DETECTION OF A COMPACT X-RAY SOURCE IN THE SUPERNOVA REMNANT G 29.6+0.1: A VARIABLE ANOMALOUS X-RAY PULSAR?

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ABSTRACT

We present follow-up observations of the serendipitously discovered 7-s x-ray pulsar AX J1845−0258, which displays characteristics similar to those observed in the anomalous x-ray pulsars (AXPs). We find a dramatic reduction in its 3-10 keV flux in both new ASCA and RXTE datasets. Within the pulsar’s position-error locus, we detect a faint point source, AX J184453−025640, surrounded by an arc of diffuse x-ray emission. This arc is coincident with the South-East quadrant of the radio shell of the newly discovered supernova remnant G29.6+0.1, reported in our companion paper (Gaensler et al. 1999). Lack of sufficient flux from the source prevents us from confirming the 7-s pulsed emission observed in the bright state; hence, at present we cannot definitively resolve whether AX J1845−0258 and AX J184453−025640 are one and the same. If they are the same, then the peak-to-peak luminosity changes recorded for AX J1845−0258 may be larger than seen in other AXPs; closer monitoring of this pulsar might lead to a resolution on the mechanism that drives AXPs.

\textit{Subject headings:} pulsars: individual (AX J1845−0258); supernova remnants: individual (G29.6+0.1); star: individual (AX J184453−025640); stars: neutron.

1. INTRODUCTION

AX J1845−0258 is a 7-s x-ray pulsar discovered during an automated search of the ASCA archival data (Gotthelf & Vasisht 1998, herein GV98; Torii et al. 1998). The pulsar lies 22′ away from the supernova remnant Kes 75, the main target of that ASCA pointing; this large angular separation makes an association between Kes 75 and the pulsar highly improbable. Arguing on the basis of its spectral and timing properties, we proposed AX J1845−0258 to be the latest addition to the class of anomalous x-ray pulsars (AXPs; GV 98; Torii et al. 1998 - for AXP phenomenology see Mereghetti & Stella 1995 and van Paradijs et al. 1995, for the AXP-magnetar interpretation see Thompson & Duncan 1996). The collective evidence included the long rotation period, large sinusoidal pulse modulation, steady x-ray flux on timescales of a day or less, and a soft power-law x-ray spectrum. A rough distance estimate derived from the large line-of-sight x-ray absorption placed the pulsar at a distance of 5 to 15 kpc, with an inferred x-ray luminosity of \( \sim 2.5 \times 10^{35}d_{15}^{2} \text{erg s}^{-1} \) (the distance being \( 15d_{15} \) kpc), not atypical for AXPs.

Since the small AXP population shows a propensity towards association with supernova remnants we undertook searches for a host supernova remnant at radio and x-ray wavelengths. In this letter, we report follow-up ASCA & RXTE x-ray observations targeted at the pulsar. In our companion paper, we reported on a VLA detection of a young radio shell coincident with the pulsar’s error circle (Gaensler, Gotthelf & Vasisht 1999; hereafter GGV99). The primary goal of our x-ray observations was to identify the pulsar and confirm or repudiate the AXP hypothesis by measuring the spin-down rate of the pulsar. As in the radio, we succeeded in finding evidence of a young x-ray SNR within the pulsar’s error circle, however, pulsed emission was not observed in these followup observations. Instead, we find a faint ASCA point source at the center of the newly discovered radio remnant G29.6+0.1 (GGV99). We argue that this faint source is indeed the pulsar AX J1845−0258 albeit in a low state, and that its location in the center of a supernova remnant additionally favors the anomalous x-ray pulsar interpretation. The angular size of G29.6+0.1 and limits on its distance suggest that the original detonation is no more than 8-kyr old (see GGV99). This implies that the slow rotator at the remnant’s core could well be a spun-down magnetar.

2. OBSERVATIONS AND ANALYSIS

A new x-ray observation of the field containing the pulsar AX J1845−0258 was obtained with the Advanced Satellite for Cosmology and Astrophysics (ASCA; Tanaka et al. 1994) on March 28-29, 1999 (UT), with with both pairs of on-board instruments, the two solid-state spectrometers (SIS) and the two gas imaging spectrometers (GIS). The SIS were in 1-CCD mode with the pulsar centered as close to the mean SIS telescope optical axis as was practical, to minimize vignetting and off-axis aberrations. The spatial resolution for the SIS is limited by the optics to \( \sim 1′ \), while the GIS spatial resolution of 2−3′ is due to an additional energy dependent instrumental blur. The GIS data were collected in the highest time resolution mode (0.5 ms or 64 \( \mu \)s, depending on the telemetry rate), with reduced spectral binning (\( \sim 47 \) eV per PHA channel). All data were edited to exclude times of high background contamination. The resulting effective observation time was 49 ks (64 ks) for each GIS (SIS) sensor.

Figure 1 displays the broad-band (1−10 keV) GIS im-

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age of the pulsar field produced by co-adding exposure corrected maps from both instruments smoothed using a 3' pixel box-car filter. Near the center of the image lies a faint ASCA source (marked by a cross), confined to the original 3 arcminute error circle for AX J1845−0258 (GV98). Inspection of the higher spatial resolution SIS image (figure 2a) resolved this emission into a 1' SIS point-source surrounded by a diffuse arc of x-rays, just south-east of the point-like emission. The arc coincides with the 4' diameter radio shell of the recently discovered supernova remnant G29.6+0.1 (see GGV99), and overlaps the sector where the radio emission is the strongest. The location of the SIS source at the center of G29.6+0.1 makes a physical association between the two very likely. The lack of a complete x-ray shell with correspondence to the radio remnant is not unexpected, considering the high foreground absorption associated with this region. The identification of the central source in the SIS allows a coordinate determination of 18°44'53.0", −02°56'40.0" (J2000) with an uncertainty of 12" radius. This reduced ASCA error circle is derived using the method developed to compensate for the temperature dependent star tracker drift in the aspect solution (Gotthelf et al. 2000). Herein we refer to this source as AX J184453−025640, and will consider in detail (§3) whether this is indeed AX J1845−0258, albeit at a lower flux level.

The source count rate at the putative pulsar location is evidently reduced in the 1999 observation. The background-subtracted source count-rate in the optimal 3−10 keV energy band is 4.0 ± 0.7 × 10^{-3} s^{-1} (combined SIS) after correcting for aperture losses, resulting in a 6σ detection. For an invariant pulsar (based on the 1993 dataset), the expected count rate would be 3.9 × 10^{-2} s^{-1}. Thus we can place a limit on the variability of a factor of 9.7 in flux between the 1993 and 1999 observation epochs, assuming the spectral shape has remained unchanged (see discussion). This low flux level (in 1999) is consistent with the marginal non-detection of the pulsar in a short (10-ks) 1997 ASCA observation of the Galactic ridge reported by Torii et al. (1998) suggesting that the pulsar was in a similar low state then.

In addition to the compact source and the new supernova remnant G29.6+0.1, and the well studied supernova remnant Kes 75 at the eastern edge of the GIS field-of-view, two additional objects are evident in the GIS image of Figure 1. Towards the southwest of G29.6+0.1, lies a moderately bright unresolved GIS point-source, which we name AX J184440−030501 based on its 2' GIS position. The source spectrum containing 550 counts, is fit using the method developed to compensate for the temperature dependent star tracker drift in the aspect solution. The source spectrum containing 550 counts, is fit using the method developed to compensate for the temperature dependent star tracker drift in the aspect solution. The source spectrum containing 550 counts, is fit using the method developed to compensate for the temperature dependent star tracker drift in the aspect solution. The source spectrum containing 550 counts, is fit using the method developed to compensate for the temperature dependent star tracker drift in the aspect solution. The source spectrum containing 550 counts, is fit using the method developed to compensate for the temperature dependent star tracker drift in the aspect solution. The source spectrum containing 550 counts, is fit using the method developed to compensate for the temperature dependent star tracker drift in the aspect solution. The source spectrum containing 550 counts, is fit using the method developed to compensate for the temperature dependent star tracker drift in the aspect solution. The source spectrum containing 550 counts, is fit using the method developed to compensate for the temperature dependent star tracker drift in the aspect solution. The source spectrum containing 550 counts, is fit using the method developed to compensate for the temperature dependent star tracker drift in the aspect solution. The source spectrum containing 550 counts, is fit using the method developed to compensate for the temperature dependent star tracker drift in the aspect solution. The source spectrum containing 550 counts, is fit using the method developed to compensate for the temperature dependent star tracker drift in the aspect solution. The source spectrum containing 550 counts, is fit using the method developed to compensate for the temperature dependent star tracker drift in the aspect solution. The source spectrum containing 550 counts, is fit using the method developed to compensate for the temperature dependent star tracker drift in the aspect solution. The source spectrum containing 550 counts, is fit using the method developed to compensate for the temperature dependent star tracker drift in the aspect solution. The source spectrum containing 550 counts, is fit using the method developed to compensate for the temperature dependent star tracker drift in the aspect solution. The source spectrum containing 550 counts, is fit using the method developed to compensate for the temperature dependent star tracker drift in the aspect solution. The source spectrum containing 550 counts, is fit using the method developed to compensate for the temperature dependent star tracker drift in the aspect solution. The source spectrum containing 550 counts, is fit using the method developed to compensate for the temperature dependent star tracker drift in the aspect solution. The source spectrum containing 550 counts, is fit using the method developed to compensate for the temperature dependent star tracker drift in the aspect solution. The source spectrum containing 550 counts, is fit using the method developed to compensate for the temperature dependent star tracker drift in the aspect solution. The source spectrum containing 550 counts, is fit using the method developed to compensate for the temperature dependent star tracker drift in the aspect solution.

We searched the GIS data for evidence of pulsed emission from AX J184453−025640 around the 7-s period. A total of 1,418 photons from the two GISs were extracted from a 8' diameter aperture and merged of which ~300 counts are expected from the compact source. The photon arrival times for each event were corrected to the solar system barycenter. The data were then folded in period space around the 1993 value with a range to accommodate spin-up or down values ([P] ≤ 1 × 10^{-13} s^{-1}) in 0.1 × P^2/2T steps, in order to search for a coherent modulation. No significant period was found. We place a limit of 0.7 on the fractional modulation (for a 5σ pulse detection threshold), higher than the modulation of 0.3 found in the discovery observations of 1993. We also searched for a signal from AX J184440−030501 in the range 0.2−500 s, but found no significant periodicity.

We also observed the region containing the pulsar using the RXTE observatory on 18 Apr 1999. Data was acquired with the Proportional Counter Array (PCA) in “Good Xenon” data mode at 0.9 μs time resolution. The PCA instrument covers an energy range of 1−40 keV with an effective area of 6,400 cm^2 over its ~ 1° × 1° field-of-view (FWHM). After processing and barycentering the Good Xenon data, we obtained a total of 38 ks of screened exposure time. Photons were further restricted to the energy range alties (see Discussion).

3. DISCUSSION

The failure to detect a pulsed source clearly corresponding to AX J1845−0258 was somewhat surprising in the light of its interpretation as an AXp, but is not completely confounding. At the same time, the discovery of the young supernova remnant G29.6+0.1 at that position does help bolster the AXp interpretation. The detection of the fainter point source, AX J184453−025640, at the core of the remnant and its co-location with the error locus of AX J1845−0258 strongly suggests that the two compact sources are one and the same. Our conclusion is that the pulsar must have undergone a factor-of-ten variability in measured fluxes between the ASCA epochs spanning six years. This behavior is somewhat unusual. There is evidence to show that the two well studied AXps, 1E 1048.1−593 and 1E 2259+586, display about a factor-of-four flux variations on year long timescales (Baykal & Swank 1996; Oosterbroek et al. 1998). The compact source in the core of RCW 103 also displays order-of-magnitude flux variations (Gotthelf, Petre & Vasishtha 1999) in the 3−10 keV band. The latter, although showing many of the same properties as AXps, is not classified as an one because of absence of pulsed emission (but see Garmire et al. 2000).

Other objects show more steady behavior - the pulsar in Kes 73 shows fluxes that are steady to within a factor-of-two over a decade of monitoring.
AX J1845−0258 is in all likelihood, highly absorbed thermal emission which is observed as a steep power-law (photon index ≈ 5 with $N_H \sim 10^{23}$ cm$^{-2}$) above 2 keV, with few photons below that energy. The emission may be modeled as surface blackbody radiance with temperature $kT \sim 0.6 \pm 0.1$ keV. When coupled with the flux, this implies a hotspot-like emitting region of fraction $0.1d_{15}^2$ of the total surface area of a neutron star of standard radius; this estimate is rough - it assumes isotropic emission and ignores any relativistic corrections. Given the BB model, it is important to clarify that the large foreground absorption can lead to observed flux variations of greater magnitude than actual intrinsic variations. For instance surface cooling on the NS (at 0.6 keV) leading to an intrinsic flux change of a factor-of-five, can lead to a factor-of-ten flux change in the observed Wien tail, given $10^{23}$ cm$^{-2}$ of foreground absorption.

This is only the third convincing association of an AXP with a supernova remnant (GGV 99). The other two cases are the associations of 1E 2259+586 with CTB 109 (Gregory & Fahlman 1980) and 1E 1851−045 with Kes 73 (Vasisht & Gotthelf 1997). The handful of other AXPs are not known to be associated with bright supernova remnants, which suggests that these are somewhat older objects (although, these field need to be imaged with greater sensitivity). If ultramagnetized, then AXPs must be the youngest observable magnetars, spanning about three decades in age grouping. There is strong observational evidence that 1E 1851−045 in Kes 73 is no more than $4 \times 10^5$ yr-old from its timing parameters, while dating of Kes 73 suggests that the PSR/SNR pair is perhaps as young as $2 \times 10^3$ yr (Vasisht & Gotthelf 1999). Anomalous pulsars that have no obvious SNR counterparts are dated to be $\sim 10^5$ years in age. Implicit in the previous statement, is the assumption that the spin-down-ages of AXPs reflect their true ages. Field decay and wind induced torques may result in significant departures the age and its estimator, especially for the older objects. Beyond the $10^5$ yr timescale, magnetic activity, which is believed responsible for powering the persistent emission in these objects (Heyl & Kulkarni 1998) declines rapidly, leading to their disappearance from the observable x-ray sky - resulting is an estimated $10^8$ yr defunct Galactic magnetars. An example of elderly magnetar may be the nearby, slow x-ray pulsar RX J0720.4−3125 (Haberl et al. 1997; Kulkarni & van Kerkwijk 1998). The soft γ-ray repeaters may well be a phase in the life of AXPs (for instance, Gaensler et al. 1999), lasting for about $10^{4−5}$ years, and triggered by a yet ill-understood mechanism.

If AX J1845−0258 is indeed a magnetar, then the magnetar mechanism must address the cause of the x-ray flux variability. In alternative accretion scenarios (which do not require invoking ultramagnetized stars), changes in $L_X$ track the mass accretion rate onto the star. We have observed flux variability of at least a factor-of-five, possibly accompanied by a change in the emission temperature (we are unable to confirm that with the current data), which exists on timescales of a few years or less. Although no short term variability or stochastic flickering, seen in accreting objects, is observed in the lightcurves of AX J1845−0258, a plunge in the mass accretion rate $\dot{M}_X$ from an ejecta-fallback disk can easily account for the drop in $L_X$ (see Chatterjee, Hernquist & Narayan 1999, Alpar 1999, Marsden et al. 1999). We do not know what mechanism sets a variability timescale of $\sim$ years in the otherwise steady $\dot{M}_X$ decline of a fallback disk. In the magnetar picture, variations in the surface flux will be driven by and will track the magnetic field dissipation inside the star. The shape of the stellar spectrum, inferred temperatures and emitting area ($\simeq 0.1A_e$) suggest thermal activity related to a heated spot on the stellar surface; this is natural as a strong field suppresses thermal conductivity perpendicular to the field vector (Hernquist 1985). The thermal conduction time in a neutron star (of surface $kT \sim 0.5$ keV), from core to surface, is about a year (Van Riper, Horn & Miller 1991), which smoothes out any surface temperature variations on timescales shorter than about a year. Detectable changes in the surface flux will be driven only by longer term internal dissipation cycles. For AX J1845−0258 the total energy released in a longterm event is about $\delta E \sim 10^{52} \tau_{var} L_X \sim 2 \times 10^{44}$ erg, the factor $10^2$ allows for most of the cooling to be in the form of neutrino emission (Thompson & Duncan 1996). A magnetar has a magnetic free energy budget to go through $10^3$ dissipation events of the given magnitude during the $\sim 10^4$ yr lifetime of AX J1845−0258. Another mechanism for variability in a magnetar could be radiative precession (with a few year timescale) of the spin axis of the star around the dipole axis if these are significantly misaligned; this results from hydrodynamic deformation induced in the star by the strong B-field (Melatos 1999).

Finally, if variability is a common aspect of the younger anomalous x-ray pulsars, then that raises a couple of interesting questions. If AXPs are magnetars (or drawn from a population $P$), and AXPs show flux variability, then strictly, is it likely that we have significantly under-counted them and therefore underestimated the birth rate of magnetars (or $P$s), estimated to be $\sim 10^{-3}$ yr$^{-1}$? Is it possible that there are such neutron stars within some of the young Galactic remnants that apparently have no compact objects or plerionic cores associated with them, as the recent discovery of the low $L_X$ compact source in Cas A (Pavlov et al. 1999, Chakrabarty et al. 2000) might suggest? The answers to these questions are unclear at present. First, we have no knowledge whether flux variations can be greater than an order of magnitude (with the current population of well monitored AXPs, that appears not to be the case). Second, we do not know the duty cycle of these variations. In the case of 1E 2259+586 and 1048.1−593 it seems to be of order a year. Thirdly, AXPs are intrinsically bright sources ($L_X \simeq 10^{35}$ erg s$^{-1}$), with the consequence that mild variability is unlikely to lead to significant under-counting. And finally, the large distances to the known population of objects and the fact that no AXP has been found nearby ($\sim$ 1 kpc), strongly suggests that these objects are indeed rare. At the moment there is little evidence to link low $L_X$ objects such as the compact sources in Cas A, Puppis A and PKS 1209−51 to the brighter AXP population. In any case, further monitoring of the levels of variability and timescales involved will lead to a better comprehension of any physical ties among these categories of sources. The physical mechanism driving the x-ray luminosity in this object (and by extension, other AXPs) could well be pinned down through monitoring the spin evolution of this pulsar (AX J1845−0258 may...
undergo additional large peak-to-peak episodes in $L_X$, or
make a recovery to the flux levels observed in the 1993
ASCA observation) through episodes of variability with
missions such as Chandra and XMM, and observing how
the stellar period tracks any changes in $L_X$.

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REFERENCES

Beyond”. Kramer, Wex & Wielebinski eds, in press
(GGV99)
Garmire, G. P., Pavlov, G. G., Garmire, A. B., Zavlin, V. E. 2000,
IAUC 7350
Gotthelf, E. V., Ueda, Y., Fujimoto, R., Kii, T. & Yamaoka, K. 2000,
Haberl, F., Motch, C., Buckley, D. A. H., Zickgraf, F. J. & Pietsch,
A&A, 334, 925
Marsden, D., Lingenfelter, R. E., Rothschild, R. E. & Higdon, J. C.
1999, Astro-ph/9912207
Pavlov, G. G., Zavlin, V. E., Aschenbach, B., Trümper, J. & Sanwal,
Torii, K., Kinugasa, K., Katayama, K., Tsunemi, H., & Yamauchi,
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Table 1

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<td>Southeast source</td>
<td>18$^h$44$^m$40$^s$</td>
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Fig. 1.— The full field-of-view of the 1999 ASCA GIS observation of AX J1845−0258. The processed image shows the new x-ray source AX J184453−025640 marked by the cross which lies within the error circle for AX J1845−0258 (dotted circle), and the two previously uncataloged x-ray sources to the northeast and southwest. The bright emission towards the eastern edge is the SNR Kes 75.

Fig. 2.— The new SNR, G29.6+0.1, containing the compact x-ray source, AX J184453−025640, within the error box of the x-ray pulsar AX J1845−0258. (LEFT) The ASCA SIS x-ray image centered on the AX J184453−025640, marked by the cross. An arc of emission surrounds the point source and overlaps with the radio shell displayed in the adjacent panel. (RIGHT) A 5 GHz VLA map of the same region, illustrating the clumpy shell G29.6+0.1. Again, the pulsar’s location is marked by the cross.