004}$ | 1.53 (57) |
| Tail 5  | $2.14^{+0.19}_{-0.17}$ | $0.15^{+0.02}_{-0.01}$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | $0.042^{+0.005}_{-0.004}$ | 1.29 (53) |
| Tail 6  | $2.91^{+0.18}_{-0.17}$ | $0.13^{+0.01}_{-0.01}$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | $0.096^{+0.007}_{-0.007}$ | 0.85 (60) |
| Tail 7  | $1.95^{+0.14}_{-0.13}$ | $0.19^{+0.02}_{-0.01}$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | $0.041^{+0.004}_{-0.004}$ | 1.29 (58) |
| Tail 8  | $1.99^{+0.14}_{-0.13}$ | $0.20^{+0.03}_{-0.02}$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | $0.053^{+0.004}_{-0.004}$ | 0.69 (62) |
| Tail 9  | $1.83^{+0.13}_{-0.12}$ | $0.21^{+0.03}_{-0.05}$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | $0.041^{+0.003}_{-0.003}$ | 1.12 (63) |

Notes. All parameter errors quoted here are 1σ confidence errors.

* Unabsorbed flux in 2.5–30 keV in units of $10^{-9}$ erg s$^{-1}$ cm$^{-2}$.

Figure 3. Variation of best-fit spectral parameters of the burst and extended tail in event A. (a) The source intensity of the event with 1 s binning. (b) The evolution of the black-body temperature. (c) The radius of the corresponding black-body emitting region. (d) The variation of the 2.5–30 keV unabsorbed flux during the burst and tail segments. All errors shown here are 1σ errors on the parameters (the errors on the flux values are relatively too small to discern in the plot).
case of a Gaussian line this test is not applicable. This is clearly described by Protassov et al. (2002), who noted that the F-test is applicable only when the null values of the additional parameters are not coinciding with any boundary of the possible values of the parameters, which is not the case for Gaussian models. Hence, we followed a prescription put forward by Protassov et al. (2002) to test the significance of adding a Gaussian component. First, we fit the data with a seed model (black body) and a test model (black body + two Gaussian line components) and calculated the observed F-statistic value. However, because the distribution of the F-statistic in our case is unknown we performed extensive simulations to determine the F-statistic distribution. We assumed the best-fit seed model to be the intrinsic model describing the spectrum (i.e., our null hypothesis was that the seed model is sufficient to describe the spectra, and no additional parameters were required). Using the best-fit parameters of the seed model, we then generated 2000 simulated spectra using the fakeit tool in XSPEC. Each simulated spectrum was then fitted with the seed and the test model, and in each case the F-statistic value was calculated. The F-distribution was constructed from the resulting 2000 F-statistic values. Our null hypothesis is that no line is present and the alternative hypothesis states that some line components

Figure 4. Spectral fit of segments corresponding to event A. The label at the top of each panel denotes the segment that the corresponding spectrum was generated from. Each panel also shows the best-fit spectral model in the 2.5–30 keV band.
are required to describe the model sufficiently well. The null-hypothesis probability is then given by the probability of obtaining an F-statistic value equal to or larger than the measured F-statistic value purely due to noise. We obtained this probability by integrating the F-distribution above the measured value and call this null-hypothesis probability the p-value. If the null-hypothesis probability is less than a certain threshold, in this case $2.7 \times 10^{-3}$ ($3\sigma$), we reject the null hypothesis in favor of the alternative hypothesis. This means that if the null-hypothesis probability is less than the threshold value we conclude that the test model is favored relative to the seed model.

From our simulations, the probability that the improvement of the chi-square on adding two Gaussian absorption lines to a single black-body component was due to noise only was obtained to be less than $5 \times 10^{-4}$. This means that two absorption lines are required to describe the spectrum corresponding to the segment Tail 2 well. The spectrum corresponding to Tail 3 also shows signatures of absorption features, however from our simulations we obtained the null-hypothesis probability of $4.7 \times 10^{-3}$ for the measured F-statistic to originate purely from noise. For the spectra during the later part of the tail, adding single or double absorption lines does not significantly improve the model fitting. It should be noted that Tail 6 corresponded to a lower intensity burst, and interestingly the black-body temperature corresponding to this segment shows a significant increase and the black-body radius shows a dip, as also observed for the primary burst.

### 3.1.2. Event B

We divided the $\sim 1600$ s long tail into time segments of 200 s. As described for event A, we again extracted spectra from each time segment as well as for the leading burst, gray, and oscillation intervals, and modeled them with thermal and non-thermal emission models. In Table 3 we list the details of the spectral fit results for event B and in Figure 5 we present the evolution of the best-fit spectral parameters during this event. The burst spectrum in this case is well described with a non-thermal single power law model (Figure 6). The fit corresponds to $\chi^2_r$ of 0.75 for 10 dof. A single black-body model fit to the burst spectrum is unacceptable with $\chi^2_r$ of 2.17 for 10 dof. The 2.5–30 keV unabsorbed flux for the burst is $25.4 \pm 2.0 \times 10^{-9}$ erg s$^{-1}$ cm$^{-2}$, which corresponds to a burst luminosity of $3.7 \times 10^{37}$ erg s$^{-1}$ assuming isotropic emission.

The spectra during the transitional (gray) intervals and the extended tail were best fitted using a black-body model, but in some cases single or multiple absorption and emission lines were additionally required. The black-body temperature exhibited a smooth cooling trend, with its value varying from $6.65^{+0.50}_{-0.44}$ to $1.48^{+0.09}_{-0.05}$ keV. The corresponding radii of the black-body component varied from 0.16 $\pm$ 0.02 to 0.34 $\pm$ 0.03 km and showed slightly different behavior; it remained around 0.23 km during the first half of the tail, and around 0.32 km during the rest (see Figure 5). For the gray region, the 2.5–30 keV unabsorbed flux ranged from $9.25 \pm 0.60 \times 10^{-9}$ to $1.59 \pm 0.14 \times 10^{-9}$ erg s$^{-1}$ cm$^{-2}$, and during the extended tail the flux decayed from $0.165 \times 10^{-9}$ to $0.033 \times 10^{-9}$ erg s$^{-1}$ cm$^{-2}$. Again, assuming isotropic emission, we found corresponding luminosity varying from $2.46 \times 10^{35}$ to $0.48 \times 10^{35}$ erg s$^{-1}$ during the extended tail emission phase. Here we also fit the temporal evolution of the flux and black-body temperature with the power law model, and obtained consistent power law indices of $-0.720 \pm 0.006$ and $-0.190 \pm 0.002$, respectively, again despite the rather poor fit statistics. Next, we give a detailed description of the spectral modeling of the segments falling in the gray, oscillation, and extended tail intervals, in particular, when more complex spectral models were needed to describe their spectra. The spectra corresponding to the various time segments along with the best-fit models are shown in Figure 6.

The spectrum of the Gray 1 segment just following the burst was best described using a single black-body model with a temperature of 6.65 keV. Note that this spectral shape is quite similar to the burst spectrum in event A. The following segment, Gray 2, was much more complex and we modeled its spectrum using a black body with a combination of absorption and emission line features: Two absorption lines at 6.56 and 10.54 keV on top of the base black-body model fitted the spectra yields $\chi^2_r$ of 1.99 for 24 dof. Adding an emission line at 13.42 keV to this model improves $\chi^2_r$ to 1.35 for 22 dof (see Figure 6). We then examined the statistical significance of the addition of these lines using the same technique as described previously for event A. In this case, our seed model was a single black body as before, and the test model was a black body + two absorption lines + an emission line. We performed the simulation by using the best-fit single black-body model as the intrinsic model and then fitted the simulated spectra using the seed and test models. F-statistic values were calculated for the seed and test models for each simulated spectra and the F-distribution was constructed. We compared the measured F-statistic value against the constructed F-distribution and obtained a p-value less than $5 \times 10^{-4}$, which strongly favors the addition of the Gaussian line components. We also checked the significance of adding the emission line along with a black body and the two absorption lines. Again from our simulations, we find that the null-hypothesis probability turns out to be $1.6 \times 10^{-3}$ when taking the black body + two absorption lines as the seed model and the black body + two absorption lines + an emission line as the test model. The spectrum corresponding to Gray 3 did not show any distinct absorption features, but was well described by a black body along with an emission line at 13.65 keV (Figure 6). As before, we calculated the significance of adding this line from the simulation by taking the single black body as the seed model and the black body with an emission line as the test model. We obtained a p-value (see previous section) of $7 \times 10^{-4}$, rendering the addition of the Gaussian parameters highly significant. The succeeding segment, Oscillation (Osc), displayed a similar spectrum and was best fit using a black-body model with an emission line at 13.89 keV (Figure 6). We obtained the null-hypothesis probability (i.e., the p-value) to be less than $5 \times 10^{-4}$, thereby strongly favoring the test model.

The extended tail began following the Oscillation segment. The first segment, Tail 1, showed a complex spectrum with multiple line features. A black-body model with absorption lines at 4.15 and 6.63 keV described the spectrum well, giving a $\chi^2_r$ of 1.69 for 58 dof. Adding an emission line at 12.97 keV improves the fit significantly: $\chi^2_r$ 1.36 for 56 dof (see Figure 6). Again from the simulation—considering the single black-body as the seed model and a black body + two absorption lines + an emission line as the test model—we found the p-value to be less than $5 \times 10^{-4}$, favoring the addition of the line components. We also performed a comparative significance
testing of the two best-fit models for the Tail 1 segment described here, by testing the significance of adding the emission line on top of the black body with the two absorption lines. In this case, the $p$-value that the seed model (black body + 2 absorption lines) better describes the data than the test model (black body + 2 absorption lines + an emission line) was $7 \times 10^{-4}$.

Following this, the tail spectra became relatively simpler and were primarily described using a single black-body model. The spectra of some of the segments, such as Tail 2 and even some of the later spectra (e.g., Tail 6), showed indications of certain absorption features, particularly around 4 keV, but none of the Gaussian line features were sufficiently significant, as obtained from our simulations. During the later part of the tail, from the spectrum of the segment Tail 5, a substantial excess was observed in the high energies above 10 keV. We modeled the high energy excess using a power law and adding such a component effectively improved the fits (see last four panels of Figure 6). Upon the addition of a power law component, $\chi^2_{\nu}$ improved from 2.07 (63 dof) to 1.15 (61) for Tail 5, 1.91 (63) to 1.27 (61) for Tail 6, 1.64 (63) to 1.10 (61) for Tail 7, and 1.40 (63) to 0.96 (61) for Tail 8, although the spectral parameters of the power law component could not be well-constrained. The addition of this power law component to the spectral fits of the preceding segments did not perceptibly improve the fit statistics. Here also we investigated the statistical significance of the addition of an extra power law component on top of the black-body component. For these spectra, we constructed and fit the simulated spectra using the black body as the seed model and the black body + power law as the test model, and computed the F-distribution. We observed that, in all cases for the last four tail segments, the
null-hypothesis probability or $p$-value was less than $5 \times 10^{-4}$, strongly favoring the addition of the power law component. Such high energy excess was previously reported for this source by den Hartog et al. (2008) and Trümper et al. (2010, 2013).

Finally, it is interesting to note that in both event A and B, the transient line features appear at similar times immediately following the burst, and then disappear as the tail decays. For both events we observed absorption line features at $\sim 4$ keV and $\sim 6.5$ keV just after the intense burst emission. Additionally, a 13–14 keV emission line was present in the spectra of event B, which was previously reported by Gavriil et al. (2011).

### 3.2. Temporal Analysis

#### 3.2.1. Variation in Pulsed Properties

As we presented in Section 3, periodic intensity modulations at the spin frequency of the underlying source are clearly visible in the tail emission of both events. To better understand burst-induced changes on the persistent emission of 4U 0142 +61, we also investigated the time evolution of the pulsation amplitudes during the extended tails of these bursts, and compared them to those during the preburst values. For this purpose, we considered the same segments during the extended tail used for the spectral analysis; again the possible weak burst features during these tail segments were not excluded because they could not be significantly distinguished from noise. For each segment, the data was folded according to the spin ephemeris given in Gavriil et al. (2011), where $\nu$ and $\dot{\nu}$ were $0.1150920955(12)$ Hz and $-2.6619(9) \times 10^{-15}$ Hz s$^{-1}$, respectively. Apart from this long-term timing solution, they inferred a glitch at an epoch of 53809.185840 MJD. The glitch affects the long-term phase coherent timing solution as the frequency and hence the phase takes sufficient time to recover back the original pre-glitch timing behavior. Therefore, we use the timing solution for frequency evolution provided by Gavriil et al. (2011), which comprises a frequency model during the glitch, along with the pre-glitch evolution:

$$\nu(t) = \nu(0) + \dot{\nu}(t - t_g)$$

(1)

and $\nu(0)$ is the pre-glitch frequency evolution, given as:

$$\nu(0) = \nu(t_g) + \dot{\nu}(t - t_g)$$

(2)

where $\Delta \nu$ is the instantaneous frequency jump at the onset of the glitch, $\Delta \nu_d$ is the change in frequency in a timescale of $\tau_d$ during the recovery, $t_g$ is the glitch epoch, and $\nu$ is the post-glitch modification to the frequency derivative of the long-term timing solution. The values of the parameters used for the final frequency evolution model were $-1.27(17) \times 10^{-8}$ Hz for $\Delta \nu$, $-3.1(1.2) \times 10^{-16}$ Hz s$^{-1}$ for $\Delta \nu_d$, and $2.0(4) \times 10^{-7}$ Hz for $\Delta \nu_d$ and 17.0(17) days for $\tau_d$ (Gavriil et al. 2011). We then constructed the pulse profiles in the energy range 2–10 keV over each spectral investigation time segment during the extended tails. Next, these profiles were modeled with a sinusoidal model, along with four harmonics following Dib et al. (2007). From the modeling, we computed the rms fractional amplitudes of the pulsation and its variation prior to the bursts and during the decaying tails. In both cases, the pulsations are significantly enhanced following the burst episode, as also reported by Gavriil et al. (2011). Because the extended light curves of tails show significant variation with energy and their spectra change with time, we also examined the energy dependence of the pulsed amplitude evolution by repeating the same pulse profile modeling technique in two constituting energy ranges: 2–5 and 5–10 keV.

For event A, the average preburst rms fractional pulsation amplitude is about 2%, which is in line with the fact that 4U 0142+61 is the magnetar with the lowest rms-pulsed fraction (Patel et al. 2003). The rms-pulsed amplitude following the leading burst went up to 15% in 50 s and remained at this level for about 100 s (see the second panel of Figure 7). It then declined down to about 7% and remained at this level for a 150 s interval that includes the time of the weaker burst in the extended tail. Interestingly, the rms-pulsed amplitude briefly drops back to the preburst level and then remains at about a 10% level until the end of extended burst tail (Figure 7). The evolution of the rms fractional amplitude in the 2–5 keV and 5–10 keV energy ranges are a bit more complicated, but to some extent resemble the behavior in 2–10 keV band (the third and fourth panels of Figure 7, respectively).

For event B, the preburst pulsation amplitude was higher, $\sim 6\%$. It shows an abrupt enhancement in conjunction with the leading burst to about 20% (the second panel of Figure 8). The pulsation amplitude then declines smoothly to the preburst level in about 800 s, and remains nearly constant at this level (or with
Figure 6. Spectral fit of segments corresponding to event B. The label at the top of each panel denotes the segment that the corresponding spectrum was generated from. Each panel also shows the best-fit spectral model in the 2.5–30 keV band.
a marginal increase) for the next 800 s (Figure 8). The energy-resolved rms-pulsed amplitude of this event is intriguing: In the 5–10 keV band, it goes up to about 23% from 3%, and then decays steadily down to about 10% until the end of the tail (the fourth panel of Figure 8). In the 2–5 keV band, however, the initial enhancement is not as large, rising from 4% to 13%, and decaying back to the preburst level in about 600 s. The rms amplitude in the lowest investigated energy regime remains constant for about 600 s and then shows an increasing trend for about 400 s, before it rapidly drops back to the preburst level. It is important to note that characteristic rms-pulsed amplitude variations seen in the 2–10 keV band during the first 600 s and the last 800 s of the extended tail are mostly due to variations in the 2–5 keV band (Figure 8).

3.2.2. Rotational Phases of the Events

We determined the rotational phases of both events to uncover any link between the burst emission and persistent X-ray output of 4U 0142+61. We used the spin ephemeris of Gavriil et al. (2011) to calculate the phases of the bursts. For event B, we also calculated the phases of the short Gray episodes, which took place in transition from the burst to the episode of the clearly visible Oscillation regime. We find that the burst corresponding to event A spans between the spin phases 0.46 and 0.58 (see top panel of Figure 9), which is entirely aligned at the maximum intensity interval of the pulse profile. For event B, the short intense burst spans a much shorter spin phase interval from 0.35 to 0.37, which also coincides with a peak intensity interval of the underlying pulse profile that is present even after removing the burst time interval. The burst interval is followed by the Gray 1 interval, which ends at the spin phase of 0.45, then by the Gray 2 segment, which ends at 0.70. The succeeding segment, Gray 3 continues until the rotation phase of 0.99 after which the Oscillation regime starts, corresponding to a duration of about 42 s comprising multiple spin cycles. The spin phase of these various segments in event B are presented in the bottom panel of Figure 9. Note the fact that the alignment of bursts with the peak of the pulse profile was also reported by Gavriil et al. (2011).
3.2.3. Search for Quasi-periodic Oscillations (QPOs)

QPOs have been detected during the giant magnetar flares (Israel et al. 2005; Strohmayer & Watts 2005) and in some short recurrent bursts (Huppenkothen et al. 2014a, 2014b). Therefore we searched the power spectra of the extended tails of the two events for the presence of QPOs. First, we segmented the extended tails into 1 s intervals and constructed the Leahy-normalized power spectra (Leahy et al. 1983) in the 2.0–14 keV energy band using a Nyquist frequency of 1024 Hz. If a power is more than 3σ significant (i.e., a probability that the power to originate purely due to noise is less than 0.27%) then we call it a signal detection. If the number of trials (i.e., the number of frequency bins searched) is taken into consideration, we find no significant signal in the acquired power spectra. We performed the same QPO search analysis over the energy bands 2.0–4.5, 4.5–8.5, and 8.5–14 keV, but still did not find any detection that satisfies our criterion.

In order to reduce the noise in the individual power spectra, we generated the averaged power spectrum of these 1 s intervals and searched for QPOs in the frequency range from 10 to 1020 Hz. We computed the chance probability of the maximum power in the relevant frequency range and found it to be greater than 0.0027 in all cases. We then recomputed the chance probability and sigma level for the maximum power detected in the averaged power spectra for the two energy ranges: 2.0–10.0 keV and 10.0–30.0 keV. Again it was a null detection when the number of trials was considered. We determined that the significance of the maximum power during the tail of event A was 1.12σ and 1.57σ in the energy ranges 2–10 and 10–30 keV, respectively. For event B, the significances of the maximum detected power were 0.06σ and 0.10σ for these two energy bands, respectively.

4. DISCUSSION

We characterized the extended tails following the bursts from 4U 0142+61 reported in Gavriil et al. (2011) with thorough spectral and temporal analyses and time evolution of its properties. The two extended burst tails we identified last longer than 463 and 1600 s, which is similar to the durations of the extended emission episodes observed from other magnetars (Ibrahim et al. 2001; Lenters et al. 2003; Göğüş et al. 2011; Şaşmaz Muş et al. 2015). In the following we discuss the implications of our detailed time-resolved spectral and temporal analysis results, and compare them with the broad spectral properties of other extended tails reported in the literature.

We showed that spectra of the extended tail episodes of both events were varied in time. Earlier, Gavriil et al. (2011) investigated the X-ray spectra of these two events, but because they accumulated a spectrum from the entire duration of each event they overlooked the time variation. The burst corresponding to event A was described by a black-body model with a temperature 5.6 keV that is consistent with the temperature reported by Gavriil et al. (2011) for the entire event duration. The subsequent extended tail spectra were also described using a thermal model and showed a smooth cooling trend; temperature decayed from 3.9 to 1.8 keV in about 400 s. Such time-dependent spectral behavior was observed from the extended tail emission following bursts from a number of magnetars (Ibrahim et al. 2001; Lenters et al. 2003; Göğüş et al. 2011; Şaşmaz Muş et al. 2015). For event B, the most adequate model for describing the burst spectrum was non-thermal: a power law with an index of 0.42. Such non-thermal behavior is also typical for magnetar bursts (van der Horst et al. 2012; Lin et al. 2013; Şaşmaz Muş et al. 2015). Following the burst, we observed the segments Gray and Oscillation, during which clear periodic modulations at 8.7 s could be seen. We found that the spectra corresponding to these regions were relatively more complex and displayed distinct signatures of spectral line features. However, the continuum of the extended tail of event B also exhibited a cooling trend from 2.5 to 1.5 keV in a slightly longer timescale, 1600 s. For other sources exhibiting extended tails as reported in the literature, the black-body temperature declined in similar fashion. For SGR 1900+14, the temperature decreased from 2.5 to 1.6 keV for the 2001 April 28 burst extended tail and from 4.4 to 1.5 keV for the 1998 August 29 burst extended tail over timescales of a few thousand seconds (Lenters et al. 2003). The temperature decayed from 3.01 to 1.73 keV, 2.37 to 1.69 keV, and 3.23 to 2.20 keV over a a few hundred seconds during the extended tails of events B, C, and D respectively, from the magnetar SGR J1550–5418 (Şaşmaz Muş et al. 2015). In the case of...
SGR 1806–20, the temperature decreased from 3.8 to 2.6 keV over 500 s during the extended tail corresponding to the event on 2004 June 22 and from 4.0 to 2.6 keV over about a thousand seconds during the extended tail corresponding to the event on 2004 October 17 (Göğüş et al. 2011). In 4U 0142+61, the gray regions precede the extended tail, where the black-body temperature was higher compared to the typical temperature observed during the onset of extended tails and, importantly, most of the prominent line features were observed during these segments.

Magnetar bursts are proposed to originate from small or large scale fracturing of the solid neutron star crust (Thompson & Duncan 1995) or from magnetic reconnection (Lyutikov 2015); in either case, this gives rise to a “fireball” trapped in the magnetosphere, comprising highly energetic charged pairs. This particles that return back to the neutron star surface from this fireball, because they could not efficiently radiate away, can heat up the stellar surface and cause the extended tail emission. The cooling of these hot-spots results in the observed temperature decay trend. Moreover, during the burst, the high temperature could initiate thermonuclear burning and release additional energy (Ibrahim et al. 2001). The fireball created during a burst event could compress the deep layers and trigger such a reaction. Such events can only take place if the burst is sufficiently energetic, resulting in a high fireball temperature, and if significant hydrogen is present to act as the burning fuel (Ibrahim et al. 2001). The timescale of the hydrogen burning process is consistent with the duration of the burst segment. The energy released by hydrogen burning also heats up the crust, which can supersede the thermal energy injected into the crust directly from the fireball (Ibrahim et al. 2001). This means that a large amount energy is released during the tail from multiple mechanisms. This phenomena is very much in accord with our observations, where we find that the energy released during the tail is quite high: 1–2 orders of magnitude larger that released during the burst. In addition, the prolonged emission is consistent with the time taken for the heat to get released from the deep layers where the burning takes place. Thus, thermonuclear burning may be another mechanism behind the long extended energetic tail emission.

We detected strong evidence of episodic spectral lines, mainly at the onset of the extended tails. We diagnosed the statistical significance of such lines through rigorous simulations in order to employ an unbiased approach to test the importance of adding the extra line components (Protassov et al. 2002). We detected an emission line at ∼13 keV and absorption lines at ∼4, ∼6.5, and ∼11 keV with high significance. If the absorption features are caused by proton cyclotron resonance (see below) these lines correspond to $1.1 \times 10^{15}$, $1.9 \times 10^{15}$, and $3.1 \times 10^{15}$ G, respectively (assuming a neutron star with a mass of $1.4 M_\odot$ and radius of 12 km). These magnetic field strengths are significantly higher than the inferred dipolar field strength of $1.3 \times 10^{14}$ G, strengthening the idea that multipolar surface magnetic field structures can be much more intense than the dipole field.

Emission and absorption features at similar energies were previously reported in the burst spectra of a number of magnetar sources like 1E 1048.1–5937 (Gavriil et al. 2002, 2006; An et al. 2014), XTE J1810–197 (Woods et al. 2005), 4U 0142+61 (Gavriil et al. 2011), SGR 1806–20 (Ibrahim et al. 2002, 2003), and SGR 1900+14 (Strohmayer & Ibrahim 2000). Strohmayer & Ibrahim (2000) detected a 6.4 keV emission line in a SGR 1900+14 burst during a 0.3 s long segment when the burst spectrum was the hardest. They also reported the indication of a weak emission line at ∼13 keV, which they suggested to be a possible harmonic of the 6.4 keV feature. Gavriil et al. (2002) found the presence of an emission line feature at about 14 keV during the initial stages of the burst, from 1E 1048.1–5937. A 5 keV absorption line was detected during a burst precursor from SGR 1806–20 by Ibrahim et al. (2002) and was attributed to proton cyclotron resonance in the ultrastrong magnetic field of a magnetar. An alternative possibility behind the origin of the line might be a redshifted absorption line arising from an atomic transition like the iron transition (Strohmayer & Ibrahim 2000), but this is unlikely given the obtained line parameters. The observed flux and temperature corresponding to the line cannot be explained by any existing theoretical model when the obtained redshift is taken into account (Ibrahim et al. 2002). A 12.6 keV emission line, with a chance probability of $<4 \times 10^{-6}$, was discovered by Woods et al. (2005) during the tail of a burst from XTE J1810–197. An et al. (2014) observed an emission line at ∼13 keV during the tail of a 1E 1048.1–5937 burst using NuStar data, and this was the first detection by a non-RXTE instrument, ruling out instrumental effects. Note that these emission and absorption features were transient events during bursts and usually occurred during the segments when the spectrum was harder.

One possible interpretation of the absorption lines at ∼4 or ∼6.5 keV during the 4U 0142+61 extended tails is that they were generated due to the electron cyclotron resonance process, but this is unlikely because it requires the magnetic field to be much lower (∼$10^{12}$ G) than the inferred dipolar field strength (∼$10^{14}$ G). The other possibility could be the ion or proton cyclotron resonance phenomenon. During a burst, a trapped fireball is formed in both the crustal fracturing (Thompson & Duncan 1995) and magnetic reconnection (Lyutikov 2015) scenarios for bursts. Photons emitted from such a fireball interact with the magnetosphere in the presence of a strong multipolar magnetic field (∼$10^{13}$ G), giving rise to the proton cyclotron features. In this case, the inferred magnetic field is quite close to the surface dipole magnetic field. As the temperature and flux decay, the proton cyclotron resonance process becomes inefficient and consequently the lines become weak or entirely absent in the late stages of the extended tail. This picture agrees with our observations of the absorption lines being transient and occurring at high intensities just following the burst. It is also important to point out that the observed properties of the line features should be strongly dependent on the latitude of the emission site and stellar rotation, both of which affect our viewing angle (Thompson et al. 2002). This might explain the presence and absence of the line features in two adjacent segments, particularly in the gray regions of the event B.

Wang et al. (2006) observed this source using Spitzer in the mid-infrared wavelength band. The IR emission was best described by a multi-temperature thermal model that indicates an extended disk origin. It was attributed to the reprocessing of incident X-rays coming from the central X-ray pulsar by the surrounding passive disk. Ertan et al. (2007) interpreted this observation as evidence of an active fallback disk with intrinsic disk emission due to viscous dissipation, along with the reprocessing of the incident radiation. The existence of such a disk was predicted previously by Chatterjee et al. (2000) and...
Alpar (2001). As such a disk is present in 4U 0142+61, the ~6.5 keV absorption line may have been caused by absorption in the disk corresponding to the Fe Kα transition (Strohmayer & Ibrahim 2000). Because the source intensity changes during the burst, the incident flux and the reprocessing from the flared up disk varies, which may in turn affect the presence of the absorption/emission line and thus can explain their transient nature.

There have been only a few reported detections of absorption and emission lines in the burst or tail phases of the emission of magnetars, as mentioned. Our observations that the spectral lines appear at similar episodes during the tail for both events where we have high intensity spectra are intriguing. Such features, if indeed originating from cyclotron resonance, provide us with a unique and independent way of determining the stellar magnetic field and its properties. Moreover, a measurement of the gravitational redshift of these lines, most likely originating from near the stellar surface, can put significant constraints on the neutron star mass and radius. An instrument with better spectral capability than RXTE would be able to precisely characterize these line features.

It has been observed that the occurrence of the extended tail and its energetics are not closely related to the energetics of the leading burst (Göğüş et al. 2011; Şanmaz Muş et al. 2015). We observed that the 2.5–30 keV isotropic energy emitted during the burst for event A was $2.3 \times 10^{36}$ erg, which was followed by an extended tail with an isotropic energy in the same range of $4.9 \times 10^{37}$ erg. For event B, the total isotropic burst energy was $4.7 \times 10^{36}$ erg, and those during the corresponding gray, oscillation, and extended tail regions were found to be $29.4 \times 10^{36}$, $41.5 \times 10^{36}$, and $2.3 \times 10^{36}$ erg, respectively. The ratio of the extended tail energy to the burst energy varies substantially between the burst events for this source. It is possible that a considerable fraction of the total energy released as a result of crustal fracturing or during a magnetic reconnection event could not be efficiently radiated away during the burst and was thus retained within the system, as also invoked by Şanmaz Muş et al. (2015). This residual energy reservoir could then power the emission during the extended tail over a prolonged period of time.

The temporal properties of 4U 0142+61 also exhibited an interesting evolution during the extended emission phase. We observed that the burst induced enhanced pulsed amplitude in both events. It is interesting to note that the variation of the pulse amplitude, particularly for event A, is not correlated with the variation in the X-ray intensity, and the pulsation remains high into the extended tail, long after the burst occurrence. We also found that the spin phases of leading bursts in both events correspond to the peak of the pulse profile. This might imply that the site of the leading burst is near the magnetic pole of the neutron star. As described in the implications of our spectral results, a major fraction of the energy was deposited back to the system that heats up the star, and in turn this could result in the significant increase in the pulsation amplitude just following the burst, as well as during the later parts of the tail. Similar phenomena were observed for event D in Şanmaz Muş et al. (2015), which had similar energetics (low energy bursts and more energetic long extended tails) much like the two events described in this work.

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