Chandra Monitoring of the Candidate Anomalous X-ray Pulsar AX J1845.0–0258

1 Introduction to AX J1845.0–0258

The 6.97-s X-ray pulsar AX J1845.0–0258 was discovered serendipitously in archival ASCA observations from 1993 (Gotthelf & Vasisht 1998; Torii et al. 1998) during a period of apparent outburst. Its slow spin period, soft spectrum \((kT \sim 0.64\text{ keV})\) and positional coincidence with the newly discovered supernova remnant G29.6+0.1 (Gaensler, Gotthelf & Vasisht 1999) were suggestive of the small but growing class of anomalous X-ray pulsars (AXPs, see review by V. Kaspi, this volume). However, without an estimate of \(\dot{P}\), and thus \(B\), the AXP identification could not be confirmed, so further attempts were made to re-detect the pulsar and pulsations. Unfortunately, it was not seen in a 1997 observation from the ASCA Galactic Plane Survey (Torii et al. 1998), and a 1999 pointed follow-up observation with ASCA found a possible counterpart, AX J184453–025640 that was almost ten times fainter, too faint for a measurement of pulsations or a spectrum (Vasisht et al. 2000). Chandra, XMM-Newton and BeppoSAX observations during 2001-2003 revealed a point source coincident with AX J184453–025640 and similar in brightness, but with a slightly harder absorbed spectrum \((kT \sim 1.0\text{ keV})\) than that seen for AX J1845.0–0258 in 1993 (Israel et al. 2004).

Presented here are the results of a Chandra X-ray Observatory monitoring campaign, conducted in 2003, with the goal of characterizing the spectral and timing properties of AX J1845.0–0258 in a post-outburst state.

2 Chandra Observations

Between June and September 2003, we obtained seven observations with Chandra ACIS-S in timed exposure...
J184454.6–025653 falls within the 1993 and 1999 error circles of AX J1845.0–0258 (black circle, Gotthelf & Vasisht 1998), and AX J184453–025640 (white circle, Vasisht et al. 2004), respectively. Also indicated are two fainter point sources, CXOU J184507.2–025657 (right box) and CXOU J184509.7–025715 (left box).

One bright point source in the 3′ ASCA error circle was found and designated CXOU J184454.6–025653 (see Fig. 1). This is likely the counterpart to AX J184453–025640, and possibly AX J1845.0–0258. There was no evidence of extended emission.

Two additional fainter point sources were detected inside the 1993 error circle of AX J1845.0–0258 but outside the 1999 error circle of AX J184453–025640 (see Fig. 1). One of them, CXOU J184507.2–025657, was found coincident with a bright near-infrared object from the 2MASS All Sky Survey; this challenges an AXP interpretation, since all confirmed near-IR counterparts to AXPs are very faint (K ~ 20 mag) and AX J1845.0–0258 is known to be highly absorbed (N_H ≥ 6×10^{22} cm^{-2}, Gotthelf & Vasisht 1998).

Case 1: CXOU J184454.6–025653 is the counterpart.

We extracted light curves from CXOU J184454.6–025653 at the highest possible time resolution (0.4 s for six observations, 3.2 s for the seventh) from each data set, in three energy ranges: 1–10, 1–3, and 3–10 keV. A fast fourier transform (FFT) was performed on barycentered event data, however, no evidence for pulsations was seen in any of the resulting power density spectra. For the longest observation and the frequency range 0.0880–0.1436 Hz, we find a 95% confidence upper limit on the pulsation amplitude of 80% in the 1–10 keV range.

The individual observations contained insufficient counts to adequately fit a spectrum, so we summed the extracted spectra into one combined spectrum. Using XSPEC 11.3.1, we found that the background-subtracted combined spectrum was equally well fit to a single-component absorbed thermal blackbody or power law: Table 1 lists the best-fit spectral parameters, and Figure 2 shows the data fit to a blackbody.

Consider two cases: 1) CXOU J184454.6–025653 is the counterpart to AX J1845.0–0258, and 2) CXOU J184454.6–025653 is unrelated to AX J1845.0–0258. The results of the following analysis were originally published in Tam et al. (2006).

Table 1 CXOU J184454.6–025653 spectral parameters. Errors reflect 90% confidence region. The absorbed flux is given for the 2–10 keV energy range, and we determine its uncertainty by fixing N_H and kT or Γ at the best-fit value and adopting the fractional uncertainty on the normalization.

| Model | N_H (10^{22} cm^{-2}) | kT (keV) | F (10^{-13} erg s^{-1} cm^{-2}) |
|-------|-----------------------|---------|--------------------------------|
| BB    | 5.6^{+1.6}_{-1.2}    | 2.0^{+0.4}_{-0.3} | 2.6 ± 0.2                      |
| PL    | 7.8^{+2.3}_{-1.6}    | 1.0^{+0.5}_{-0.3} | 2.8 ± 0.2                      |

Case 2: CXOU J184454.6–025653 is unrelated to AX J1845.0–0258.

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3 Timing and Spectral Analysis

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Fixing N_H and kT at their best-fit blackbody values but allowing the normalization to vary, we fitted the data from the seven individual observations and found that the observed 2–10 keV flux at each epoch was consistent with CXOU J184454.6–025653 being constant over the 4-month Chandra observing period, at the combined flux value. The inset plot of Figure 3 shows this.
the two additional faint sources detected in the 3σ error region, but in all instances there were not enough counts to detect pulsations or fit a spectral model. However, we noticed that most of the photons from CXOU J184507.2–025657 were below 2 keV, which contradicts what is known of AX J1845.0–0258, namely that it is highly absorbed. Because of this and the aforementioned evidence in [42], we consider CXOU J184507.2–025657 an unlikely counterpart to AX J1845.0–0258. For CXOU J184509.7–025715, the data were insufficient for us to draw meaningful conclusions about this source as candidate.

AX J1845.0–0258 may not have been re-detected at all, falling below the 3σ background flux level. We estimated an upper limit on a hypothetical point source to be \( \sim 8 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \) (2–10 keV), based on a variety of likely spectral models (see Fig. [8]).

![Graph](image)

**Fig. 2** The spectrum of CXOU J184454.6–025653 shown with its best-fit blackbody model.

4 A Transient AXP?

Whether CXOU J184454.6–025653 is truly the counterpart or not, its flux in 2003 is a factor of \( \sim 13 \) smaller than AX J1845.0–0258’s in 1993. However if AX J1845.0–0258 has not been re-detected at all, then this factor grows significantly larger to \( \sim 260 \)–430, representing an unprecedented range in variability for AXPs. Figure [8] outlines the 10-year flux evolution of AX J1845.0–0258 and its potential counterparts.

Comparable flux variability on large time scales has been seen in at least one other AXP. The 5.5-s transient AXP (TAXP) XTE J1810–197 was also discovered when it was in a high state, in 2003 [Ibrahim et al. 2004], and has since faded back towards its “quiescent” flux level [Gotthelf & Halpern 2005], as measured in archival ROSAT observations from 1993 [Gotthelf et al. 2004]. The pre-outburst source flux, which is nearly 2 orders of magnitude lower than its peak outburst flux, is much fainter than that of any non-transient AXPs, bringing to mind the question of how many more TAXPs have gone undetected in the Galaxy.

TAXPs are not accounted for in the framework of the magnetar model [Thompson & Duncan 1995, 1996], which attributes their persistent high-energy emission to continual heating of and stresses on magnetar’s crust. The source of this crustal stress and heating is the gradual decay of its ultra-high (\( \sim 10^{15} \) G) magnetic field, and can be used to predict an X-ray luminosity that is well matched by that seen in quiescent non-transient AXPs [Thompson, Lyutikov & Kulkarni 2002]. X-ray bursts, like those now observed in four AXPs including XTE J1810–197 [Woods et al. 2005], are thought to result from the sudden fracturing of the magnetar’s surface and reconfiguring of its field lines. So the question remains: if these common elements link transient and non-transient AXPs as magnetars, what is the cause of their differences?

Spectrally, we previously saw that AX J1845.0–0258 was not unlike other AXPs, which typically have soft spectra (recall \( kT \sim 0.64 \text{ keV} \) during outburst). For this reason, the observed hardness of the Chandra source (\( kT \sim 2 \text{ keV} \)) brings into question the proposed association with AX J1845.0–0258, and an overall AXP interpretation. Moreover, XTE J1810–197, the bona fide TAXP, was observed to be harder in outburst than quiescence (\( kT \sim 0.67 \text{ keV} \) compared to \( kT \sim 0.18 \text{ keV} \), respectively, from [Gotthelf et al. 2004]), which is the opposite to what we have witnessed if CXOU J184454.6–025653 is indeed a TAXP.

5 Alternate Endings

Given the uncertainty in the identity of CXOU J184454.6–025653, it seems prudent to consider other plausible alternatives. We argue on the basis of key observable properties, such as its relatively hard spectrum, intrinsic luminosity \( L_X \approx 10^{33}(d/5) \text{ kpc} \), and apparent stability on time scales of days to weeks.

**Active galactic nuclei.** The measured photon index \( \Gamma \sim 1.0 \) from the power law model is not unlike that seen for an active galactic nucleus (AGN, Watanabe et al. 2004; Nandra et al. 2005). Using *Chandra* ACIS-I, Ebisawa et al. (2004) studied the faint X-ray emission from an “empty” Galactic plane region that was conveniently centered only 1° away from our target, meaning that they might have local properties in common such as \( N_H \). From their models of Galactic source populations, we estimate a \( \sim 2\% \) likelihood that a circular region 3’ in radius would contain a coincident AGN, \( 3 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2} \) (2–10 keV) or brighter. Predicted optical/IR magnitudes fall at the limits of what current observatories are capable of, which will make it difficult to conclusively confirm or rule out an AGN interpretation through such means.
Fig. 3 The 10-year flux history of AX J1845.0–0258, originally presented in Tam et al. (2002). The filled triangle is the original 1993 ASCA detection of AX J1845.0–0258; the open triangle is the 1999 ASCA detection of AX J184453–025640, and assumes the 1993 outburst spectrum. The circle is the BeppoSAX detection of a possible counterpart, and assumes the spectrum given by Israel et al. (2004). Squares indicate the Chandra detections of CXOU J184454.6–025653 reported here, and assume the best-fit blackbody spectrum. We also represent the observed background levels as upper limits—in case the detections made were of unrelated objects—that assume the spectrum of AX J1845.0–0258 in outburst (thick arrows) and XTE J1810–197 in quiescence (thin arrows). The Chandra points are magnified in the inset plot, where the flux measured from the combined data set is indicated by the dashed line.

**Galactic sources.** Winds from massive stars have similar spectral and flux properties, as do some high-mass X-ray binaries (Muno et al. 2004). These systems, however, would tend to be bright in optical/IR, which disagrees with the faint upper limit set by Israel et al. (2004) of $H > 21$ mag.

Another group of Galactic objects with similar properties are cataclysmic variables (CVs). According to Muno et al. (2004), the IR emission of CVs at comparable distances and extinctions to our Chandra source ought to be relatively faint, roughly $K \approx 22–25$ mag. Therefore, it seems clear that optical/IR observations alone will be insufficient to identify this source.

**6 Conclusions**

We have observed and analysed the Chandra point source CXOU J184454.6–025653, which may be the transient X-ray pulsar and candidate AXP AX J1845.0–0258. If it is the counterpart, then either AX J1845.0–0258 is not actually an AXP, or AXPs are much more diverse in their spectral and flux characteristics during quiescence than previously thought. If it is not the counterpart and AX J1845.0–0258 is an AXP, then the exhibited flux variability presents a challenge to our current understanding of AXPs as magnetars, and hints at a much larger population of faint AXPs that remain undetected.

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**References**

Ebisawa, K., Tsujimoto, M., Paizis, A. et al. ApJ, 635, 214 (2005)
Gotthelf, E. V., Halpern, J. P. ApJ, 526, L37 (1999)
Gotthelf, E. V., Halpern, J. P., Buxton, M. et al. ApJ 605, 368 (2004)
Gotthelf, E. V., Vasisht, G. New Astronomy, 3, 293 (1998)
Ibrahim, A. I., Markwardt, C. B., Swank, J. H. et al. ApJ, 609, L21 (2004)
Israel, G., Stella, L., Covino, S. et al. in Proceedings of IAU Symposium 218, Camilo, F., Gaensler, B. (eds) San Francisco (PASP), p. 247 (2004)
Muno, M. P., Arabadjis, J. S., Baganoff, F. K. et al. ApJ, 613, 1179 (2004)
Nandra, K., Laird, E. S., Adelberger, K. et al. MNRAS, 356, 568 (2005)
Tam, C. R., Kaspi, V. K., Gaensler, B. M. et al. ApJ, in press (astro-ph/0602522)
Thompson, C., Duncan, R. C. MNRAS, 275, 255 (1995)
Thompson, C., Duncan, R. C. ApJ, 473, 322 (1996)
Thompson, C., Lyutikov, M., Kulkarni, S. R. ApJ, 574, 332 (2002)
Torii, K., Kinugasa, K., Katayama, K. et al. ApJ, 503, 843 (1998)
Vasisht, G., Gotthelf, E. V., Torii, K. et al. ApJ, 542, L49 (2000)
Watanabe, C., Ohta, K., Akiyama, M. et al. ApJ, 610, 128 (2004)
Woods, P. M., Kouveliotou, C., Gavriil, F. P. et al. ApJ, 629, 985 (2005)