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DETECTION OF A COMPACT X-RAY SOURCE IN THE SUPERNOVA REMNANT G29.6+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 *Rossi X-Ray Timing Explorer* data sets. Within the pulsar's position error locus, we find a faint point source, AX J184453−025640, surrounded by an arc of diffuse X-ray emission. This arc is coincident with the southeast quadrant of the radio shell of the newly discovered supernova remnant G29.6+0.1, recently reported by Gaensler et al. 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.

Subject headings: ISM: individual (G29.6+0.1) — pulsars: individual (AX J1845−0258) — stars: individual (AX J184453−025640) — stars: neutron

1. INTRODUCTION

AX J1845−0258 is a 7 s X-ray pulsar discovered during an automated search of *Advance Satellite for Cosmology and Astrophysics* (*ASCA*) archival data (Gotthelf & Vasisht 1998, hereafter GV98; Torii et al. 1998). The pulsar lies 22′ away from the supernova remnant (SNR) 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; GV98; Torii et al. 1998; for AXP phenomenology see Mereghetti & Stella 1995 and van Paradijs, Taam, & van den Heuvel 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 5–5 kpc, with an inferred X-ray luminosity of $\sim 2.5 \times 10^{35} d_{15}^2$ ergs s^{-1} (the distance being $15 d_{15}$ kpc), not atypical for AXPs.

Since the small AXP population shows a propensity toward association with SNRs, we undertook searches for a host SNR at radio and X-ray wavelengths. In this Letter, we report follow-up *ASCA* and *Rossi X-Ray Timing Explorer* (*RXTE*) X-ray observations targeted at the pulsar. In our companion paper, we reported on a Very Large Array (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 follow-up 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 an SNR in addition favors the AXP 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

A new X-ray observation of the field containing the pulsar AX J1845−0258 was obtained with *ASCA* (Tanaka, Inoue, & Holt 1994) on 1999 March 28–29 (UT) with both pairs of onboard instruments, the two solid-state spectrometers (SISs) and the two gas imaging spectrometers (GISs). The SIS data 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 ∼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 μs, depending on the telemetry rate), with reduced spectral binning (∼47 eV per pulse-height analyzer 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 broadband (1–10 keV) GIS image of the pulsar field produced by co-adding exposure-corrected maps from both instruments smoothed using a 3 × 3 pixels boxcar filter. Near the center of the image lies a faint *ASCA* source (marked by a cross), confined to the original 3′ error circle for AX J1845−0258 (GV98). Inspection of the higher spatial resolution SIS image (Fig. 2*a*) resolved this emission into a 1′ SIS point source surrounded by a diffuse arc of X-rays, just southeast of the pointlike emission. The arc coincides with the 4′ diameter radio shell of the recently dis-

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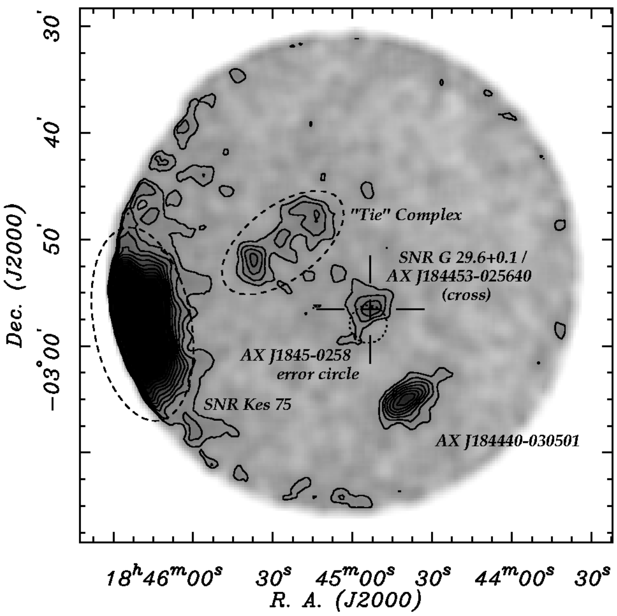

FIG. 1.—Full field of view of the 1999 *ASCA* GIS observation of AX J1845−0258. The processed image shows the new X-ray source AX J184453−025640 marked by the cross that lies within the error circle for AX J1845−0258 (*dotted circle*) and the two previously uncataloged X-ray sources to the northeast and southwest. The bright emission toward the eastern edge is the SNR Kes 75.

covered SNR 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 $18^h44^m53^s$, $-02°56'40''$ (J2000) with an uncertainty of 20″ 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 $4.0 \pm 0.7 \times 10^{-3}\ s^{-1}$ (combined SIS) after correcting for aperture losses, resulting in a 6 σ detection. For an invariant pulsar (based on the 1993 data set), the expected count rate would be $3.9 \times 10^{-2}\ s^{-1}$. 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 nondetection 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 SNR G29.6+0.1, and the well-studied SNR Kes 75 at the eastern edge of the GIS field of view, two additional objects are evident in the GIS image of Figure 1. Toward 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 well by an absorbed power law of photon index 1.7 with an $N_H = 6 \times 10^{22}\ cm^2$. The unabsorbed flux is 3×10^{-12} ergs $cm^{-2}\ s^{-1}$ (2–10 keV). Although this source is located off our SIS and VLA maps, examination of databases of this region shows that AX J184440−030501 lies at the edge of a complex radio/IR region cataloged variously as GRS 029.39+00.10/PMN J1844−0306/F3R 1015. No other cataloged object in any wavelength is recorded for these coordinates. We also find hard

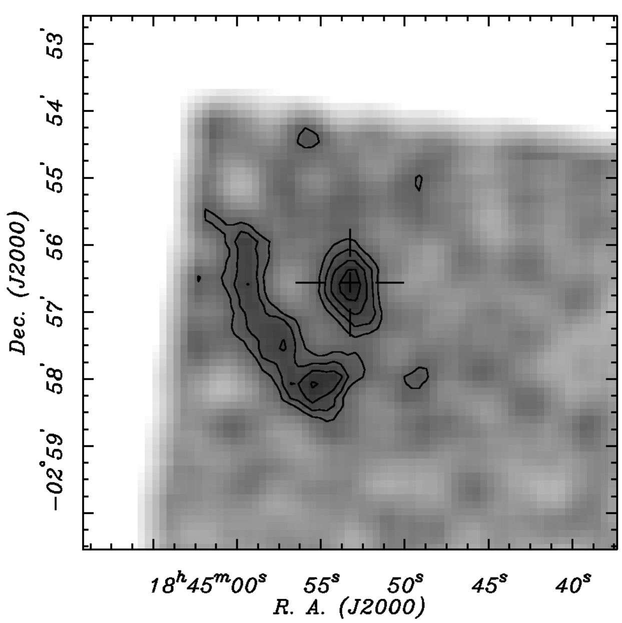

FIG. 2*a*

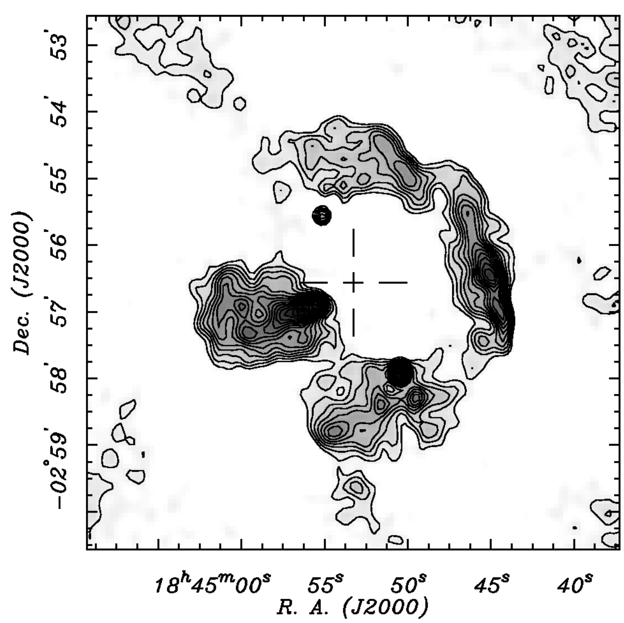

FIG. 2*b*

FIG. 2.—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 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.

diffuse emission that is offset ∼10′ due northeast of the remnant. The morphology is of an extended bow tie–like structure that could well be a partial shell SNR. We found no cataloged counterparts for this object. Table 1 summarizes the positions of these sources.

We searched the GIS data for evidence of pulsed emission from AX J184453−025640 around the 7 s period. A total of 1418 photons from the two GISs were extracted from an 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 spin-down values ($|\dot{P}| \leq 1 \times 10^{-10}$ s s^{-1}) in $0.1 \times P^2/2T$ 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 5 σ 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 0.02–500 s but found no significant periodicity.

We also observed the region containing the pulsar using the *RXTE* observatory on 1999 April 18. 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 6400 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 ≲10 keV from layer 1 only. Since the *RXTE* data was nearly contemporaneous with the *ASCA* observation, we expect the pulsar to be in the low state. In any case, we searched for the pulsar in a manner similar to that for the *ASCA* data using data below 6 keV to cut off excess background. No significant periodicities (above 5 σ) were found. Given the count rate expected in the low state, no useful modulation limits may be set with this data set.

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 SNR 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 colocation 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 10 variability in measured flux interim to the *ASCA* epochs spanning 6 yr. 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 4 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, & Vasisht 1999) in the 3–10 keV band. The latter, although showing many of the same properties as AXPs, is not classified as one because of the 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 2 over a decade of monitoring.

In GV98 we argued that the AX J1845−0258 X-ray spectrum is in all likelihood highly absorbed thermal emission that 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 hot spot–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 blackbody 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 neutron star (at 0.6 keV) leading to an intrinsic flux change of a factor of 5 can lead to a factor of 10 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 an SNR (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 SNRs, which suggests that these are somewhat older objects (although these fields 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 4×10^3 yr old from its timing parameters, while dating of Kes 73 suggests that the pulsar-SNR pair is perhaps as young as 2×10^3 yr (Vasisht & Gotthelf 1997). Anomalous pulsars that have no obvious SNR counterparts are dated to be ∼10^5 yr 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 of 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 in an estimated 10^8 defunct Galactic magnetars. An example of an 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 2000), lasting for about 10^4–10^5 yr 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 5, 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.

TABLE 1
COORDINATES OF FIELD X-RAY SOURCES

Object	R.A. (J2000)	Decl. (J2000)	Uncertainty
AX J184453−025640	18 44 53	−02 56 40	20″
Southeast source	18 44 40	−03 05 01	1′
Center of "tie"	18 45 27	−02 50 02	2′
Northern "tie"	18 45 15	−02 47 50	2′
Southern "tie"	18 45 38	−02 51 52	2′

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

Although no short-term variability or stochastic flickering, seen in accreting objects, is observed in the light curves 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 2000; Marsden et al. 2000). We do not know what mechanism sets a variability timescale of a few 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 ($\simeq 0.1 A_s$) 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, Epstein, & Miller 1991), which smooths out any surface temperature variations on timescales shorter than about a year. Detectable changes in the surface flux will be driven only by long-term internal dissipation cycles. For AX J1845−0258, the total energy released in a long-term event is about $\delta E \sim 10^2 \tau_{var} L_X \sim 2 \times 10^{44}$ ergs; 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 timescale of a few years) 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 AXPs, then that raises a couple of interesting questions. If AXPs are magnetars (or drawn from a population *P*) and show flux variability, then is it likely that we have significantly undercounted them and therefore underestimated the birthrate of magnetars (or *P*), 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. 2000; 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. Third, AXPs are intrinsically bright sources ($L_X \simeq 10^{35}$ ergs s^{-1}), with the consequence that mild variability is unlikely to lead to significant undercounting. And finally, the large distances to the known population of objects and the fact that no AXP has been found nearby (∼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 by 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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