XMM-NEWTON OBSERVATIONS OF CXOU J010043.1−721134: THE FIRST DEEP LOOK AT THE SOFT X-RAY EMISSION OF A MAGNETAR

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ABSTRACT

We present the analysis of six XMM-Newton observations of the anomalous X-ray pulsar CXOU J010043.1−721134, the magnetar candidate characterized by the lowest interstellar absorption. In contrast with all the other magnetar candidates, its X-ray spectrum cannot be fitted by an absorbed power-law plus blackbody model. The sum of two (absorbed) blackbody components with $kT_1 = 0.30 \pm 0.02$ keV and $kT_2 = 0.7 \pm 0.1$ keV gives an acceptable fit, and the radii of the corresponding blackbody emission regions are $R_{\text{BB1}} = 12.1_{-2.4}^{+19}$ km and $R_{\text{BB2}} = 1.7_{-0.6}^{+0.9}$ km. The former value is consistent with emission from a large fraction of a neutron star surface, and given the well-known distance of CXOU J010043.1−721134, which is located in the Small Magellanic Cloud, it provides the most constraining lower limit to a magnetar radius ever obtained. A more physical model, where resonant cyclotron scattering in the magnetar magnetosphere is taken into account, has also been successfully applied to this source.

Subject headings: pulsars: individual (CXOU J010043.1−721134) — stars: neutron

1. INTRODUCTION

The anomalous X-ray pulsars (AXPs; see Mereghetti 2008 for a recent review) were initially identified as a subclass of accreting X-ray pulsars. Their much softer X-ray spectrum and the lack of a bright optical counterpart distinguished them from the vast majority of X-ray pulsars, which are neutron stars accreting in high-mass X-ray binaries. AXPs have rotation periods of several seconds and show a secular spin-down on timescales of $10^7$−$10^9$ yr, but their rotational energy loss is smaller than their X-ray luminosity, excluding that they are rotation powered, like radio pulsars. It is generally believed that the AXPs, as well as another small class of high-energy sources with similar properties, the soft gamma-ray repeaters (SGRs), are magnetars, i.e., neutron stars powered by their extremely high magnetic field ($\sim 10^{15}$ G; Duncan & Thompson 1992; Thompson & Duncan 1996).

The soft X-ray ($1$−$10$ keV) spectra of magnetars cannot be adequately fitted with single-component models whenever data with good count statistics are available. Successful fits are instead obtained by a two-component model consisting of a steep power law (photon index $\sim 3$−$4$) and a blackbody ($kT \sim 0.5$ keV).

Some attempts have been made, also based on phase-resolved spectroscopy, to attribute the two components to physically distinct processes (e.g., Tiengo et al. 2005), but no particularly compelling interpretations could be obtained.

One problem with this model is that it tends to give best-fit values of the interstellar absorption higher than those independently estimated in other ways (e.g., Durant & van Kerkwijk 2006). Another problem is that the power-law component cannot be extrapolated at lower energies without exceeding the flux of the near-infrared (NIR) and optical counterparts (e.g., Hullman et al. 2004). Drastic, and possibly unphysical, cut-offs in the power-law component are required to match the low optical/NIR fluxes.

In some AXPs good spectral fits are obtained with the sum of two blackbody components with different temperatures. Since this model does not suffer from the problems described above, it is usually preferred to the power-law plus blackbody model (e.g., Halpern & Gotthelf 2005). However, this model is also only phenomenological, and it is inadequate to represent the non-thermal phenomena that are expected to occur in the highly magnetized magnetosphere of magnetars (e.g., Lyutikov & Gavriil 2006). More physical models of the X-ray spectra, including the effects of the strong magnetic field and charged currents, have recently been developed and successfully applied to a sample of magnetar candidates (Fernández & Thompson 2007; Güver et al. 2007; Rea et al. 2008).

From a purely observational point of view, it has not been possible to discriminate between the different models that reproduce the magnetar X-ray spectra. This is mainly due to the low sensitivity of hard X-ray detectors above $\sim 10$ keV and to the large uncertainties in the fits introduced by the high interstellar absorption, which severely suppresses the flux below $\sim 1$ keV.

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2. OBSERVATIONS AND DATA ANALYSIS

The field containing CXOU J010043.1−721134 was observed six times$^4$ with the XMM-Newton satellite (see Table 1). Here we report the analysis of the data collected by the EPIC instrument, which is composed of one PN (Strüder et al. 2001) and two MOS X-ray cameras (Turner et al. 2001).

CXOU J010043.1−721134 was not the main target of the observations, but, being at an off-axis angle of $\sim 6^\circ$, it was always well inside the field of view of the EPIC instrument ($\sim 15^\circ$ radius). All the observations were performed with the medium optical blocking filter and in full-frame mode (time resolution of $73$ ms

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$^4$ Only the data from the two first observations have already been published (Lamb et al. 2002; Nazé et al. 2004; Majid et al. 2004; McGarry et al. 2005; Nakagawa et al. 2007); we reanalyzed them using more recent calibration files, in order to consistently compare the results with those of the new observations.
and 2.6 s for the PN and MOS, respectively), except for the first PN observation, done in extended full-frame mode (time resolution of 200 ms). All the data were processed using the XMM-Newton Science Analysis Software (SAS version 7.1.0) and the calibration files released in 2007 August. The standard pattern selection criteria (patterns 0–4 for PN and 0–12 for MOS) were adopted.

Source spectra were extracted for each observation from circular regions with 25″ radius. The background spectra were extracted from a 94″ × 72″ box centered at R.A. = 01h00m56.8, decl. = −72°11′33″ and rotated such that it intercepts no CCD gaps in any PN image. Response matrices and ancillary files for each spectrum were produced using the SAS software.

The spectra were fitted to a set of models (power law, blackbody plus power law, and two blackbodies, all modified by photoelectric absorption) using XSPEC version 11.3.1. The single-component models gave only marginally acceptable fits in most observations, while better results were obtained with the two-component models. The best-fit parameters of the latter models are reported in Table 2.

In order to check for flux variability, we have also simultaneously fitted the five available PN spectra and the two MOS spectra for observation C with a double blackbody model with all parameters linked to the same value and a variable normalization factor. From this analysis we can exclude significant (>3 σ) flux variations larger than ~20% among the different XMM-Newton observations.

Since no significant differences in the spectral parameters are detected and the calibration of the PN instrument has proved to be very stable throughout the XMM-Newton mission (see, e.g., Kirsch et al. 2005), a cumulative spectrum of the PN data of observations B, D, E, and F has also been extracted. The resulting net exposure time is 58 ks. Only the double blackbody model gives an acceptable fit to the cumulative spectrum with \( kT_1 \sim 0.3 \text{ keV} \) and \( kT_2 \sim 0.7 \text{ keV} \) (see Fig. 1 and Table 2). The hydrogen column density is in good agreement with the average value of \( N_H = 5.9 \times 10^{20} \text{ cm}^{-2} \) expected toward this region of the SMC (Dickey & Lockman 1990). The observed flux in the 2–10 keV energy range is \( 1.4 \times 10^{-11} \text{ ergs cm}^{-2} \text{s}^{-1} \), corresponding to an unabsorbed luminosity of \( 6.1 \times 10^{35} \text{ ergs s}^{-1} \) for a distance of 60 kpc. The double blackbody model also gave the lowest \( \chi^2 \) values for the spectra of the single observations, but in those cases it was not the only one compatible with the data.

Observation A has been excluded because it was taken in a different operating mode, while no PN data were available for observation C.

### Table 2
Summary of the EPIC spectral results in the 0.1–10 keV energy range

| Observation | Model | \( N_H \) (10\(^{20}\) cm\(^{-2}\)) | \( \Gamma \) | Normalization | \( k_{\text{BB1}} \) (keV) | \( R_{\text{BB1}} \) (km) | \( k_{\text{BB2}} \) (keV) | \( R_{\text{BB2}} \) (km) | \( \chi^2 \) (dof) |
|-------------|-------|----------------------------------|-----|----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| A           | PL+BB | 4.8±.4                          | 1.3±.1 | 0.8±.3         | 0.35±0.02       | 9.1±1.4         | ...             | ...             | 1.18 (83)       |
| B           | BB1+BB2 | 8.1±.5                         | ...   | 2.0±.2         | 0.27±0.04       | 12.9±.3         | 0.5±0.1         | 3.6±.3         | 1.11 (83)       |
| C           | BB1+BB2 | 4.3±.3                         | 1.7±.5 | 2.0±.2         | 0.36±0.02       | 8.5±.3         | ...             | ...             | 0.93 (115)      |
| D           | BB1+BB2 | 4.2±.3                         | 1.7±.5 | 2.0±.2         | 0.31±0.03       | 11.0±1.6        | 0.7±0.1         | 1.6±0.4         | 0.72 (115)      |
| E           | BB1+BB2 | 7.8±.3                         | 1.6±.3 | 2.0±.2         | 0.34±0.04       | 9.6±1.3         | ...             | ...             | 1.16 (107)      |
| F           | BB1+BB2 | 5.3±.3                         | ...   | 2.0±.2         | <0.39           | ...             | ...             | ...             | ...             |
| G           | BB1+BB2 | 3.6±.6                         | 1.6±.3 | 2.0±.2         | 0.36±0.02       | 8.2±1.0         | ...             | ...             | 1.07 (83)       |
| H           | BB1+BB2 | 4.2±.3                         | 1.4±.5 | 1.5±.3         | 0.37±0.03       | 8.3±1.0         | ...             | ...             | 0.82 (84)       |
| I           | BB1+BB2 | 4.4±.3                         | ...   | 2.0±.2         | 0.33±0.04       | 10.1±1.7        | 0.8±0.1         | 1.2±0.7         | 0.75 (84)       |
| J           | BB1+BB2 | 7.6±.5                         | 1.6±.3 | 2.6±2.1        | 0.34±0.02       | 9.3±0.9         | ...             | ...             | 1.75 (100)      |
| K           | BB1+BB2 | 6.6±.4                         | ...   | ...            | 0.31±0.04       | 11.7±1.4        | 0.8±0.1         | 1.0±0.4         | 1.30 (65)       |
| L           | BB1+BB2 | 9.1±.6                         | 2.0±.5 | 2.0±.2         | 0.30±0.02       | 12.1±1.4        | 0.68±0.07       | 1.7±0.8         | 1.14 (100)      |

Note.—Errors are given at the 90% confidence level.

\(^a\) A free normalization factor has been introduced to account for inaccurate flux reconstruction in the MOS spectra, where, in most cases, the source is located on a CCD gap.

\(^b\) Assuming the photoelectric absorption cross section from Balucinska-Church & McCammon (1992) and abundances from Anders & Grevesse (1989).

\(^c\) In units of \( 10^{-11} \text{ photons cm}^{-2} \text{s}^{-1} \text{ keV}^{-1} \), at 1 keV.

\(^d\) Assuming a distance of 60 kpc.

\(^e\) Only PN data.

\(^f\) Only MOS data.
In particular, the power-law plus blackbody model, which is rejected with high confidence by the fit to the cumulative spectrum, gave acceptable fits to all the single spectra.

In addition to the phenomenological models described above, we have also fitted the cumulative spectrum with the magnetar spectral model described in Rea et al. (2008). This model, originally proposed by Lyutikov & Gavriil (2006), is based on clotted resonant scattering of blackbody radiation in a twisted magnetosphere (Thompson et al. 2002). Although the resulting χ² (1.20 for 100 degrees of freedom) is slightly worse than for the double blackbody model, the fit is acceptable. The photo-electric absorption (N_H = 5 ± 1 × 10²⁵ cm⁻²) and blackbody temperature (kT = 0.32 ± 0.08 keV) are consistent with the values derived from the double blackbody fit (N_H = 6.3^{1.0}_{-0.8} × 10²⁵ cm⁻² and kT = 0.30 ± 0.02 keV for the cooler blackbody).

The best-fit values of the other spectral parameters are a resonant scattering optical depth of γ = 1.2 ± 0.2 and a particle velocity of β_p = 0.48 ± 0.12. These parameters are in the same range as the ones observed in the other magnetar candidates (Rea et al. 2008). Although direct information on the size of the emitting region cannot be derived in the current version of this model, an approximate estimate gives a radius similar to that of the cooler component in the double blackbody model.

By inspecting the residuals from the best-fit models, we found no significant absorption or emission narrow-line features. We computed upper limits on narrow lines' equivalent widths as a function of the assumed line energy and width σ_e. This was done by adding Gaussian components to the double blackbody model and computing the allowed range in their normalization. The results for the high-statistics cumulative PN spectrum are summarized in Figure 3, where the plotted curves represent the 3σ upper limits for σ_e = 0 eV.

We performed a timing analysis to measure the source pulse period in each data set. After correcting the photon arrival times to the solar system barycenter, we derived the best period values based on a Z2 periodogram analysis (Buccheri et al. 1983). The resulting values are indicated in Table 1. Considering also the periods measured by Chandra (McGarry et al. 2005), a linear fit to the 10 values yields a period derivative dP/dt = (1.9 ± 0.1) × 10⁻¹¹ s⁻¹ (χ² of 1.32 for 8 degrees of freedom).

Since observations D and E were performed only 2 days apart, we tried to better constrain the spin-down rate through a phase-coherent timing analysis of the two data sets. However, the periods' uncertainties during each observation are too large to allow the prediction of the phase of the next observation to better than a pulse cycle.

Many AXPs and SGRs are known to exhibit significant changes in their pulse profiles (e.g., Kaspi 2007; Gőgőş et al. 2002). To search for possible pulse shape variations in CXOU J010043.1–721134 as a function of time, we compared the folded light curves using a Kolmogorov-Smirnov test. Taking into account the unknown relative phase alignment, all the light curves are compatible with the same profile. We therefore summed them after appropriate phase shifts. The resulting pulse profiles in the soft (0.2–1 keV, S) and hard (1–10 keV, H) energy ranges, together with their hardness ratio [computed as (H – S)/(H + S)] are shown in Figure 2. This analysis does not show any significant profile changes with energy. The pulsed fraction in the 0.2–6 keV energy range is (32 ± 3)%.

4 We selected the shifts that maximized the Kolmogorov-Smirnov statistics when comparing subsequent observations.

7 The pulsed fraction is defined as (C_pul/C_max – C_sum/C_max + C_sum), where C_pul and C_sum are the background-subtracted count rates at the peak and at the minimum.
pulsation below 1 keV (see Fig. 2), where this component dominates (see Fig. 1), indicates that it cannot come from the whole neutron star surface. A similarly large blackbody radius (∼10 km) was also derived from the spectrum of the AXP XTE J1810−158 observed by ROSAT before the onset of its outburst in 2003 (Halpern & Gotthelf 2005) and from phase-resolved spectroscopy of XMM-Newton observations of the same object (Israel et al. 2008) and of the AXP 1E 1048.1−5937 (Tiengo et al. 2005). However, in these cases, the less accurately known distance and the high interstellar absorption produce large uncertainties on the emitting region size.

Assuming that the thermal photons are produced on the neutron star surface (and not, for instance, in the magnetosphere) and considering that the blackbody is the most efficient thermal emission process at a given temperature, the radius of the region emitting the colder blackbody in CXOU J010043.1−721134 is a firm lower limit to the radius of the compact object. This limit is not large enough to exclude any of the most popular equations of state for neutron stars, but it is the most constraining lower limit ever obtained for a magnetar.

Magnetar spectra are expected to be more complex than a double blackbody. In fact most magnetar spectra cannot be fitted by such a simple model, which underestimates their emission in the 5–10 keV energy range. In all these cases a power-law tail in hard X-rays (>20 keV) has been detected (see, e.g., Kuiper et al. 2006; Götz et al. 2006; Leyder et al. 2008) and it is likely responsible also for the hard excess below 10 keV (Nakagawa et al. 2007). From a theoretical point of view, the emission expected from a magnetar has two components, with a thermal part directly from the surface and a nonthermal one due to emission reprocessed in the magnetosphere (Lytikov & Gavriil 2006; Fernández & Thompson 2007). We found that CXOU J010043.1−721134 can also be fitted by a model of this kind (Rea et al. 2008).

No compelling detections of spectral features in the persistent X-ray emission of magnetars have been reported so far. XMM-Newton and Chandra observations yielded strong upper limits (equivalent width ≤10 eV) for 4U 0142+61 (Juett et al. 2002), 1E 1048.1−5937 (Tiengo et al. 2005), and 1E 2259+586 (Woods et al. 2004) in the 0.7–5 keV range. However, the high interstellar absorption toward these objects makes a series of absorption edges in the observed spectrum at low energies, introducing large systematic uncertainties in the search for features in the intrinsic AXP spectrum. A hint of a spectral feature at ∼0.9 keV was noted by Durant & van Kerkwijk (2006) in the spectrum of the AXP 4U 0142+61, after its deconvolution from interstellar absorption using the edges directly observed in the high resolution X-ray spectra, but this measure is also affected by the poorly constrained abundances of most interstellar elements. As shown in Figure 3, for CXOU J010043.1−721134 we did not find evidence for lines, but although this source is one of the dimmest AXPs, we could put stringent limits on narrow features in the soft X-ray band, which are virtually independent of the photoelectric absorption model. The dipolar magnetic field derived from the spin-down rate of CXOU J010043.1−721134 is 4 × 10^{13} G, corresponding to a proton cyclotron energy of ∼2.5 keV; however, a cyclotron line at lower energies is expected if the cyclotron emission or absorption process occurs far from the neutron star surface, while a feature at higher energies is produced if strong multipolar magnetic field components are present. These effects, in addition to other processes that can suppress the spectral features (see, e.g., Ho & Lai 2003), make the lack of proton cyclotron lines in the X-ray spectra of magnetars compatible with their magnetic fields of (6−250) × 10^{13} G (corresponding to proton cyclotron energies of 0.4–15 keV) derived from their timing properties.

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