Identification of CXOU J171405.7−381031 as a New Magnetar with XMM-Newton

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Abstract

We have observed the 3.8 s pulsar CXOU J171405.7−381031 with XMM-Newton, and discovered the significant $\dot{P}$ of $6.40 \pm 0.14 \times 10^{-11}$ s s$^{-1}$ from this source for the first time, with the aid of archival Chandra data. The characteristic age (950 yr), the magnetic field strength ($5 \times 10^{14}$ G), and the spin-down luminosity ($4.5 \times 10^{34}$ erg s$^{-1}$) derived from $P$ and $\dot{P}$ lead us to conclude that CXOU J171405.7−381031 should be identified as a new magnetar. The obtained characteristic age indicates that CXOU J171405.7−381031 is youngest among all known anomalous X-ray pulsars, which is consistent with the age estimation from the thermal X-rays of the associated supernova remnant. The ratio between 2−10 keV luminosity and spin-down luminosity is almost unity, which implies that CXOU J171405.7−381031 is the key source to connect magnetars and traditional radio pulsars.

Key words: stars: pulsars: individual (CXOU J171405.7−381031) — stars: magnetic fields — X-rays: individual (CXOU J171405.7−381031)

1. Introduction

Anomalous X-ray Pulsars (AXPs) have been distinguished from the other type of pulsars by their peculiarity such as a long spin period of a neutron star ($P$ =2−12 s) and moderately bright X-ray emission with $L_X \approx 10^{33−35}$ erg s$^{-1}$ that is in general much greater than the spin-
down luminosity of the neutron star ($\dot{E} \approx 10^{31-34}\ \text{erg s}^{-1}$). Since there is no evidence of mass accretion, it has been thought that the X-ray emission is replenished with magnetic energy of the neutron star. As a matter of fact, the magnetic field strength, estimated on the basis of the dipole radiation framework, of the AXPs with known $\dot{P}$ is all in excess of the critical magnetic field $B_c = 4.4 \times 10^{13}$ G, above which the differential energy of the neighboring Landau levels exceeds the rest mass energy of an electron. The AXPs, together with Soft Gamma-ray Repeaters (SGRs), are now classified as so-called “magnetars” (Duncan & Thompson 1992; Thompson & Duncan 1995; Thompson & Duncan 1996). As of June 9, 2010, 10 AXPs and 9 SGRs have been known. It is, however, still unclear how such extraordinary nature are endowed to the magnetars, compared with the other conventional pulsars. One of the difficulties is that only a few magnetars are found associated with host supernova remnants (SNRs) that provide us with information on their progenitors, independent age estimation, and so on. Obviously we need more magnetar samples with the SNR association.

CXOU J171405.7−381031 is discovered in the course of identifying Galactic TeV sources. Aharonian et al. (2006) discovered the TeV source HESS J1713−381 with the atmospheric Cherenkov telescope H.E.S.S. and indicated its association with the supernova remnant (SNR) CTB37B. Using Chandra data, Aharonian et al. (2008) identified the point source CXOU J171405.7−381031 in the radio shell of CTB37B (Kassim et al. 1991). Its location is slightly offset ($\approx 1'$) from the peak of the H.E.S.S. brightness contour (see Fig. 2 of Nakamura et al. 2009). Nakamura et al. (2009) observed CTB37B with Suzaku (Mitsuda et al. 2007), and found that its spectrum is represented well by a power law with a photon index of $3.3 \pm 0.2$. The hydrogen column density to CXOU J171405.7−381031 ($\approx 4 \times 10^{22}$ cm$^{-2}$) is consistent with that of diffuse thermal emission of CTB37B, which strengthens the association of CXOU J171405.7−381031 to the SNR. The distance to this SNR is estimated to be $10.2 \pm 3.5$ kpc (Caswell et al. 1975), and we cite this value in this paper. These facts lead them to conclude that CXOU J171405.7−381031 is probably a new AXP, although limited time resolution of the XIS (8 s: Koyama et al. 2007) onboard Suzaku in the full-frame mode and the ACIS (3.24 s: Garmire et al. 2000) onboard Chandra in the imaging mode preclude them to detect pulsation. Halpern & Gotthelf (2010) finally discovered using the Chandra cc mode observation data that CXOU J171405.7−381031 pulsates at the period of $3.82305 \pm 0.00002$ s on 2009 January 25, which is well within the range of the AXP pulse period. The pulse shape is sinusoidal with a pulse fraction of 31%. They also detected an excess emission above the power-law spectrum above $\sim 6$ keV, which is one of the common features among the AXPs.

To further strengthen the identification of CXOU J171405.7−381031 as an AXP, it is important to measure $\dot{P}$. The known $\dot{P}$ of AXPs exceeds $10^{-12}$ s s$^{-1}$, which is systematically larger than the other rotation-powered pulsars. Furthermore, under the dipole radiation assumption, we are able to estimate the strength of the magnetic field, which is important to

* http://www.physics.mcgill.ca/~pulsar/magnetar/main.html
see if CXOU J171405.7−381031 is a magnetar. In order to evaluate $\dot{P}$, we have carried out an observation of CTB37B with XMM-Newton (Jansen et al. 2001). Monitoring X-ray flux is also important, since most magnetars show X-ray time variability. Halpern & Gotthelf (2010) showed that its flux changed between Suzaku and Chandra observations, although Suzaku low spatial resolution prevented us to conclude this source showed the time variability since there could be contamination of diffuse nonthermal X-rays, which is quite common in young SNRs (Bamba et al. 2005).

In § 2, we describe how the observation and data screening have been carried out. In § 3, we present the results of our timing and spectral analysis. We have clearly detected pulsation from the source. Compared with the Chandra pulse period (Halpern & Gotthelf 2010), we detected $\dot{P}$ significantly. We calculate the characteristic age and the magnetic field strength in § 4 and argue that CXOU J171405.7−381031 should be regarded as a new magnetar.

2. Observation and Data Reduction

The XMM-Newton observation of the SNR CTB37B was carried out from 2010 March 17 13:16 (UT) to March 18 23:06 (UT). Our primary objective is timing analysis to determine the physical parameter of CXOU J171405.7−381031. Hence, we concentrate on data taken with the EPIC pn (Strüder et al. 2001) whose time resolution is 73.4 ms, which is much better than EPIC MOS (2.6 s; Turner et al. 2001). We have carried out the data analysis with SAS ver 9.0.0. We have first checked the background flare using the cleaned event file pipe-line-processed with the CCF dated on 2010 April 30 in the data package. We have extracted a light curve in the band 10–12 keV, and produced a GTI file that excludes time intervals with a 10–12 counting rate of $>0.35$ c s$^{-1}$. We then have revised the event file by applying this GTI file. As a result, the effective exposure time became 40.264 ks. Using the new event file thus processed, we have constructed a pn image in the band 1–10 keV, as shown in Fig. 1. CXOU J171405.7−381031 is clearly detected at $\ell = 348^\circ50'51''087$, $b = 0^\circ22'15''820$, which is consistent with that from Chandra (Aharonian et al. 2008). The non-thermal diffuse emission extending to the south from CXOU J171405.7−381031 (Nakamura et al. 2009) is also detected. The small green circle, with a radius of 30$''$, is the extraction region of the source photons, whereas the other dashed circle, with a radius of 2$'$ is that for the background. The intensity of CXOU J171405.7−381031 is 0.264±0.003 c s$^{-1}$ in the 1–10 keV band after subtracting the background.

Figure 2 shows the background-subtracted spectrum together with the best-fit model and the fit residuals. We can see deeply absorbed and hard emission. We have fitted an absorbed power-law model to the data. The metal composition of Anders & Grevesse (1989) is adopted as the solar abundance for the absorbing material. The fit is accepted with $\chi^2$/d.o.f. of 372.34/341. The best-fit photon index, the hydrogen column density, and the observed and intrinsic flux in the 2.0-10.0 keV band are $3.45^{+0.09}_{-0.08}$, $3.95^{+0.15}_{-0.14} \times 10^{22}$ cm$^{-2}$, $(1.51 \pm 0.03) \times 10^{-12}$ erg cm$^{-2}$s$^{-1}$, 3
Fig. 1. The XMM-Newton pn image of CTB37B region in the 1–10 keV band. The image is smoothed with a Gaussian with $\sigma = 3$ pixels. The small green circle with a radius of 30″ is the region for extraction of the source photons, whereas the other dashed circle ($r = 2'$) is the region for background extraction.

Fig. 2. The XMM-Newton pn spectra of CXOU J171405.7−381031 and the two background regions. The background spectra are corrected for the aperture size.

and $(2.68 \pm 0.09) \times 10^{-12}$ erg cm$^{-2}$s$^{-1}$, respectively (the errors represent single-parameter 90% confidence limit). We can see positive residuals above $\sim$5 keV, which is probably the hard tail which is common among the magnetars (Muno et al. 2007; Naik et al. 2008; Nakagawa et al. 2009; Enoto et al. 2010). Detailed spectral analysis will be presented in the forthcoming paper.

3. Timing Analysis

Since there is nearly no source flux below $\sim$1 keV, we have carried out timing analysis in the band 1–10 keV. After barycentric correction to the event file, we have created a light curve with the minimum time resolution (73.4 ms), and have first made a power spectrum in the frequency range below 0.5 Hz. The result is shown in Fig. 3(a). A highly significant peak ($\sim$100 $\sigma$) appears at 0.2614 Hz. We then have carried out epoch folding analysis near this
Fig. 3. (a) Power spectrum of CXOU J171405.7−381031 in the 1–10 keV band. A highly significant peak is detected at a frequency of 0.2614 Hz. (b) Periodogram around the 0.2614 Hz. The pulsation period is obtained to be $P = 3.82535 \pm 0.00005$ s. (c) The light curve folded at this period.

frequency. The resultant periodogram is shown in Fig. 3(b). The rotational period is obtained to be $P = 3.82535 \pm 0.00005$ s. No other period except for the harmonics were significant. Compared to the period obtained from the Chandra cc mode data (Halpern & Gotthelf 2010), $3.82305 \pm 0.00002$ s, the period becomes longer by $0.00230 \pm 0.00005$ s. The time has elapsed since the Chandra observation (beginning at 2009 Jan 25 06:55:08) by 416.264676 d, thereby the average period derivative is obtained to be $\dot{P} = 6.40 \pm 0.14 \times 10^{-11}$ s s$^{-1}$. Figure 3(c) shows the light curve folded at the best spin period. The pulse profile is similar to that obtained by Halpern & Gotthelf (2010) including the pulse fraction.

4. Discussion

From the timing analysis of the XMM-Newton pn data, we have obtained $\dot{P} = 6.40 \pm 0.14 \times 10^{-11}$ s s$^{-1}$. Together with $P = 3.82535$ s, we can derive the spin-down luminosity
\( \dot{E} = 3.9 \times 10^{46} \dot{P} P^{-3} \) erg s\(^{-1}\), characteristic age \( t_c = P/(2 \dot{P}) \) s, and the dipole surface magnetic field \( B_s = 3.2 \times 10^{19} \sqrt{P \dot{P}} \) G) to be \( 4.5 \times 10^{34} \) ergs s\(^{-1}\), \( 9.5 \times 10^{2} \) yr, and \( 5.0 \times 10^{14} \) G, respectively. All these estimated parameters are within the range of the known AXPs, and we thus conclude that CXOU J171405.7–381031 is a new magnetar, together with the large photon index of its spectrum. The ratio of 2–10 keV luminosity \( (L_x) \) to \( \dot{E} \) is 0.4, which is much smaller than the typical magnetars. PSR J1846–0258 is a radio pulsar with \( B_s \) larger than the critical magnetic field which shows the \( L_x/\dot{E} \) of 0.2 (Helfand et al. 2003) including its pulsar wind nebula (PWN), and should be a key source to connect magnetars and conventional radio pulsars. CXOU J171405.7–381031 thus closely resembles PSR J1846–0258 and a new key source between magnetars and radio pulsars.

Note that this source is the youngest AXP and the second youngest magnetar so far, in the next place of SGR 1806–20 \( (t_c = 0.22 \) kyr; Mereghetti et al. 2005). Another important point is that this magnetar is associated with a young SNR. Nakamura et al. (2009) obtained the ionization age of the thermal plasma associated with CTB37B is \( 650^{+2500}_{-300} \) yr. Possible association of CTB37B with the historical SNR SN 393 has long been discussed (Clark & Stephenson 1975; Stephenson & Green 2002). The characteristic age we obtained is consistent with these discussions. Vink & Bamba (2009) discovered a pulsar wind nebula around the second youngest AXP, 1E 1547.0–5408 \( (t_c = 1.4 \) kyr: Camilo et al. 2007). CXOU J171405.7–381031 is now a good target to search for a PWN, which will be a future work with better spatial resolution. This will lead to better understanding of the young magnetars.

Some magnetars show X-ray flares and long term variability, and hence we have investigated whether CXOU J171405.7–381031 has X-ray time variability. The absorbed 2–10 keV flux is \( (1.1 \pm 0.2) \times 10^{-12} \) ergs cm\(^{-2}\)s\(^{-1}\) on 2007 Feb. 2 by Chandra (Nakamura et al. 2009), \( 1.8 \times 10^{-12} \) ergs cm\(^{-2}\)s\(^{-1}\) on 2009 Jan. 25 by Chandra (Halpern & Gotthelf 2010), and \( (1.51 \pm 0.03) \times 10^{-12} \) ergs cm\(^{-2}\)s\(^{-1}\) on 2010 Mar. 17-18 by XMM-Newton by this work. We thus concluded that CXOU J171405.7–381031 showed significant time variability in these years.

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