Long-term evolution of the emission from the anomalous X-ray pulsar 4U 0142+61

M. E. Gonzalez[1], V. M. Kaspi[1], P. M. Woods[2], F. P. Gavriil[3], C. Tam[1]
[1]McGill University (Montreal), [2]Dynetics/URSA/NSSTC, [3]NASA/GSFC

We present results obtained from X-ray and infrared observations of the anomalous X-ray pulsar 4U 0142+61 taken between 2000-2007. We observe a long-term evolution of the pulse profile, pulsed fraction and spectrum. The pulse profile is observed to become more sinusoidal, while the pulsed fraction increases with time. These results support those obtained using RXTE by Dib et al. (2007) and expand the observed evolution to energies below 2 keV. We find that these temporal changes are accompanied by a softening of the phase-averaged spectrum while the total flux is consistent with being constant (although a slight decrease is suggested). In observations taken after April 2006 (when the recent burst activity from the source became evident) an increase in the total X-ray flux of ~10% is seen accompanied by a hardening of the spectrum. Infrared observations after the burst activity show no detectable change in the flux at those wavelengths. We also fit a wide range of spectral models to the data and find that the standard blackbody plus power-law model does not provide the best fit to the emission from 4U 0142+61. We will discuss our results in light of current models for these sources.

Introduction

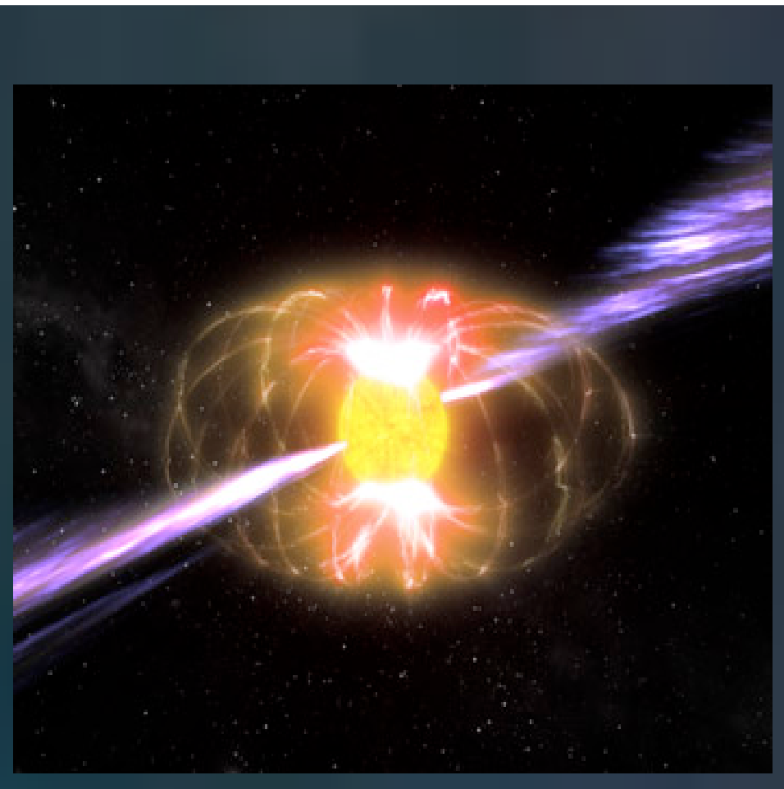

Figure 1. Artist's impression of a magnetar (Credit: J. Rowe)

- Magnetars are isolated neutron stars with magnetic fields ≳ 10^{14} G whose bright X-ray emission is believed to be powered by field decay. They exhibit variability in a wide range of time scales, from years to millisecond bursts. Studying their properties at all these timescales can help us determine the underlying physical mechanisms in these extreme objects.
- 4U 0142+61 is the brightest of the anomalous X-ray pulsars (AXPs), believed to be magnetars. It has a period of 8.2 s, inferred surface dipole magnetic field of 1.3×10^{14} G and has been detected from the mid-IR to hard X-rays (Israel et al. 1994; Gavriil & Kaspi 2002; den Hartog et al. 2007). The origin of each spectral component is a subject of debate.
- The mid-IR emission was proposed to arise from a passive, non-accreting disk (Wang et al. 2006). The optical emission has a pulsed fraction of ~29%, suggesting a magnetospheric origin (Dhillon et al. 2005).
- 4U 0142+61 was stable for many years, then entered an active phase with various bursts in 2006 and 2007 (Gavriil et al. 2007, in preparation).
- Here we report on soft X-ray observations of 4U 0142+61 taken by XMM-Newton, Chandra and Swift from 2000-2007, as well as Gemini observations taken after two bursts.

X-ray Observations

- Archival and proprietary XMM-Newton PN observations of 4U 0142+61 were used (see Table 1).
- Three Chandra observations in Continuous Clocking mode were also used, mainly for timing analysis. The calibration uncertainties do not allow us to reliably constrain the spectral properties.
- Two Swift observations were used as they provided enough counts to study the spectral and timing properties.

Date	MJD	CCD Mode/Exp. Time	Counts[a]
XMM–Newton:			
13/02/2002	52318.3	Small-Window/2.9 ks	1.29×10^5
24/01/2003	52663.9	Small-Window/3.8 ks	1.62×10^5
01/03/2004	53065.5	Timing/29.4 ks	1.47×10^6
24/07/2004	53211.3	Timing/21.2 ks	1.07×10^6
28/07/2006	53944.8	Small-Window/3.7 ks	1.71×10^5
13/01/2007	54113.8	Small-Window/4.4 ks	1.95×10^5
10/02/2007	54141.1	Timing/8.6 ks	4.24×10^5
Chandra:			
21/05/2000	51685.8	Continuous Clocking/5.9 ks	1.23×10^5
29/05/2006	53915.4	Continuous Clocking/18.6 ks	3.86×10^5
10/02/2007	54141.3	Continuous Clocking/20.1 ks	4.0×10^5
Swift:			
13/02/2005	53414.8	Windowed-Timing/6.6 ks	2.84×10^4
10/02/2007	54141.2	Windowed-Timing/3.5 ks	1.60×10^4

[a] Net counts in the 0.5–10.0 keV range.

Table 1. Summary of the X-ray observations of 4U 0142+61 used for this analysis.

Infrared Observations

- Two observations of 4U 0142+61 were obtained with the Gemini North Telescope, on 6 June 2006 and 13 February 2007. K_s band images were made with the Near-Infrared Imager (NIRI).

Timing Results

- Sample pulse profiles are shown in Figure 2. Over the last 7 years, the profile has become more sinusoidal, with the dip between the two peaks getting shallower while the relative height of the two components changes.
- This evolution was noted in RXTE profiles for energies > 2 keV by Dib et al. (2007). We can now confirm that changes are also present at lower energies.

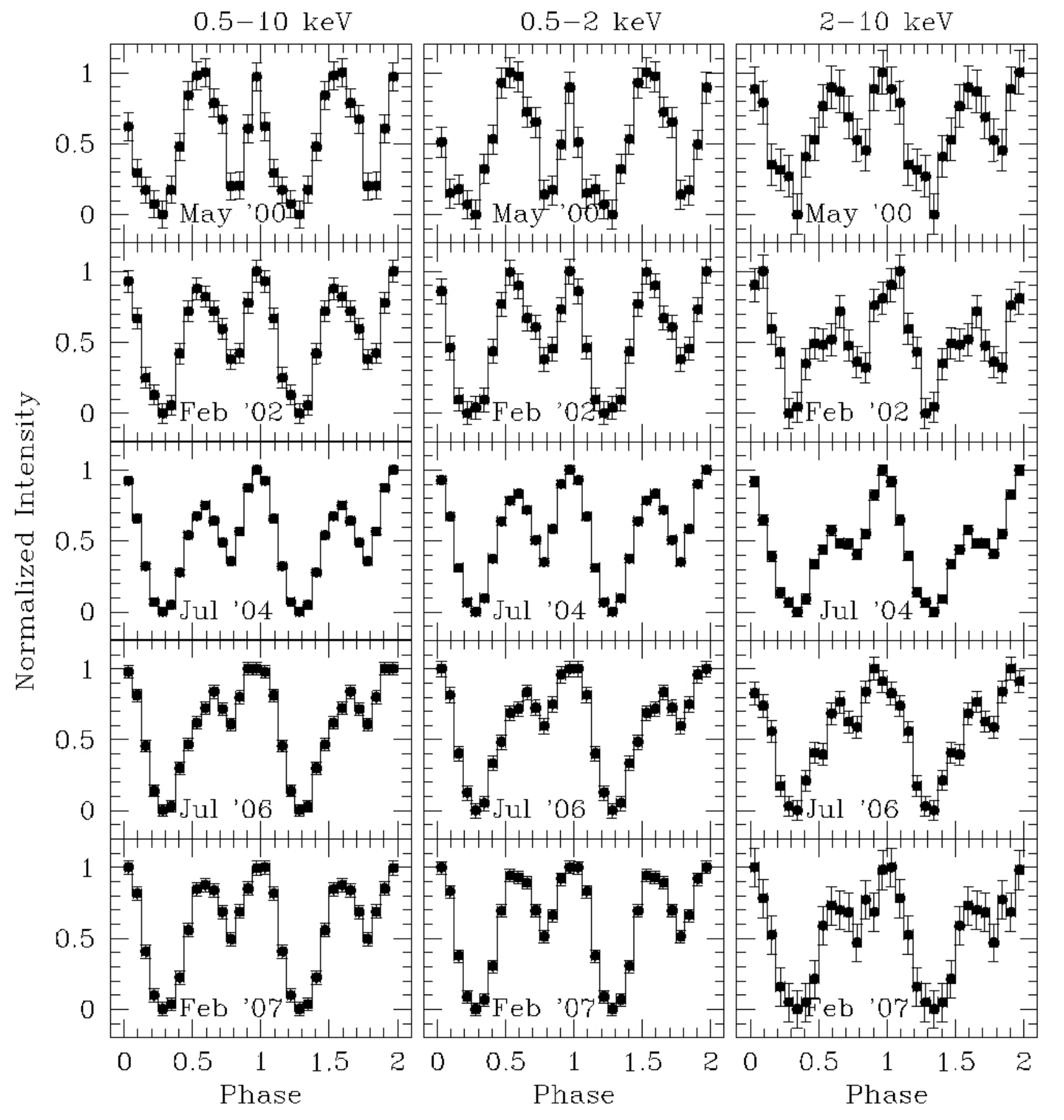

Figure 2. Pulse profiles of 4U 0142+61. The top row was obtained with Chandra, the rest with XMM.

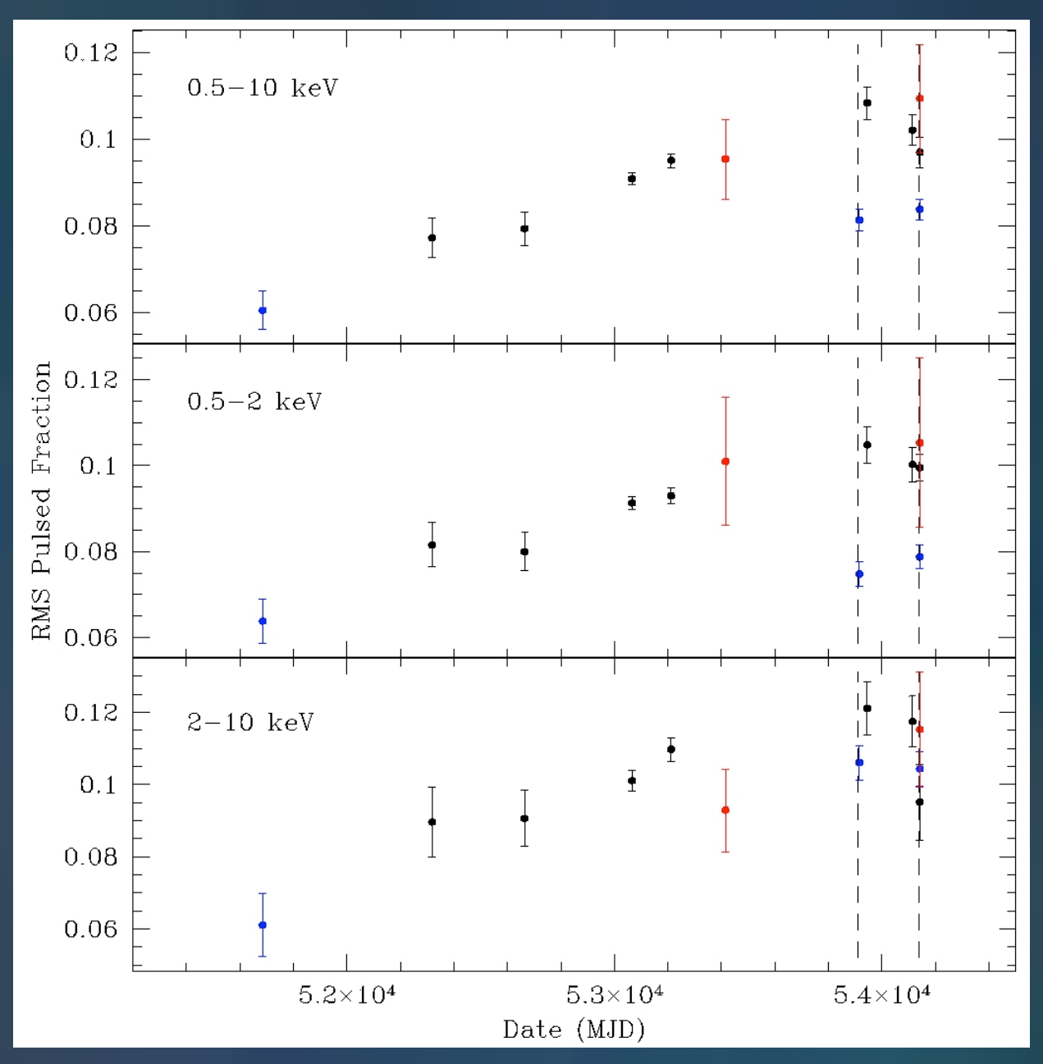

Figure 3. RMS pulsed fractions from XMM (black), Chandra (blue) and Swift (red).

- Figure 3 shows the RMS pulsed fractions (the dashed lines mark the known burst epochs).
- Although the Chandra points (blue) should be taken with caution because of uncertainties in the operating mode, an increase in the pulsed fraction of 4U 0142+61 over time is clearly visible.

Spectral Results

- The PN data were used to study the long-term spectral evolution of the pulsar.

Parameter	Range of values
Blackbody+Powerlaw (BB+PL):	
N_H	$9.81(1)\times10^{21}$ cm^{-2}
kT, R	0.39–0.44 keV, 5.7–7.3 km
Γ	3.69–3.77
χ^2(dof)	7407(6843)
Probability	1.1×10^{-6}
2 Blackbodies+Powerlaw (2BB+PL):	
N_H	$7.0(2)\times10^{21}$ cm^{-2}
$(kT, R)_{cool}$	0.29–0.31 keV, 14–16 km
$(kT, R)_{hot}$	0.53–0.57 keV, 3.0–3.8 km
Γ	2.8–2.95
χ^2(dof)	6558(6834)
Probability	0.991
2 Blackbodies+Broken Powerlaw (2BB+BknPL):	
N_H	$6.03(4)\times10^{21}$ cm^{-2}
$(kT, R)_{cool}$	0.27–0.32 keV, 15–19 km
$(kT, R)_{hot}$	0.52–0.61 keV, 2.5–4.4 km
Γ	1.42–1.73
χ^2(dof)	6777(6833)
Probability	0.684

Table 2. Spectral values for the models fit to 4U0142+61.

- Table 2 summarizes the best-fit parameters for various multi-components models to the 7 XMM observations. Figure 4 shows these sample models.
- Statistically, the 2BB+PL model described the observed spectrum significantly better than the traditional BB+PL model.

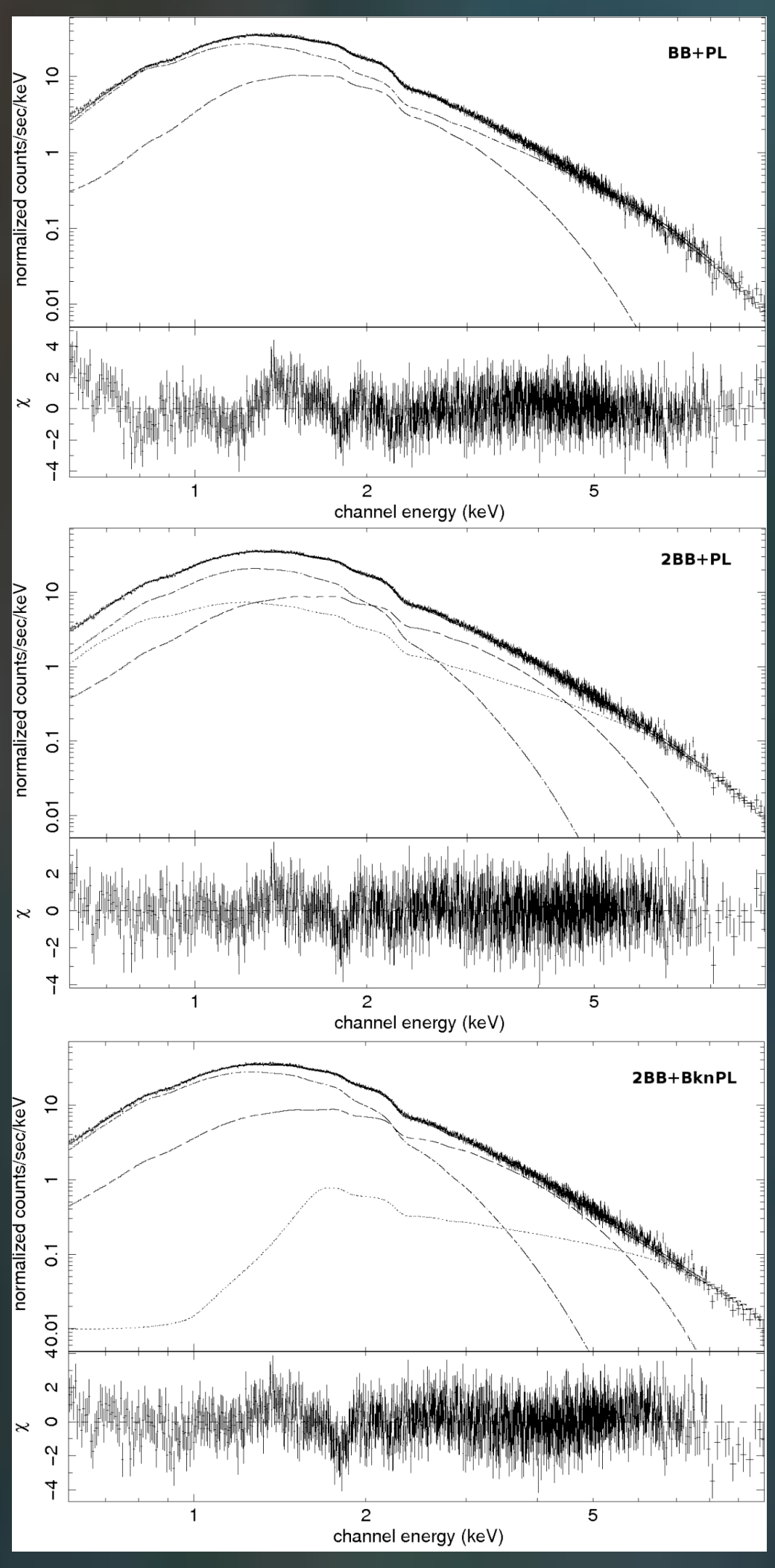

Figure 4. Sample spectral models for 4U 0142+61.

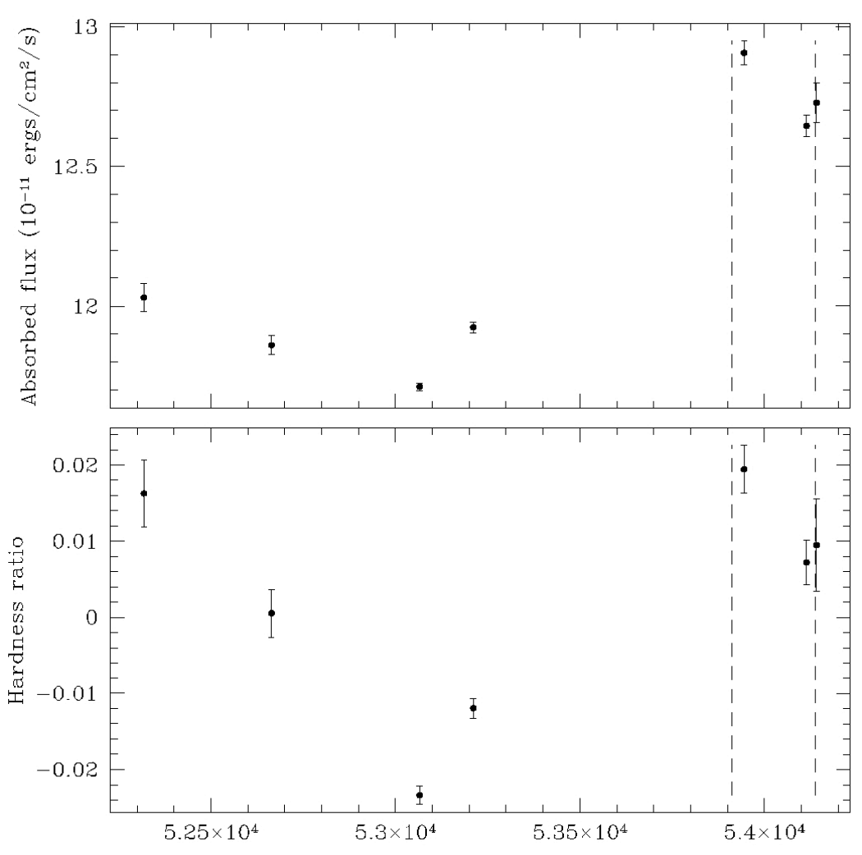

Figure 5. Top: 0.5-10 keV total absorbed flux. Bottom: Hardness for the observations.

- Independent of the model used, the phase-averaged XMM flux suggests that an increase of ~10% occurred between 2004 and 2006 (see Figure 5).
- The data also suggest that a correlation exists between the flux and hardness of the source (Hardness = [H-S] / [S+H], with H = flux in 2-10 keV range and S = flux in 0.5-2 keV range).

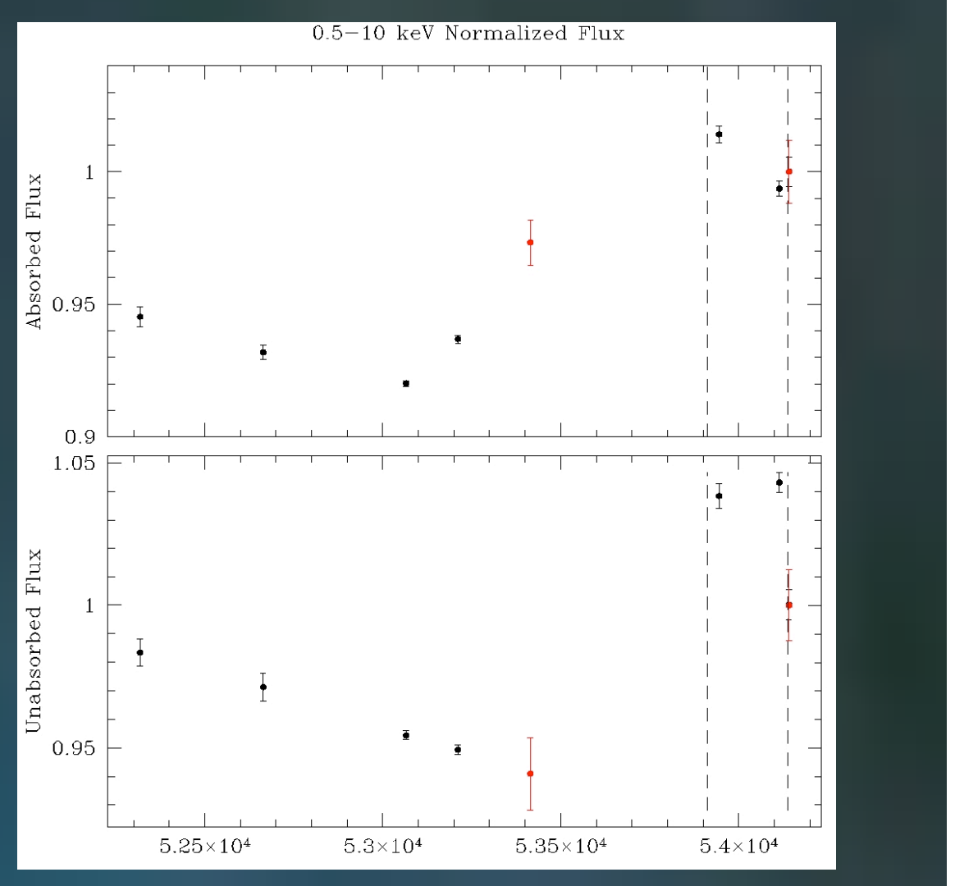

Figure 6. Fluxes for XMM (black) and Swift (red).

- Figure 6 shows the absorbed and unabsorbed fluxes for XMM and Swift using the 2BB+PL model. The values were normalized to that of the last observation (was carried out the same day for both telescopes) to account for cross-calibration differences. Again, significant changes in the emission characteristics are suggested by both telescopes.
- The Gemini observations give magnitudes of K_s = 19.70 ± 0.04 and K_s = 19.86 ± 0.02 for June 2006 and February 2007, respectively. These are in agreement with those previously reported for the source (K~19.68-20.78; Hulleman et al. 2004; Durant & van Kerkwijk 2006) and give no evidence for large changes in the emission characteristics at these wavelengths following the X-ray bursts.

Discussion

- These observations, and others, are revealing that variability in AXPs is common. This variability takes many forms, ranging from pulse profile changes to spectral variations. In some cases, such AXP radiative changes are accompanied by timing events (e.g., 1E 2259+586 showed a simultaneous glitch and outburst; Kaspi et al. 2003). However, this has yet to be unambiguously demonstrated for 4U 0142+61 despite its recent burst activity.
- In the magnetar model (Thompson et al. 2002), a twisted magnetosphere upscatters soft X-ray photons to produce the high-energy tail observed above the thermal peak. Changes in the emission are thought to represent changes to the twist angle of the star: larger twists produce brighter, harder emission. Very large twists disrupt the star enough to result in bursts. For 4U 0142+61, we see an increased flux and a hardening of the spectrum that coincides with a period of increased burst activity. These results appear to support the general predictions given by the magnetar model. Detailed predictions for the behavior of the pulse shape and pulsed fraction are not currently available for this model.
- In the case of 4U 0142+61, the discovery of IR emission from a possible disk has prompted debate whether it is a passive (Wang et al. 2006) or an active disk (Ertan et al. 2006). Depending on the model used, changes in the X-rays might or might not be accompanied by changes at longer wavelengths due to uncertainties in the reprocessing efficiency of the disk. Unfortunately, previously-reported IR fluxes from 4U 0142+61 fluctuate by up to ~1 mag and do not allow for intrinsic changes of several percent to be readily detected.