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 d prior to and 1.5 d subsequent to two remarkable events that were detected with Swift on 2006 September 21 from the candidate magnetar CXOU J164710.2–455216: (i) a 20-ms burst with an energy of $10^{37}$ erg (15–150 keV), and (ii) 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 $1 \times 10^{33}$ to $1 \times 10^{35}$ 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 distinct 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 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: magnetic fields – stars: neutron – pulsars: individual: CXOU J164710.2–455216 – X-rays: bursts.

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), high spin-down rates ($\dot{P} \gtrsim 10^{-12}$ s$^{-1}$), X-ray luminosities ($L_X \gtrsim 10^{33}$ 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 ($B \gtrsim 10^{15}$ 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 time-scales of weeks to years (Gotthelf et al. 2004; Woods 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, 2005; Palmer et al. 2005). Finally, changes in the coupling between the bulk of the crust and a superfluid component appear to change the angular momentum of the crust, as is suggested by both secular variations in the spin-down rates on time-scales of weeks (Gavriil & Kaspi 2004; Woods et al. 2007), and sudden, day-long episodes of spin-up (‘glitches’) or

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spin-down (Woods et al. 1999, 2004; Dall’Osso et al. 2003; Gavriil & Kaspi 2003; Kaspi et al. 2003). 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), which 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. 2006). 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 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 d 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 $3 \times 10^{56}$ 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 d 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. The images from the EPIC-pn data are displayed in Fig. 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 arcsec of the location of CXOU J164710.2–455216 [$\alpha, \delta = 25^h 79^m 25^s, -45\degr 87\arcmin 16\arcsec$ (J2000)]. Estimates of the background were extracted from a 30-arcsec circular region that was located 1.5 arcmin 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 Fig. 2.

We modelled 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 ($\chi^2/\nu = 59.9/67$), but was inconsistent with the data from September 22 ($\chi^2/\nu = 2225/1136$). 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 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 d after the burst than it was 4.3 d before the burst. The increase in flux was largely because the area of the $\approx 0.5$-keV blackbody increased from 0.1 km$^2$ before the burst to $\approx 3$ km$^2$ after the burst. It also resulted from the prominence of the hard component after the burst. Modelled 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). Modelled as a $\Gamma = 2.07$ 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...
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 fluxes of $3 \times 10^{-11}$ cm$^{-2}$ s$^{-1}$ (for a $\Gamma = 1.8$ power law; Krimm et al. 2006), or an energy of $<2 \times 10^{35}$ erg (0.5–8.0 keV; $D = 5$ kpc).

### 3 Discussion

In the 5.8 d 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 $L_X = 1 \times 10^{33}$ to $1 \times 10^{35}$ erg s$^{-1}$ (0.5–8.0 keV; Fig. 1; Campa & Israel 2006), and the spectrum hardened (Table 1). Energetically, this is the most important feature of this active period. In the 1.5 d after the burst, if we conservatively assume that the persistent flux from CXOU J164710.2–455216 was constant, the total energy released was $\sim 10^{40}$ erg (0.5–8.0 keV).

Secondly, a 20 ms long burst with an energy of $3 \times 10^{37}$ erg (15–150 keV) was detected from this source with the BAT on board Swift (Krimm et al. 2006). Thirdly, a glitch was observed in the spin period of the pulsar, with $\Delta P/P \sim 10^{-4}$ occurred between these two observations (Israel et al. 2006); a discussion of this result will be presented elsewhere (Israel et al. 2007).

We used these ephemerides to compute the pulsation profiles in the full band of 0.5–8.0 keV, and three sub-bands: 0.5–2.0, 2.0–3.5 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 Fig. 3. Before the burst, the pulse at all energies was single-peaked, and the differences in the pulse profile as a function of energy were not very pronounced. After the burst, the pulse in the full band displayed three 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. 2007) 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 (Gotthelf et al. 2004; Ibrahim et al. 2004) have been observed to increase by factors of 100, from $\sim 10^{35}$ to $\sim 10^{39}$ erg s$^{-1}$ (0.5–10 keV). The larger luminosities, $\sim 10^{39}$ 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 $L_X \approx 10^{35}$ 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 heat 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 $\lesssim 5$ d.

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; Gögüs et al. in press) and a single peak during and after (Woods et al. 2001). For the SGRs, the changes in the pulse profiles are thought to occur because the 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 that most of the star rotates as a solid body, is of the order of $\Delta E_{\text{rot}} \sim I \Omega \Delta \Omega$, 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, $\Omega = 0.6$ rad s$^{-1}$ and $\Delta \Omega = 6 \times 10^{-5}$ rad s$^{-1}$, so $\Delta E_{\text{rot}} \sim 10^{40}$ 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 $\sim 10^{39}$ 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 with that from CXOU J164710.2–455216 in Fig. 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. 2007).

For the SGRs, the changes in the pulse profiles are thought to occur because the multipole structure of the external magnetic fields is 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 $E_B \approx \frac{1}{2} B_0^2 R^3 \sim 10^{44}$ G, where we take $B_{\text{ext}} \sim 10^{14}$ 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 external 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 hotspot where the opacity of the highly magnetized atmosphere is lowest (Heyl & Hernquist 1998). A single hotspot on the surface could explain the single-peaked, fully modulated ($\approx 70$ per cent rms) pulse in quiescence (Özel, Psaltis & 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 to 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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