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Exciting the Magnetosphere of the Magnetar CXOU J164710.2-455216 in Westerlund 1

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ABSTRACT

We describe *XMM-Newton* observations taken 4.3 days prior to and 1.5 days subsequent to two remarkable events that were detected with *Swift* on 2006 September 21 from the candidate magnetar CXOU J164710.2-455216: (1) a 20 ms burst with an energy of 10^{37} erg (15–150 keV), and (2) a rapid spin-down (glitch) with $\Delta P/P \sim -10^{-4}$. We find that the luminosity of the pulsar increased by a factor of 100 in the interval between observations, from 1×10^{33} to 1×10^{35} erg s^{-1} (0.5–8.0 keV), and that its spectrum hardened. The pulsed count rate increased by a factor of 10 (0.5–8.0 keV), but the fractional rms amplitude of the pulses decreased from 65 to 11 per cent, and their profile changed from being single-peaked to exhibiting three peaks. Similar changes have been observed from other magnetars in response to outbursts, such as that of 1E 2259+586 in 2002 June. We suggest that a plastic deformation of the neutron star's crust induced a very slight twist in the external magnetic field, which in turn generated currents in the magnetosphere that were the direct cause of the X-ray outburst.

Key words: stars: neutron — pulsar: individual (CXOU J164710.2-455216) — X-rays: bursts — stars: magnetic fields

1 INTRODUCTION

Young, isolated neutron stars come in a variety of manifestations, including ordinary radio pulsars, compact central objects in supernova remnants, soft gamma repeaters (SGRs), and anomalous X-ray pulsars (AXPs). The latter two classes of source share long rotational periods (P=5–10 s), rapid spin-down rates ($\dot{P}\gtrsim10^{-12}$ s s^{-1}), X-ray luminosities ($L_{\rm X}\gtrsim10^{33}$ erg s^{-1}) that exceed their spin-down power, and the frequent production of second-long soft gamma-ray bursts (Woods & Thompson 2006). These properties suggest that they are magnetars, neutron stars powered by the unwinding of extremely strong ($B\gtrsim10^{15}$ G) internal magnetic fields (Thompson & Duncan 1995, 1996).

The phenomenology associated with magnetars is thought to be driven by how the unwinding internal fields interact with the crusts of the neutron stars, which in turn determines the geometries of the external magnetic fields (Thompson & Duncan 1995, 1996; Thompson, Lyutikov, & Kulkarni 2002). In some cases, the crusts respond to the unwinding fields plastically, and the energy is gradually deposited into the magnetospheres. This causes transient 'active periods,' in which the persistent fluxes increase on timescales of weeks to years (Woods et al. 2004; Gotthelf et al. 2004). Fractures may also occur in the crust, which generate waves in the external fields, and in turn produce sudden soft gamma-ray 'bursts' with energies up to 10^{41} erg (Göğüş et al. 2001; Gavriil, Kaspi, & Woods 2002). In the most extreme cases, instabilities can rearrange the entire external magnetic field, producing 'giant flares' with energies of $10^{44} - 10^{46}$ erg (Hurley et al. 1999; Palmer et al. 2005; Hurley et al. 2005). Finally, changes in the coupling between the bulk of the crust and a superfluid component appear to change the crust's angular momentum, as is suggested by both secular variations in the spin down rates

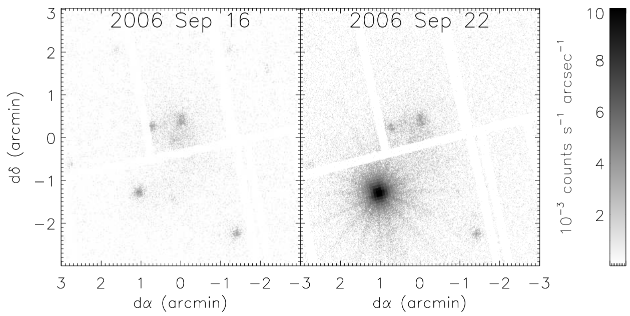

Figure 1. Images of the counts received by the EPIC-pn in the 0.5–10 keV band on 2006 September 16 (left) and 22 (right). The images are centred on the core of the star cluster Westerlund 1 (α, δ = 251.$^{\rm h}$76792 –45.$^\circ$84972 [J2000]). In addition to the AXP CXOU J164710.2-455216, also visible in the images are three bright OB/WR stars. The blank strips in the image are gaps between the chips in the detector array.

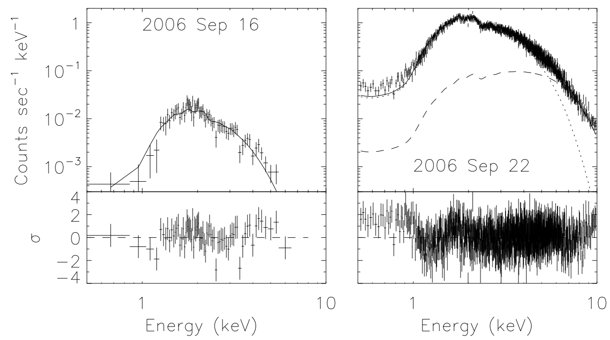

Figure 2. Phase-averaged spectra of CXOU J164710.2-455216 taken on 2006 September 16 and 22 (top panels), in units of detector counts. Models for the spectra are shown with a solid line: a single absorbed blackbody on September 16, and two absorbed blackbodies on September 22. For the latter spectrum, the cool and hot blackbodies are indicated with the dotted and dashed lines, respectively. The bottom panels display the difference between the data and the models, in units of the 1σ uncertainty on the data. There are systematic residuals at low energies in the September 22 spectrum, but these are not significant enough to affect the overall model.

on time-scales of weeks (Gavriil & Kaspi 2004; Woods et al. 2006) or sudden, day-long episodes of spin-up ('glitches') or spin-down (Woods et al. 1999; Gavriil & Kaspi 2003; Dall'Osso et al. 2003; Kaspi et al. 2003; Woods et al. 2004). Unfortunately, the frequent, sensitive monitoring observations that are required to identify transient active periods, to detect bursts, and to track the rotation of these pulsars have not always been available. Therefore, in many cases the causal connections between these phenomena have been unclear (e.g., Gavriil & Kaspi 2003; Woods et al. 2005).

Here we report *XMM-Newton* observations of the 10.6 s X-ray pulsar, CXOU J164710.2-455216 (Muno et al. 2006), that bracketed a series of events that occurred near 2006 September 21. Near this time, *Swift* detected a soft gamma-ray burst (Krimm et al. 2006) and a glitch with $\Delta P/P \sim -10^{-4}$ (Israel et al. 2007). These events confirm our original hypothesis that this source is a magnetar (Muno et al. 2006). We find that during the interval between our two *XMM-Newton* observations, there were also dramatic changes in the luminosity, spectrum, and pulse profile of CXOU J164710.2-455216. We compare these to changes observed during active periods from other magnetars, and discuss the implications for the interaction between the magnetic fields and crusts of the these neutron stars.

2 OBSERVATIONS

As part of the guest observer programme, *XMM-Newton* observed CXOU J164710.2-455216 for 46 ks starting on 2005 September 16 at 18:59:38 (UTC). Fortuitously, 4.3 days later, on 2006 September 21 at 01:34:53 (UTC), the *Swift* Burst Alert Telescope (BAT) detected a 20 ms burst from the direction of Westerlund 1 (Krimm et al. 2006), with an energy of 3×10^{37} erg (15–150 keV; for a distance D=5 kpc; Clark et al. 2005). In response, the director of *XMM-Newton* carried out an observation lasting 30 ks beginning 1.5 days later on 2006 September 22 at 12:40:27 (UTC). We analysed the *XMM-Newton* observations in order to study changes in the X-ray flux, spectrum, and pulse profile.

We analysed the data taken with the European Photon Imaging Camera (EPIC). For most of the timing and spectral analysis, we used data taken with 73.4 ms time resolution using the pn array. The data from the MOS arrays were taken with 2.4 s time resolution, which was inadequate for studying the profile of this 10.6 s pulsar. Moreover, the data suffered from pile-up during the second observation, when the source was bright (see below). Therefore, we only used the MOS data to generate spectra for the first observation.

We processed the observation data files using the standard tools (`epchain` and `emchain`) from the Science Analysis Software version 7.0. The events were filtered in the standard manner, and we adjusted the arrival times of the events to the Solar System barycentre. Images from the EPIC-pn data are displayed in Figure 1. Comparing the data from before and after the *Swift* burst, we find that CXOU J164710.2-455216 increased in count rate by a factor of 80 (0.5–8.0 keV).

Next, we extracted pulse-phase-averaged spectra from within 15$''$ of the location of CXOU J164710.2-455216 (α, δ = 251.$^{\rm h}$79250, –45.$^\circ$87136 [J2000]). Estimates of the background were extracted from a 30$''$ circular region that was located 1$'$.5 west of the source region. We obtained the detector response and effective area using standard tools (`rmfgen` and `arfgen`). The EPIC-pn spectra are displayed in Figure 2.

We modeled these spectra using `XSPEC` version 12.2.1. We first assumed that the spectra could be described as blackbody emission absorbed by interstellar gas and scattered by dust. This model was acceptable for the observations before the burst on September 16 (χ^2/ν = 59.4/67), but was inconsistent with the data from September 22 (χ^2/ν = 2255/1136). For the later observation, we could model the spectrum with two continuum components, either the sum of two blackbodies, or a blackbody plus power law continuum. We assumed that the interstellar absorption column toward the source did not change between observations. The spectral parameters, fluxes, and luminosities for the above models are listed in Table 1. For completeness, we also list

Table 1. Spectral Models for CXOU J164710.2-455216

	2005 May–Jun	2006 Sep 16	2006 Sep 22
Two Blackbodies			
$N_{\rm H}$ (10^{22} cm^{-2})	1.28	1.28	1.28(2)
kT_1 (keV)	0.60(1)	0.54(1)	0.67(1)
$A_{\rm bb,1}$ (km^2)	0.09(1)	0.08(1)	3.62(2)
kT_2 (keV)	...	...	1.7(1)
$A_{\rm bb,2}$ (km^2)	...	...	0.021(6)
$F_{\rm X}$ (10^{-13} erg cm^{-2} s^{-1})	2.3	1.5	215.7
$L_{\rm X}$ (10^{33} erg s^{-1})	1.4	1.0	109.7
Blackbody Plus Power Law			
$N_{\rm H}$ (10^{22} cm^{-2})	1.44	1.44	1.44(1)
kT_1 (keV)	0.58(2)	0.52(1)	0.68(1)
$A_{\rm bb,1}$ (km^2)	0.11(1)	0.11(1)	2.87(3)
Γ	...	...	2.07(4)
N_Γ (10^{-3} cm^{-2} s^{-1} keV^{-1})	...	...	3.7(9)
$F_{\rm X}$ (10^{-13} erg cm^{-2} s^{-1})	2.3	1.5	214.1
$L_{\rm X}$ (10^{33} erg s^{-1})	1.5	1.1	130.3

The reduced chi-squared for both joint fits were 1423/1298. The interstellar absorption was assumed not to have changed over the course of these observations. To compute the area of the blackbody emission, we assumed D=5 kpc. N_Γ is the photon flux density of the power law at 1 keV. Uncertainties are 1σ, for one degree of freedom. Fluxes are in the 0.5–8.0 keV band.

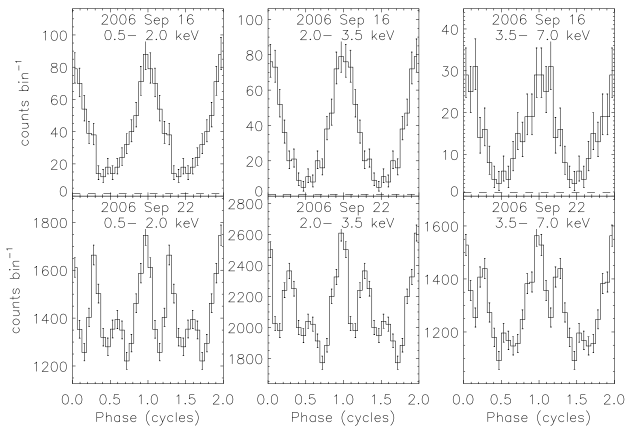

Figure 3. Pulse profiles of CXOU J164710.2-455216 taken on 2006 September 16 (top panels) and 2006 September 22 (bottom panels), and in three energy bands: 0.5–2.0 keV (left panels), 2.0–3.5 keV (middle panels), and 3.5–7.0 keV (right panels). Two identical cycles are repeated in each panel. The dashed line in the top panel represents the background count rate.

parameters from models of the spectra taken with *Chandra* during 2005 May and June (Muno et al. 2006).

For both models, we found that the luminosity was a factor of 100 higher (0.5–8.0 keV) 1.5 days after the burst than it was 4.3 days before the burst. The increase in flux was largely because the area of the ≈0.5 keV blackbody increased from 0.1 km^2 before the burst to ≈3 km^2 after the burst. It also resulted from the prominence of the hard component after the burst. Modeled as a kT=1.7 keV blackbody, it produced 26 per cent of the observed flux on 2006 September 22 (18 per cent of the absorption-correction flux). Modeled as a Γ=2.07 power law, it produced 50 per cent of the observed flux (70 per cent of the intrinsic flux; 0.5-8.0 keV). If we add these components to our models for the spectra taken on 2006 September 16, we find that their fractional contribution to the observed flux was lower: <15 per cent for the blackbody, and <35 per cent for the power law.

To identify pulsations from CXOU J164710.2-455216, we computed Fourier periodograms using the Rayleigh statistic. (A search for pulsations from other point sources in the field revealed no other pulsars.) This provided an initial estimate of the pulse period, which we then refined by computing pulse profiles from non-overlapping 5000 s intervals during each observation, measuring their phases by cross-correlating them with the average pulse profile from each observation, and modeling the differences between the assumed and measured phases using first-order polynomials. The best-fitting periods were 10.61065(7) s and 10.61064(8) s for 2006 September 16 and 22, respectively. These values are within 1.5σ of the periods measured in 2005 May and June, 10.6112(4) s and 10.6107(1) s, respectively (Muno et al. 2006). The reference epochs of the pulse maxima for the two observations in 2006 September were 53994.786313(2) and 54000.526588(1) (MJD, Barycentre Dynamical Time). Monitoring observations taken with *Swift* reveal that a glitch with a fractional period change of $\Delta P/P \sim -10^{-4}$ occurred between these two observations; a discussion of this result is presented in (Israel et al. 2007).

We used these ephemerides to compute the pulse profiles in the full band of 0.5–8.0 keV, and three sub-bands: 0.5–2.0 keV, 2.0–3.5 keV, and 3.5–7.0 keV. The root-mean-squared (rms) amplitudes of the pulsations in the full band (0.5–8.0 keV) increased from 0.02 count s^{-1} before the burst, to 0.29 count s^{-1} after the burst. At the same time, the fractional rms amplitudes declined from 64 per cent before the burst to 11 per cent after the burst. Moreover, the pulse profile changed dramatically after the burst, as can be seen in the profiles from the sub-bands displayed in Figure 3. Before the burst, the pulse at all energies was single peaked, and the differences in the pulse profile as a function of energy are not very pronounced. After the burst, the pulse in the full band displayed three distinct peaks, and a dependence on energy developed. Specifically, in the 3.5–7.0 keV band, the third peak was absent and the flux between the first two peaks (phases 0.1–0.3) was larger, so that the overall profile was more sinusoidal at high energies than at low.

We examined whether phase-resolved spectroscopy could provide any insight into the origin of the pulses. Unfortunately, CXOU J164710.2-455216 was too faint on 2006 September 16 to generate spectra for all but the peak of the pulse. We did examine phase-resolved spectra for 2006 September 22, but found no systematic trend relating the spectral parameters with the intensity as a function of phase.

Finally, we searched for bursts by examining the time series of events recorded by the EPIC-pn. We found no evidence for bursts producing more than 4 counts within the 73.4 ms frame time, which placed an upper limit to their observed fluence of 3×10^{-11} erg cm^{-2} (for a Γ=1.8 power law; Krimm et al. 2006), or an energy of $<2\times10^{35}$ erg (0.5–8.0 keV; D=5 kpc).

3 DISCUSSION

In the 5.8 days between our two *XMM-Newton* observations of CXOU J164710.2-455216, a remarkable set of events occurred. First, the phase-averaged luminosity of CXOU J164710.2-455216 increased by a factor of $\sim$100, from $L_{\rm X} = 1 \times 10^{33}$ to $L_{\rm X} = 1 \times 10^{35}$ erg s^{-1} (0.5–8.0 keV; Fig. 1; Campana & Israel 2006), and the spectrum hardened (Table 1). Energetically, this is the most important feature of this active period. In the 1.5 days after the burst, if we conservatively assume the persistent flux from CXOU J164710.2-455216 was constant, the total energy released was $\sim 10^{40}$ erg (0.5–8.0 keV). Second, a 20 ms long burst with an energy of 3×10^{37} erg (15–150 keV) was detected from this source with the BAT on board *Swift* (Krimm et al. 2006). Third, a glitch was observed in the spin period of the pulsar, with $\Delta P/P \sim -10^{-4}$ (Israel et al. 2007). Fourth, the pulse profile changed from having a simple, single-peaked structure, to exhibiting three distinct peaks with pronounced energy dependence (Fig. 3). Similar changes in the fluxes, spectra, and timing properties of magnetars have been observed before, but the combination observed from CXOU J164710.2-455216 is unique.

It is common for the persistent luminosities of magnetars to vary on time scales of weeks to years. The persistent luminosities from the SGRs 1900+14 (Woods et al. 2001) and 1806–20 (Woods et al. 2006) and the bright AXPs 1E 1048.1–5937 (Gavriil & Kaspi 2004; Tiengo et al. 2005) and 1E 2259+586 (Woods et al. 2004) have been observed to vary by factors of 2–3 around $\sim 10^{34} - 10^{35}$ erg s^{-1} (0.5–10 keV). The luminosities of SGR 1627–41 (Kouveliotou et al. 2003) and the transient AXP XTE J1810–597 (Ibrahim et al. 2004; Gotthelf et al. 2004) have been observed to increase by factors of 100, from $\sim 10^{33}$ to $\sim 10^{35}$ erg s^{-1} (0.5–10 keV). The larger luminosities, $\sim 10^{35}$ erg s^{-1}, appear to be a rough upper envelope for the persistent 0.5–8.0 keV fluxes of magnetars (not counting bursts and giant flares). Indeed, the active period from CXOU J164710.2-455216 also had $L_{\rm X} \approx 10^{35}$ erg s^{-1} (0.5–8.0 keV). This persistent flux is generally assumed to be produced because the unwinding internal fields induce gradual, plastic deformations in the crust and external magnetic fields, which in turn heats the surface or magnetosphere (Thompson & Duncan 1995, 1996). Therefore, the increase in the flux from CXOU J164710.2-455216 demonstrates that either the unwinding of the internal fields, or the response of the crust to that unwinding, is intermittent and can activate in $\lesssim$5 days.

The active periods from magnetars are often accompanied by second-long bursts. These bursts are the hallmarks of SGRs, and during their active periods hundreds will occur over the course of a year with energies of up to 10^{41} erg (2–60 keV; Göğüş et al. 2001).The bursts detected from AXPs have all been weaker, with peak energies of $\lesssim 10^{38}$ erg (2–60 keV). In the AXPs XTE J1810–597 (Woods et al. 2005) and 1E 1048.1–5937 (Gavriil, Kaspi, & Woods 2006), the bursts that have been detected are infrequent and relatively isolated. In 1E 2259+586 (Woods et al. 2004), a series of bursts were detected during an 11 ks observation that occurred within 7 days of the start of an active period in 2002 June. The burst detected from CXOU J164710.2-455216 resembles those from 1E 2259+586, in that it occurred very near the start of an active period. The energy of the burst (3×10^{37} erg; 15–150 keV) is trivial compared to that released as persistent flux ($\gtrsim 10^{40}$ erg; 0.5–8.0 keV), so it is probably not a trigger, but a symptom of the active period. Under the magnetar model, the bursts that accompany the active periods are caused by fractures that occur in the crust. These fractures inject into the magnetosphere currents that are unstable to to wave motion, which quickly generates hot, X-ray emitting plasma (Thompson & Duncan 1995, 1996). It is reasonable to expect that such fractures would be stronger and occur more frequently when the persistent flux is higher, because the crust is already under stress.

Variations in the spin-down rates have been observed from several luminous ($L_{\rm X} \gtrsim 10^{34}$ erg s^{-1}; 0.5–8.0 keV) magnetars. Torque variations have been detected from 1E 1048.1–5937 (Gavriil & Kaspi 2004) and SGR 1806–20 (Woods et al. 2006), in association with their active periods. Sudden period changes have been seen in three cases. Two glitches have been detected from 1RXS J170849–400910 with $\Delta P/P \sim -1 \times 10^{-6}$ and -6×10^{-6} (Gavriil & Kaspi 2003; Dall'Osso et al. 2003). Neither were associated with active periods, but the monitoring observations were sparse, so one could have been missed (Dall'Osso et al. 2003). One glitch accompanied the 2002 June active period of 1E 2259+586 in which the spin period decreased by $\Delta P/P \sim -10^{-6}$ (Kaspi et al. 2003; Woods et al. 2004). Finally, a dramatic episode of spin-down occurred near the time of a 10^{44} erg (3–100 keV) giant flare from SGR 1900+14, with $\Delta P/P \sim 10^{-4}$ (Woods et al. 1999). This is of comparable magnitude to the glitch from CXOU J164710.2-455216, albeit of the opposite sign (Israel et al. 2007).

The glitch appears to have been a major energetic component of the outburst from CXOU J164710.2-455216. Glitches are ascribed to sudden changes in the moments of inertia of the neutron stars that occur when crustal movements change how superfluid in the interior is coupled to the bulk of the crust (e.g., Dall'Osso et al. 2003; Kaspi et al. 2003). The change in rotational energy during the glitch, assuming most of the star rotates as a solid body, is on order $\Delta E_{\rm rot} \sim I\Omega\Delta\Omega$, where $I \sim 10^{45}$ g cm^2 is the moment of inertia of a neutron star with mass M=1.4 M$_\odot$ and radius R=1 km. For CXOU J164710.2-455216 Ω=0.6 rad s^{-1} and $\Delta\Omega = 6 \times 10^{-5}$ rad s^{-1}, so $\Delta E_{\rm rot} \sim 10^{40}$ erg. However, a larger input of energy into the stellar interior may be required to unpin the superfluid vortices and initiate the glitch, $\sim 10^{42}$ erg (e.g., Link & Epstein 1996; Thompson et al. 2000). In contrast, the radiative output of CXOU J164710.2-455216 in the first week of this active period was only $\sim 10^{40}$ erg (0.5–8.0 keV). Whereas for the giant flare from SGR 1900+14 and the 2002 June active period from 1E 2259+586 it appeared that most of the energy was radiated away from the magnetosphere (Thompson et al. 2000; Woods et al. 2004), for CXOU J164710.2-455216 most of the energy was probably input into the interior of the neutron star.

The change in the pulse profile of CXOU J164710.2-455216 is also difficult to understand from an energetic standpoint. Changes in the qualitative shape of the pulse profiles (as opposed to changes in the pulsed fraction) have only been seen previously from three sources. For 1E 2259+586, the profile before the 2002 June burst exhibited two distinct peaks, whereas after the burst the phases between the peaks contained more flux, so that part of the profile resembled a single plateau of emission (Woods et al. 2004). This change is minor compared to that from CXOU J164710.2-455216 in Figure 3. Large changes in the harmonic structure of the pulse profile have only been observed in response to the giant flares from SGRs. For SGR 1900+14 the profile had three peaks before the flare in 1998, and a single peak during and after (Woods et al. 2001). For SGR 1806–20, the opposite change occurred in 2004: it shifted from having a simple, single-pulsed profile to having multiple peaks (Woods et al. 2006).

For the SGRs, the changes in the pulse profiles are thought to occur because the multipole structure of the external magnetic fields are rearranged. This is reasonable, because the giant flares release a significant fraction of the energy in the external fields. For a dipole, this would be $E_B \approx \frac{1}{12} B_{\rm ext}^2 R^3 \sim 10^{45}$ G, where we take $B_{\rm ext}{\sim}10^{14}$ G, and $R{\sim}10$ km (Woods et al. 1999; Hurley et al. 2005). However, for CXOU J164710.2-455216, and to a lesser degree for 1E 2259+586, it is unreasonable to suggest that active periods releasing only $\sim 10^{40}$ erg of X-rays resulted from a significant rearrangement of the exterior magnetic fields.

Instead, we suggest that a change occurred in the distribution of currents in the magnetosphere. We hypothesize that the emission in quiescence is thermal emission from the cooling neutron star, which emerges through a hot spot where the opacity of the highly-magnetized atmosphere is lowest (Heyl & Hernquist 1998). A single hot spot on the surface could explain the single-peaked, fully modulated (≈70 per cent rms) pulse in quiescence (Özel, Psaltiz, & Kaspi 2001). We suggest that the active period was initiated when a very small twist was imparted to the magnetic field by plastic motions of the crust. Currents formed to compensate for this twist, which heated the surface of the star and resonantly scattered the emission from its surface (Table 1). Both of these would contribute to creating the complex pulse profile (Thompson et al. 2002). If our scenario is correct, when this source returns to quiescence, the pulse should regain its single-peaked profile.

4 CONCLUSIONS

We have examined the X-ray luminosity, spectrum, and pulse profile of CXOU J164710.2-455216 before and after an interval during which *Swift* detected a soft gamma-ray burst and a timing glitch from the source. The energy radiated from the exterior was too small to have resulted from a significant rearrangement of the external magnetic fields of CXOU J164710.2-455216. Instead, the dramatic change in the pulse profile indicates that the underlying emission mechanism changed. Before the burst, the X-ray emission was probably powered by the thermal energy of the star, whereas afterwards it was powered by currents in the magnetosphere. Moreover, the glitch required an energy at least as large as the energy released as X-rays, $\gtrsim 10^{40}$ erg, which suggests that much of the energy of this event was input into the interior of the neutron star. Future X-ray observations of this source will reveal the duration and duty cycle of this active period, which would constrain the amount of energy input into the interior. This could help answer why the emission, which is thought to be produced as the internal fields of magnetars unwind, can remain inactive for years and then suddenly turn on in a few days.

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