SEARCHEING FOR X-RAY VARIABILITY IN THE GLITCHING ANOMALOUS X-RAY PULSAR 1E 1841−045 IN KES 73

WEIWEI ZHU AND VICTORIA M. KASPI
Department of Physics, McGill University, Montreal, QC H3A 2T8, Canada; zhuww@physics.mcgill.ca, vkaspi@physics.mcgill.ca

Received 2010 March 8; accepted 2010 June 13; published 2010 July 20

ABSTRACT
Anomalous X-ray pulsars (AXPs) are now established to exhibit significant X-ray variability and be prolific glitchers, with some glitches being accompanied by large radiative changes. An open issue is whether AXPs glitches are generically accompanied by radiative changes, relevant for understanding magnetar physical properties. Here we report on an analysis of archival X-ray data from the AXP 1E 1841−045, obtained between 1993 and 2007. This AXP, located in the center of the supernova remnant Kes 73, has exhibited three glitches between 2002 and 2007, as determined by RXTE monitoring since 1999. We have searched for evidence of phase-averaged flux variability that could be present if glitches in AXPs are usually accompanied by radiative changes. We find no evidence for glitch-correlated flux changes from this source after 1999, supporting the existence of radiatively silent glitches in AXPs.

Key words: pulsars: individual (1E 1841−045) – stars: neutron – X-rays: stars

1. INTRODUCTION

X-ray variability in anomalous X-ray pulsars (AXPs) is now established as a characteristic property of this source class. Their fluxes and spectra vary on a variety of different timescales, from a few milliseconds (e.g., Gavriil et al. 2002) to several years (Dib et al. 2007). See Kaspi (2007) and Mereghetti (2008) for recent reviews of AXP variability.

AXPs are also now known to be prolific glitchers, and include some of the most active glitchers known in the neutron-star population (Dib et al. 2008a). By “glitch” we mean a sudden rotational spin-up, or a similar timing anomaly. One of the largest glitches seen so far, from AXP 1E 2259+586, was accompanied by major radiative changes, including bursts and a factor of ∼20 pulsed and persistent flux increase (Kaspi et al. 2003; Woods et al. 2004). Dib et al. (2009) showed that glitches in AXP 1E 1048.1−5937 were also accompanied with radiative enhancements. Such events are thought to be the result of sudden yielding of the neutron-star crust due to internal stresses caused by the decay of the magnetar-strength field. The restructuring results in changes to the stellar interior—as evidenced by the glitch—and to the stellar exterior—as evidenced by the dramatic radiative changes. Observations of such AXP outbursts are a potentially powerful probe of the physics of magnetars (e.g., Eichler & Shaisultanov 2010).

Links between the X-ray variability and glitches of AXP RXS J170849.0−400910 have also been reported (Rea et al. 2005; Campana et al. 2007; Israel et al. 2007; Götz et al. 2007). These authors suggest the existence of a general correlation between magnetars’ flux and glitch epochs. Specifically, Götz et al. (2007) reported ∼40% flux changes in RXS J170849.0−400910 based on eight observations made over the course of ∼9 yr, during which they report four glitches. If correct, this suggests that glitches are usually, and possibly always, accompanied by radiative changes. However, the sparsity of observing epochs compared to the number of glitches for this AXP thus far is problematic in proving that the variability is glitch-correlated. Additionally, no comparable pulsed flux changes were observed in the same time span, during which such measurements were available regularly on a monthly basis (Dib et al. 2008a). This apparent conflict could, however, be explained if the pulsed fraction were precisely anti-correlated with flux. An anti-correlation between pulsed fraction and flux has been seen in AXP 1E 1048.1−5937 (Tiengo et al. 2005; Tam et al. 2008), although not to a degree that render pulsed flux variations absent.

Here we investigate the hypothesis that AXPs glitches are generically accompanied by radiative changes by considering AXP 1E 1841−045 in supernova remnant (SNR) Kes 73, one of the most frequent glitchers among AXPs. From RXTE monitoring, we know that 1E 1841−045 has had three glitches between 1999 and 2008 (Dib et al. 2008a). The glitches occurred on 2002 July 9, 2003 December 24, and 2006 March 29, had Δν/ν of 5.63 × 10⁻⁶, 2.45 × 10⁻⁶, and 1.39 × 10⁻⁷, respectively, and were not accompanied by any X-ray-pulsed flux changes. If, as seen in 1E 2259+586 and 1E 1048.1−5937 and reported for RXS J170849.0−400910, glitches are generically accompanied by radiative changes, and, if as for RXS J170849.0−400910, such radiative changes are not necessarily apparent in the pulsed flux data, it is possible that the phase-averaged flux (unavailable from RXTE monitoring) varies in concert with glitches in 1E 1841−045. We investigate this possibility here. Also worth noting is that Gotthelf et al. (1999) studied the timing of AXP 1E 1841−045 using archival GINGA, ASCA, ROSAT, and RXTE data taken between 1993 and 1999 and found no glitches with Δν/ν > 5 × 10⁻⁶.

In this paper, we report on our analysis of archival X-ray data for 1E 1841−045 collected by ASCA, Chandra, XMM-Newton, and Suzaku during the past 17 years, including two observations that were made fortuitously very closely following glitches. We have looked for correlations between the AXP’s flux variability and glitch epochs. In Section 2, we describe the observations and data reduction process. In Section 3, we describe our spectral analysis and AXP flux extraction method. Our results and conclusions are discussed in Section 4.

2. OBSERVATIONS

For this study, we searched online X-ray archives for all existing observations of the Kes 73 field. We found a total of

1 Canada Research Chair; Lorne Trottier Chair; R. Howard Webster Fellow of CIFAR.
11 observations from 4 different focusing X-ray observatories (listed in Table 1). We do not include in our analysis the many RXTE observations, as due to its non-focusing nature, these provide only pulsed flux measurements, and are already published (Dib et al. 2008a). Next we report on our analysis of the 11 focusing-telescope observations.

### 2.1. ASCA Observations

Seven ASCA (Tanaka et al. 1994) observations of the AXP 1E 1841–045 and the SNR Kes 73 were taken between 1993 and 1999 (see Table 1). Our analysis began with the screened data from the two Gas Imaging Spectrometers (GISs; Burke et al. 1994), which were filtered with the standard revision 2 screening criteria. Given the angular resolution of the GISs, the SNR (∼2′) was unsolvable in the images, and therefore the spectra we extracted from the GISs contain photons from both the AXP and the SNR. Using the ftool xselect, we extracted spectra from source regions of radius 9.8′ (a region large enough to encircle the extended emission from AXP 1E 1841–045 and Kes 73) and background spectra from regions of radius ∼5′, away from the source region for all the ASCA GIS observations. The GIS spectra were then combined with Redistribution Matrices File (RMF) of the GISs and Auxiliary Response File (ARF) generated using the ftool ascaarf, and grouped with a minimum of 25 counts per bin. Finally, the exposure of the grouped spectra were corrected for the dead-time effect using the ftool deadtime. In this study, we did not include the spectra extracted from the two Solid-state Imaging Spectrometers (SISs; Ohashi et al. 1996), primarily because of the significantly fewer counts collected by these instruments.

### 2.2. Chandra Observation

The AXP and SNR were observed by the Chandra X-ray Observatory with the Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2003) in the timed exposure (TE) mode on 2000 July 23 and in the continuous clocking (CC) mode on 2000 July 29 (Table 1). The data were analyzed and reported by Morii et al. (2003). Here we used Ciao version 3.4.3. Because the spectrum of the pulsar in the TE mode was heavily affected by pile-up, we did not use these data; instead we extracted the spectrum of AXP 1E 1841–045 from the CC mode data. In these data, the images of the pulsar and SNR were collapsed into one dimension. From the level 2 event list provided by the Chandra X-ray Center, we extracted the spectrum of the pulsar using a box-shaped region capturing a 2.5′ long segment along the one-dimensional image and centered on the pulsar. The background spectrum was extracted from two 7.5′ long segments adjacent to the source region. The resulting source and background spectra were then combined with RMF and ARF files generated using the psextract command and grouped with a minimum of 25 counts per bin.

### 2.3. XMM-Newton Observations

The AXP was observed by the XMM-Newton observatory (Jansen et al. 2001) on 2002 October 5 and 2002 October 7 (Table 1) with the European Photon Imaging Camera (EPIC) pn (Strüder et al. 2001) camera operating in the large window mode and the EPIC MOS cameras (Turner et al. 2001) in the full window mode. For our analysis, we used the XMM-Newton Science Analysis System (SAS) version 8.0.4β and calibrations (updated 2008 October 3). Given the pn and MOS cameras’ angular resolution, 1E 1841–045 can be resolved from Kes 73. For the two XMM-Newton observations, we used only the data from the EPIC pn camera to take advantage of its larger photon collecting area and to avoid cross-calibration issues between the pn camera and the mos cameras. Two sets of spectra were extracted from each XMM-Newton observation: the spectrum of only the pulsar and the spectrum of the entire SNR Kes 73 including the pulsar. We extracted the pulsar’s spectrum from a circular region of radius 32.5′ (a radius large enough to capture more than 90% of the photon events from the point source) centered on the pulsar. Background spectra were extracted from an annular region of radius between 35′ and 115′ centered on the pulsar which included most of the emission from Kes 73, in order to remove the SNR contribution left in the source region. For the spectrum of the entire SNR, we used a circular source region of radius 115′ and a circular background region located on the same CCD as the pulsar but at a different Y position. Ideally, we want to extract background photons from the region centered on the same Y position of the CCD; however, this is not possible because of the extended emissions of the SNR. So, we verified our result by choosing a different background region on an adjacent CCD, and found that the difference it makes in the final spectrum is negligible. Both of the spectra were grouped with a minimum of 25 counts per bin and then combined with the background spectrum and RMF and ARF files generated by the SAS software.

### 2.4. Suzaku Observations

AXP 1E 1841–045 and Kes 73 were also observed by the Suzaku observatory (Mitsuda et al. 2007) on 2006 April 19 (Table 1). The data analysis was reported by Morii et al. (2008). On board Suzaku, there are two X-ray detectors: the X-ray Imaging Spectrometer (XIS; Koyama et al. 2007; consisting of four CCDs sensitive in the soft X-ray band) and the Hard X-ray Detector (HXD; Takahashi et al. 2007; sensitive to 10–600 keV X-rays). Here we present a spectral analysis of the XIS data only. Given the angular resolution of the XIS, the SNR was unresolvable in the XIS image. Therefore, the

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**Table 1**

| Date        | Observatory | $t$ (ks) | Offset$^{a}$ (′) |
|-------------|-------------|---------|------------------|
| 1993 Oct 11 | ASCA        | 40      | 6.8              |
| 1997 Apr 21 | ASCA        | 9       | 7.3              |
| 1998 Mar 27 | ASCA        | 39      | 6.5              |
| 1999 Mar 22 | ASCA        | 20      | 5.2              |
| 1999 Mar 29 | ASCA        | 20      | 5.2              |
| 1999 Apr 6  | ASCA        | 19      | 5.2              |
| 1999 Apr 13 | ASCA        | 21      | 5.2              |
| 2000 Jul 29 | Chandra     | 10      | 0.097            |
| 2002 Oct 5  | XMM-Newton  | 3.8     | 1.152            |
| 2002 Oct 7  | XMM-Newton  | 4.4     | 1.144            |
| 2006 Apr 19 | Suzaku      | 98      | 3.9              |

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Notes.

$^{a}$ The effective exposure time of the instrument used for the spectral analysis in this paper.

$^{b}$ The pointing offsets of the observations relative to the position of the AXP.

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2.2. Chandra Observation

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http://heasarc.gsfc.nasa.gov/ftools/xselect/

http://131.142.185.90/ciao3.4/index.html

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See http://xmm.esac.esa.int/sas/8.0.0/

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spectra we extracted from the XIS detectors contain photons from both the AXP and the SNR. We used cleaned events screened by the standard pipeline processing version 2.0.6.13.5 The source spectra were extracted from a circular region of 260″ radius. Background spectra were extracted from an annulus region of radius between 260″ and 520″. The extracted spectra were grouped with a minimum of 25 counts per bin, and then combined with the RMF and ARF files generated using the ftools xisrmfgen and xissimarfgen.

3. SPECTROSCOPY

Among the 11 observations we used, the AXP can be resolved from the SNR Kes 73 only in the Chandra and XMM-Newton observations. For these, it is possible to extract either the neutron star’s spectrum or the combined spectrum of the neutron star and the SNR. By contrast, only the combined spectra can be extracted from the ASCA and Suzaku observations.

The spectra of AXPs are often parameterized by a blackbody plus a power law (although this is known to be an approximation to a likely Comptonized blackbody spectrum—see Thompson et al. 2002 and, for example, Rea et al. 2008). The spectra of SNRs are often fit with models such as VSEDOV (a plane-parallel shock radiation model with separate ion and electron temperatures), VNEI (a non-equilibrium ionization collisional plasma model), or VPSHOCK (a plane-parallel shocked plasma model). See Borkowski et al. (2001) for a review of these models. In this paper, we modeled the neutron-star radiation with a blackbody plus power law (BB+POW), and the SNR radiation with a VSEDOV model, using xspec 12.5.0.5 The focus of our investigation is on the AXP’s X-ray flux; in modeling the SNR, we sought only a suitable parameterization to allow us to subtract off its flux reliably. As we show below, the VSEDOV model is adequate for these purposes. We modeled the interstellar absorption by multiplying a WABS (a photoelectric absorption model), which in the interstellar absorption is characterized by a single parameter \( N_H \), the neutral hydrogen column density along the line of sight) model to both the BB+POW and VSEDOV models.

Figure 1 shows the combined spectra from XMM-Newton and the components of the best-fit model. The AXP power-law component clearly dominates the spectra above \( \sim 4 \) keV. Therefore, we chose to study the AXP flux in the 4–10 keV band only, in order to minimize SNR contamination. Nevertheless, we still attempted to remove the remaining small contribution of SNR in this band for the fluxes measured from ASCA and Suzaku observations, so that we could compare them with the neutron-star-only fluxes measured with Chandra and XMM-Newton.

It is reasonable to assume that both the interstellar absorption and SNR radiation do not change over a timescale of about a decade. Consequently, in our attempt to remove the SNR flux, we used the same \( N_H \) and VSEDOV parameters for all the spectra of the different observations, and allowed only the BB+POW model to vary from observation to observation.

When fitting a WABS (BB+POW+VSEDOV) model to those spectra containing emission from both the AXP and SNR, it is challenging to constrain the normalization parameters of both the BB and VSEDOV models simultaneously, because these two models dominate the same energy band and their parameters are highly covariant. Fortunately, the neutron star can be spatially resolved out in the XMM-Newton observations, so we can use them to determine the relative strength of the two spectral components. We therefore fit a WABS (BB+POW+VSEDOV) model to the combined (AXP+SNR) XMM-Newton spectrum. To ensure that we had the correct BB+POW model for the neutron star, we simultaneously fit the spectrum extracted from only the neutron star, requiring common neutron-star spectral parameters. Hence, we could determine the parameters and normalization of the VSEDOV model for the SNR.

To further improve the spectral model, next we included the ASCA and Suzaku spectra and the Chandra CC-model neutron-star spectrum and performed a large joint fit, which required multiple iterations in order to converge. The result was a value for \( N_H \) and for the VSEDOV model parameters that fit all the SNR spectra reasonably well, albeit not perfectly (reduced

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5 http://heasarc.nasa.gov/docs/suzaku/processing/criteria_xis.html
6 http://heasarc.nasa.gov/docs/xanadu/xspec/

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Table 2

| Parameter | Value |
|-----------|-------|
| \( N_H \) | \( 2.77 \times 10^{22} \) cm\(^{-2} \) |
| \( kT_b \) | 0.56 keV |
| \( kT_e \) | 0.56 keV |
| Mg | 0.63 \(^a\) |
| Si | 1.10 |
| S | 1.92 |
| Ca | 0.32 |
| Fe | 0.57 |
| Ni | 2.51 |
| \( \tau \) | 1.50 \times 10^{11} \) s |
| Redshift | 0.00 |
| Norm\(^b\) | 0.33 |
| H...Ar\(^c\) | 1.0 |

Notes.

\(^a\) The element abundances quoted here are the relative abundances based on the solar mixture abundances.

\(^b\) Normalization parameter for the VSEDOV model, \( \frac{4\pi D_{L}(1+z)}{r_{\text{sun}}^2} N_{\text{H}} \) A where \( D_L \) is the angular diameter distance to the source (cm), and \( n_e, n_H \) (cm\(^{-3}\)) are the electron and hydrogen densities, respectively.

\(^c\) Elements H...Ar: H, He, C, N, O, Ne, and Ar were fixed to the solar abundance because the SNR spectra are not sensitive to them.
χ² = 1.36 for 3801 degrees of freedom for the joint fit). The best-fit \( N_H \) and VSEDOV parameters can be found in Table 2.

Note that for all the spectral fitting described above, we used the 0.8–10 keV band. However, for Suzaku, we found that there were always significant residuals in the range 1.7–3.5 keV and above 9 keV, and in general these residuals differed significantly among the four XIS instruments. Therefore, we ignored the 1.7–3.5 keV band and above 9 keV for the Suzaku spectra. Furthermore, the SNR Kes 73 is larger than the field of view of the Suzaku XISs and was not entirely captured. Therefore, when fitting the Suzaku spectrum, we allowed the VSEDOV normalization parameter to vary.

Finally, by using the best-fit \( N_H \) and VSEDOV model, we could remove the SNR flux contribution from the ASCA and Suzaku observations in separate fits to their spectra, hence measuring the AXP fluxes. For the Chandra and XMM-Newton observations, we simply fitted the resolved AXP spectra with an absorbed BB+POW model. The best-fit BB+POW parameters, the measured 4–10 keV unabsorbed fluxes of the AXP, and the reduced χ² are presented in Table 3. The fluxes are also plotted in Figure 2. The uncertainties we report on the measured fractional uncertainties on the 4–10 keV absorbed neutron-star flux did not vary by more than ~30% in 13 years.

This is not necessarily surprising given that the summed, overall spectrum of the entire SNR Kes 73 is probably more complicated than a single VSEDOV model can describe. However, this issue likely affects the overall flux normalization for the SNR spectrum very little. Since here we are concerned with the flux of the AXP only, not the spectrum of the SNR, the SNR flux normalization should be good enough for our purposes.

Indeed, to confirm the robustness of the measured AXP flux values, we repeated the entire above analysis by modeling the SNR spectra in different ways. We found that both the VNEI and VPSHOCK models can fit the SNR spectra as well as the VSEDOV model, and that the 4–10 keV unabsorbed neutron-star fluxes we measured using these models are consistent within reported uncertainties with the values we found using the VSEDOV model. Therefore, we feel confident that the phase-averaged AXP flux values we report are well constrained and robust. However, the BB+POW spectral parameters we measured when fitting the SNR with different models were not as robust as the 4–10 keV fluxes, changing significantly with the SNR model. As we do not believe them to be reliably determined, we do not quote their uncertainties in Table 3, and do not consider them further.

Also in Figure 2, we show the AXP’s 2–10 keV pulsed flux as measured in monitoring observations with RXTE since early 1999. Details about how these pulsed fluxes were determined are provided in Dib et al. (2008a). The RXTE pulsed fluxes show no significant variations. The vertical lines in Figure 2 indicate the epochs of the three observed glitches (Dib et al. 2008a).

### 4. DISCUSSION AND SUMMARY

The goal of this study was to see whether the prolific glitching AXP 1E 1841–045 shows phase-averaged flux variability, in spite of showing no evidence for pulsed flux variability. Also, we wished to determine whether any variability is correlated with its glitches as has been seen in AXP 1E 2259+586 in its 2002 major outburst, in 1E 1048.1–5937, and also reported for RXS J170849.0–400910.

As is clear from Figure 2(a), in the 4–10 keV band, the neutron star’s flux did not vary by more than ~30% in 13 years.
Interestingly, the largest variations we find are in the multiple pre-1999 ASCA observations: in those seven observations, a fit to a constant flux results in a reduced $\chi^2$ of 3.7 for 6 degrees of freedom, which has a probability of occurring by chance of $\sim 0.001$. However, during this time, there were certainly no large glitches ($\Delta \nu/\nu < 5 \times 10^{-6}$; Gotthelf et al. 1999).

The ASCA fluxes appear to be $\sim 30\%$ higher than the fluxes measured from other observations. Snowden (2002) studied the cross-calibration accuracy among ASCA, XMM-Newton, and Chandra, and found that their flux difference due to calibration should be $< 20\%$. This suggests that the AXP’s flux dropped around 2000. However, we did not see any significant changes in the pulsed flux as monitored by RXTE at that epoch (Figure 2(b)). In principle, it is possible for the pulsar’s total flux to vary while the pulsed flux remains constant. In that case, the pulsed fraction of the pulsar must have also changed during the same epoch and it must be precisely anti-correlated with the total flux. An anti-correlation between pulsed fraction and flux has been observed from AXP 1E 1048.1−5937 during one of its active phases, but the variability in its pulsed flux was still very significant (Tiengo et al. 2005; Tam et al. 2008).

The fluxes measured from the last four observations taken by Chandra, XMM-Newton, and Suzaku can be fitted with a constant flux model (reduced $\chi^2 = 1.9$ for 3 degrees of freedom, corresponding to a probability of having occurred by chance of 0.125). Thus, we conclude that the phase-averaged 4–10 keV fluxes of the last four observations were consistent with being constant, and we put an upper limit of 11% on long-term variability in this energy band. Importantly, the two XMM-Newton observations were taken only 88 and 90 days after the first glitch, and the Suzaku observation was taken only 27 days after the third glitch. In contrast, the 4–10 keV flux of 1E 2259+586 was 50% higher than in quiescence 21 days after its 2002 glitch (Zhu et al. 2008), that of 1E 1048.1−5937 was a factor of 6 higher $\geq 38$ days after its 2007 glitches (Tam et al. 2008), and was 50%–70% higher for RXS J170849.0−400910 $\sim 53$ days after its first 2005 glitch as inferred from Götz et al. (2007). Therefore, we conclude that unlike the glitches observed in 1E 2259+586, 1E 1048.1−5937, and possibly RXS J170849.0−400910, the 2002 and 2006 glitches of 1E 1841−045 were not accompanied by significant X-ray flux variations when compared to the 2000 Chandra flux. More generally speaking, we found no evidence for glitch-correlated flux changes in AXP 1E 1841−045 after 1999. However, we cannot rule out glitch-correlated flux changes before 1999 due to the sparsity of the observations.

One caveat of our study is that we were limited to the harder part of the neutron star’s emission spectrum. The flux from the blackbody component was not well constrained. Therefore, we cannot rule out changes in the neutron star’s thermal radiation, only changes in the power-law component in the 4–10 keV band, which we note constitutes $\sim0.25$ of the stellar flux (BB+POW) in the 1–10 keV band.

Thus, our results suggest the existence of radiatively silent glitches in AXPs, further supporting the argument that glitches in AXPs can be either radiatively loud or radiatively silent (Dib et al. 2008a). There is of course precedent for radiatively silent glitches in neutron stars, in that no rotation-powered pulsar glitch has ever been reported to be accompanied with any radiative change, although rapid X-ray follow up has been accomplished in only one case (Helfand et al. 2001). Any physical model of magnetar glitches will have to explain the simultaneous existence of both types. This is true for even a single source, as there is evidence that AXP 1E 2259+586 has both, given that its most recent glitch showed no pulssed flux change (Dib et al. 2008b). Recently, Eichler & Shaisultanov (2010) have argued that AXP glitches are triggered by energy releases at depths below $\sim 100$ m in the crust, with angular momentum vortex unpinning being due to global mechanical motion triggered by the energy release, not by heat as has been proposed in the context of rotation-powered pulsars glitches (Link & Epstein 1996; Link & Cutler 2002). If mechanical triggering occurs, then radiatively silent glitches of the same amplitude as radiatively loud glitches are possible since less energy is required to trigger a glitch than to cause a substantial X-ray brightening. If so, then Eichler & Shaisultanov (2010) predict that all AXP glitches should occur simultaneously with or before the observed X-ray brightening; this can be tested with continuous (daily or better) X-ray monitoring observations. Moreover, although mechanical unpinning of vortices by activity in the lower crust does result in heat release, the latter could take as much as several years to reach the surface. This could help explain the long-term X-ray variability trends that have been reported in some AXPs (e.g., Dib et al. 2007).

We thank Koji Mukai of the ASCA GOF for assistance with the ASCA data and David Eichler for useful conversations. We also thank Rim Dib for providing the RXTE pulsed fluxes. V.M.K. acknowledges support from NSERC via a Discovery Grant, FQRNT via the Centre de Recherche en Astrophysique du Québec, CIFAR and holds a Canada Research Chair and Lorne Trottier Chair in Astrophysics and Cosmology.

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