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Discovery of a 7 second anomalous X-ray pulsar in the distant Milky Way

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Abstract

We report the serendipitous discovery of a 7-s X-ray pulsar using data acquired with the *Advanced Satellite for Cosmology and Astrophysics* (ASCA). The pulsar is detected as an unresolved source located towards a region of the Galactic plane ($l,b \simeq 29.5,0.08$) that coincides with an overdensity of star-formation tracers. The signal suffers tremendous foreground absorption, equivalent to $N_{\rm H} \simeq 10^{23}\,{\rm cm}^{-2}$; the absorption correlates well with a line-of-sight that is tangential to the inner spiral arms and the 4-kpc molecular ring. The pulsar is not associated with any known supernova remnants or other cataloged objects in that direction. The near sinusoidal pulse (period $P \simeq 6.9712$) is modulated at 35% pulsed amplitude, and the steep spectrum is characteristic of hot black-body emission with temperature $kT \sim 0.65$ keV. We characterize the source as an anomalous X-ray pulsar (AXP). © 1998 Elsevier Science B.V.

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1. Introduction

A canonical young pulsar (period ~ 100 ms and stellar dipole field $\sim 3 \times 10^{12}$ G) is a rapidly rotating neutron star, created as the stellar remnant during a Type II (or Ib) supernova explosion of a massive star. The birthrate of pulsars is known to be close to 1–3 per century, and it is estimated that there are about 10^5 active and 10^8 defunct neutron stars in the Galaxy (see Lorimer et al. (1993) and references therein).

In the last few years, there has been growing recognition of a population of ultra-magnetized neutron stars, or ''magnetars'' (Thompson & Duncan, 1993). The mostly circumstantial evidence comes from investigations of the following categories of objects: the soft gamma-ray repeaters (Thompson & Duncan, 1995; Frail et al., 1997), long period pulsars in supernova remnants (Vasisht & Gotthelf (1997) and references therein), other seem-

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ingly isolated, young, long period pulsars (Thompson & Duncan, 1996) nowadays referred to as the anomalous X-ray pulsars (van Paradijs et al., 1995), and perhaps their older variants (Kulkarni & van Kerkwijk, 1998). These objects share some common properties; they are steady, bright X-ray sources ($L_X \gtrsim 10^{35}\,\mathrm{erg\,s^{-1}}$) which show no signs for an accompanying companion, those with known periods are found to be spinning down, and all are relatively young ($\lesssim 10^5$ yr).

The evolutionary consequences of such large dipole fields are reflected in the properties listed above. Most importantly, large braking torques acting on the star cause it to spin-down rapidly, and the magnetic free energy quickly dominates over the rotation energy, i.e., within several hundred years. For the above sources, the rotation rates lie between 6–12 s, with ages $\lesssim 10^5$ yr (for the SGRs the evidence for periods is indirect, however, their ages are well constrained due to their association with supernova remnants). It is believed that field decay, which is expected for ultramagnetized neutron stars (Thompson & Duncan (1996); also Goldreich & Reisenegger (1992)), influences the thermal evolution and powers the large X-ray luminosities observed for the purported magnetars, $L_X \gtrsim 10^{35}\,\mathrm{erg\,s^{-1}}$.

If magnetars represent the tail-end of the magnetic field distribution of neutron stars, then they are bound to be rare. Assume that their birthrate is 10% the birthrate of neutron stars (some justification for this comes from the estimated birthrates of SGRs; Kulkarni et al., 1994), and that they have active X-ray lifetimes of $\sim 10^5$ yr. These assumptions imply that at present there are only ~ 100 active magnetars in the Galaxy, a conclusion that is borne out by the observations of the aforementioned objects. The fact that we observe the five known AXPs through large column densities in the Galaxy, $N_{\mathrm{H}} \gtrsim 10^{22}\,\mathrm{cm^{-2}}$, suggests that they are indeed that rare, and the fact that they are often associated with supernova remnants or lie near star-formation regions (in spite of the large random velocities usually attributed to neutron stars; Lyne & Lorimer, 1994) suggests that they are young. Similarly, only two Galactic SGRs are known, and it has been suggested that the SGR population census is nearly complete (Kouveliotou, 1995).

In summary, AXPs have long rotation periods, hot blackbody-like spectra ($kT \sim 0.5$ keV) with 10^{35-36} $\mathrm{erg\,s^{-1}}$ steady luminosities, and have thus far only been observed at X-ray wavelengths. A search for new AXPs in the ASCA database has turned up another candidate, which we refer to as AX J1845 − 0258.

2. Observations

The supernova remnant Kes 75 was observed with the ASCA Observatory (Tanaka et al., 1994) on Dec 10, 1993, as a Performance and Verification target. Details of the Kes 75 observation are already published in Blanton & Helfand (1996). Herein, we summarize information that is pertinent to the current analysis. Data were acquired by the two gas imaging spectrometers (GIS2 and GIS3) and collected in the highest time resolution modes (61 μs or 4.88 ms depending on data acquisition rate). The GIS offers $\sim 8\%\ (6/E\,(\mathrm{keV}))^{1/2}$ spectral resolution over its ~ 1–10 keV energy band-pass. Each GIS sits at the focus of a conical foil mirror and the combination results in a spatial resolution of 1–3 arcmin (depending on energy) over a ~ 44 arcmin diameter active field-of-view. In this report, we concentrate exclusively on the GIS data since the target lies outside the field-of-view of the two other focal plane instruments (the SISs).

We analyzed data made available from the ASCA public archive, which were edited to exclude times of high background contamination using the standard screening criteria. This rejects time intervals of South Atlantic Anomaly passages, Earth occultations, bright Earth limb in the field-of-view, and other periods of high particle activity. An effective exposure of $\simeq 4.4 \times 10^4$ s was obtained with each detector. Event data from both detectors were co-added and the arrival times of each photon corrected to the solar system barycenter.

Fig. 1 displays a smoothed, flat-fielded, broad-

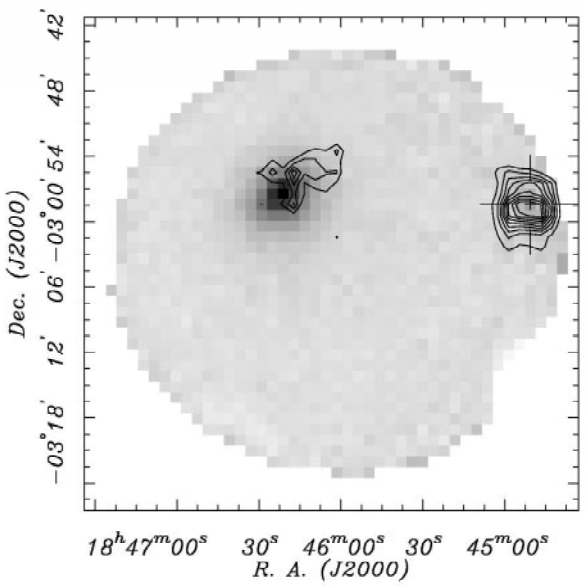

Fig. 1. The ASCA GIS broad-band image (greyscale) of the region containing Kes 75, the central bright source. The location of the pulsar AX J1845 − 0258 is marked by the cross. The overlayed contour plot shows the pulsed emission component only. The pulsar is clearly visible towards the West; the low contours near Kes 75 are not statistically significant. The images are scaled by the square root of the intensity while the contours are spaced in 10% increments.

band image of the Kes 75 observation, centered near the X-ray bright SNR. To the West, at the edge of the GIS FOV, we find an unresolved point source $18^{\rm h}45^{\rm m}$, $-02°58'$ (J2000). This source lies far off-axis, roughly $17'$ from the mean GIS optical axis where its flux suffers strong vignetting; the source is also in a high background region of the detector. Although the source has severe off-axis aberrations and its flux is reduced, the photon limited detection is quite significant, $\sim 21\sigma$ (see Gotthelf & Kaspi (1998) for a description of the recipe used to infer the statistical significance). Due to the off-axis location, and the reduced GIS spatial-mode resolution ($\sim 1' \times 1'$ pixels), the position reconstruction is rather crude and has large uncertainties of order $\sim 3'$, larger than those for a typical on-axis measurement (see Gotthelf, 1994).

3. Timing results

Our strategy involved a pulsar search in existing ASCA GIS Galactic plane fields, to locate candidate AXPs. The search was optimized to detect long period (1–100 s) pulsars for reasons of computational efficiency. A barycentered light curve was generated at each test location using photons extracted from a $4'$ aperture, binned in 0.5 s time intervals. We then used Fast Fourier transforms to find significant periodicities in the data. In the GIS field containing Kes 75 we detected a single, highly significant peak in the power spectral density plot with no overtones, at a period of $P \sim 7$ s. This detection is centered on the faint source, localized to a few arcmin on to the edge of the GIS FOV (see Fig. 1); it is not observed anywhere else in the image, making it unlikely to be an instrumental artifact.

In order to refine the pulse period, we generated a χ^2 periodogram by folding the timeseries. After extracting 2550 photons, again using a $4'$ radius aperture centered on the source, and restricting the energy range to 2–8 keV for optimal sensitivity, we folded the data into 10 phase bins for each trial period and searched a range of periods within ± 0.5 s of the expected period, oversampled with period increments of $0.05 \times P^2/T$, were P is the test period and T the observation duration. The periodogram produced a 14-σ detection at the period of $P \simeq 6.9712 \pm 0.0001$ s (see Fig. 2). When the substantial background is taken into account (see Section 2), the signal modulation is at $\sim 35\%$ amplitude of the mean flux in the $4'$ radius aperture. In order to verify that the pulsed emission indeed arises from the pointlike source, we generated an image of the pulsar by subtracting the off-pulse flux from the pulsed emission (Fig. 1). This reveals just the pulsar, at the expected location, and no other significant flux in the image (contours near Kes 75 are artifact of the noisy subtraction in this region). The pulse profile shows no detectable evidence for energy dependence.

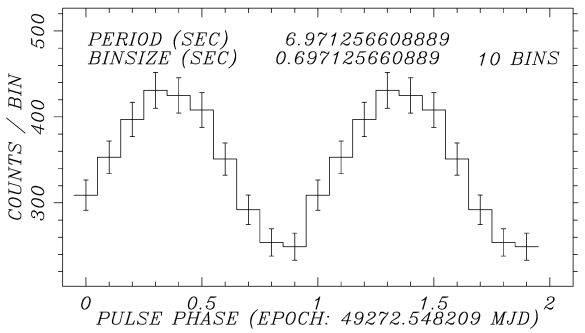

Fig. 2. The folded GIS pulse profile of AX J1845 − 0258 using 10 phase bins and a folding period of 6.9712 s. The profile is roughly sinusoidal, with ~35% modulation, after accounting for the background. Two cycles are shown for clarity.

Given the length of the observation and the source count rate, we were able to segment the data into 4×20 ks intervals to search for variability in the period over the observation time, but none was found to within the measurement errors of $\sim \pm 4 \times 10^{-4}$ s, implying a period derivative $\dot{P} < 4.7 \times 10^{-9}$ s s^{-1} (not terribly constraining). In addition, the light curve is consistent with that of a steady source placed at the edge of the GIS FOV. The low frequency spectrum shows no obvious pink noise that is typical of accretion powered sources.

3.1. The pulsar spectrum

We extracted GIS 2 & 3 source and background spectra from a 6′ region centered on the pulsar. A sample background was taken from a nearby off-source region also at the edge of the detector to match the high local background, mainly due to particle interaction with the detector walls. Response matrices were created following the standard procedure and the spectra and responses of the two detectors were co-added. An absorbed, powerlaw was first used to characterize the spectrum (see Fig. 3). The input spectrum was grouped with a minimum of 60 counts per spectral bin, to ensure adequate statistics after background subtraction. Both the Galactic plane and instrument backgrounds are substantial, forcing us to restrict the fits to 1–7 keV, the

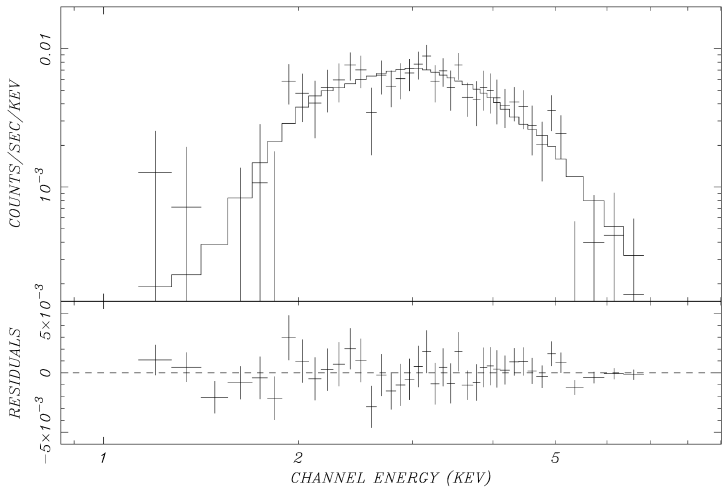

Fig. 3. This figure displays the background subtracted GIS pulse height spectrum of the AX J1845 − 0258 emission. GIS 2 and 3 data are summed after gain corrections. The data are fit with a single powerlaw + foreground absorption model, yielding a photon index $\Gamma \simeq 5$ (see Section 3.1 for details).

energy range where the background flux does not dominate the source. The power-law produced an acceptable fit (reduced $\chi^2 \simeq 0.9$ for 25 dof), with a steep photon index of $\Gamma = 5.2^{+1.1}_{-1.0}$ and $N_{\rm H} \simeq 1.1^{+0.3}_{-0.2} \times 10^{23}\,{\rm cm}^{-2}$. The steep index is indicative of the tail of an intrinsically thermal spectrum. An absorbed blackbody also gives a good fit (reduced $\chi^2 \simeq 0.8$ for 25 dof) with a temperature fit of $kT \simeq 0.64^{+0.11}_{-0.09}\,{\rm keV}$ and a somewhat lower absorption, $N_{\rm H} \simeq 6 \times 10^{22}\,{\rm cm}^{-2}$. The residuals show no evidence for additional emission components. We deduce the unabsorbed blackbody flux in the 1–10 keV band to be $1.2 \times 10^{-11}\,{\rm erg\,cm}^{-2}\,{\rm s}^{-1}$.

We also fit the on-pulse spectrum directly, using the off-pulse data as a background and thereby derive a slightly harder spectral index of $\Gamma \simeq 4.7^{+1.8}_{-1.2}$ for the on-pulse emission. This is independent confirmation that our background subtraction was successful and gives a reasonable source spectrum, to within the derived uncertainties.

4. The nature of AX J1845 − 0258: a brief discussion

On the basis of its long rotation period, steady X-ray flux, steep spectral characteristics, and location in the Galactic plane ($|b| \leq 0.5$), we classify AX J1845 − 0258 as an anomalous X-ray pulsar (see Table 1). The high foreground absorption suggests that the pulsar is distant, and its line of sight along the tangent to the Sagittarius-Carina and Scutum-Crux spiral arms, and the 4-kpc molecular ring justifies its enormous foreground absorption (see Fig. 4). Its $N_{\rm H}$ is roughly twice that of the nearby remnant Kes 75 for which quoted distances lie between 10–20 kpc (Blanton & Helfand, 1996). However, the disparity in $N_{\rm H}$ does not in itself imply a great dissimilarity in distances. For instance, at 10 kpc the lines of sight vectors to these two objects are already separated by $\sim 100\,{\rm pc}$, the typical sizes and scale heights of dense giant molecular clouds which are likely to be responsible for most of the absorbing gas. For the purposes of this article we assume the distance to be 15 kpc, an estimate likely to be accurate to within a factor of two.

The steep X-ray spectrum is characteristic of the Wien tail of a blackbody radiator. Using the best fit blackbody parameters the isotropic X-ray luminosity is $L_X \simeq 2.5 \times 10^{35} d_{15}^2\,{\rm erg\,s}^{-1}$, the distance being $15 d_{15}\,{\rm kpc}$. In effect, the X-ray pulsations can be ascribed to the viewing of a rotating stellar hotspot of area $0.15 A_s d_{15}^2$, where A_s is the area of a neutron star of radius 10 km; this estimate ignores any relativistic corrections to the inferred area. Note that the spectrum is unlike that of any accreting high-mass neutron star binary. Although such binaries have periods in the range 0.07–900 s, and sometimes go into low luminosity states with $L_X \sim 10^{35}\,{\rm erg\,s}^{-1}$, they generally display very hard spectra ($0.8 < \Gamma <$

Table 1
Anomalous X-ray pulsars and their properties

Pulsar	SNR	Ref.	P (s)	$P/2\dot{P}$ (yr)	Γ	kT (keV)	Luminosity [a] ($\times 10^{35}$erg s^{-1})	$N_{\rm H}$ ($\times 10^{22}$ cm^2)
AX J1845 − 0258	...	...	6.97	...	5	0.64	$3 d^2_{15\ {\rm kpc}}$	10
1E 1841 − 045	Kes 73	b	11.76	3.4×10^3	3.2	0.55	$3 d^2_{7\ {\rm kpc}}$	2
1E 2259 + 586	CTB 109	c	6.98	1.5×10^5	4.1	0.41	$0.8 d^2_{4\ {\rm kpc}}$	1
4U 0142 + 615	...	d	8.69	6×10^4	4	0.39	$10 d^2_{4\ {\rm kpc}}$	1
1E 1048 − 5937	...	e	6.44	1×10^4	3	0.64	$5 d^2_{10\ {\rm kpc}}$	2
RX J170849.0 − 400910	...	f	11.00	...	3.5	...	$10 d^2_{10\ {\rm kpc}}$	2

[a] All luminosities are corrected for the effect of absorption and are quoted in the ~1–10 keV energy band. [b] Vasisht & Gotthelf (1997); [c] Corbet et al. (1995), Iwasawa et al. (1992), and references therein; [d] White et al. (1996), Mereghetti & Stella (1995), and references therein.; [e] Parmar et al. (1998), Mereghetti et al. (1997), Corbet & Mihara (1997), and references therein; [f] Sugizaki et al. (1997). The 8-s pulsar RXJ 0720.4 − 3125 is not included in this table as it does not have the properties of a young AXP (Haberl et al., 1997; Kulkarni & van Kerkwijk, 1998).

1.5), and show stochastic variability on all time scales (Nagase, 1989; Koyama et al., 1989) as is generally seen in accretion powered sources. We find no evidence for such variability in our data.

With an AXP classification in hand we can compare the properties of AX J1845 − 0258 with those of five other members of the AXP family in Table 1. A few years ago Schwentker (1994) reported weak 5-s pulsations from RX J1838.4 − 0301 which have not yet been confirmed, Mereghetti et al. (1997) have argued that this X-ray source might be due to coronal emission from a late type star. We, therefore, exclude this source from our list. Although only a future $\dot{P}$ measurement can help determine the linear spindown age of AX J1845 − 0258 (an estimator for the age of an isolated neutron star), its location in the Galactic plane suggests that it is young, $\tau < 10^5$ yr. We consider it extremely likely that the pulsar is associated with one of the several star-formation complexes expected to lie along this line-of-sight (see Fig. 4), out to a distance of 20 kpc. The pulsar lies along a rich region of the Galaxy; there are 10 supernova remnants, several radio pulsars, and the γ-ray source GRO J1838 − 04, all within a $3 \times 3\,\mathrm{deg}^2$ patch of sky surrounding AX J1845 − 0258. However, to the best of our knowledge no cataloged sources are associated with it.

We now describe other models that address the unique properties of AXPs. It is often noted in the literature, that the inferred accretion rate for the

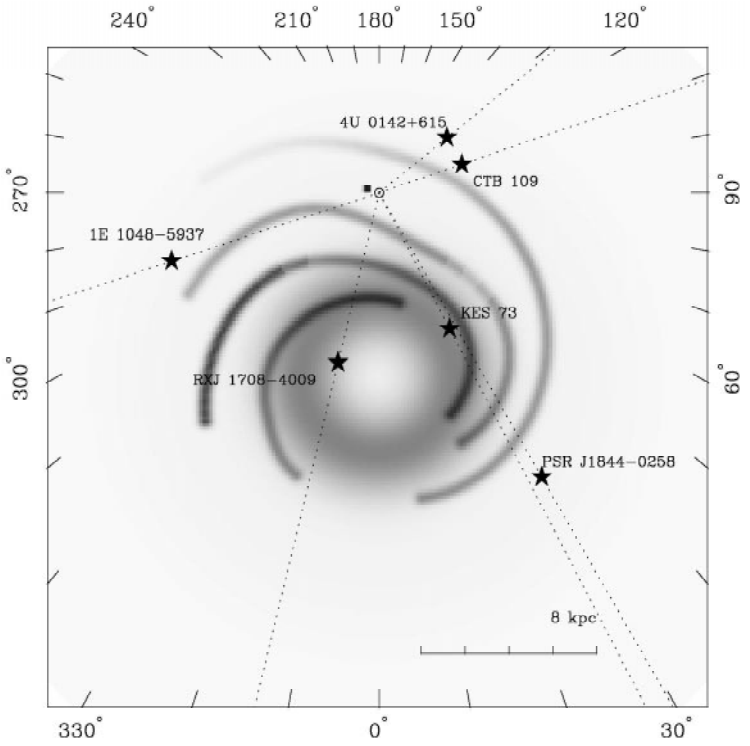

Fig. 4. This figure illustrates the rough electron density distribution in the Milky Way tracing out its spiral arms represented in greyscale (Taylor & Cordes, 1993). The lines-of-sight to sources listed in Table 1 are sketched with the ''stars'' marking their rough distances and the likely intervening overdense regions may be seen. The distribution of AXPs shows that they are rare objects and are likely to be detectable throughout the Galaxy in 1–10.0 keV X-rays.

pulsars in Table 1 are close to those expected for accretion powered pulsars with field strengths $B \sim 10^{11-12}$ G, spinning at their equilibrium periods P_{eq} (see Bhattacharya & van den Heuvel, 1991). This motivated Mereghetti & Stella (1995) to suggest that these pulsars are members of a subclass of low mass X-ray binaries (LMXBs) in equilibrium rotation, with the stellar magnetic field of order $B_s \sim 10^{11}$ G. In contrast, van Paradijs et al. (1995) argue that these objects are isolated neutron stars accreting from a fossil disk, while Ghosh et al. (1997) suggest that AXPs are formed as the result of a Thorne-Żytkov phase of a high mass X-ray binary with strong spherical accretion leading to the soft X-ray spectra with high foreground absorption. It is worth mentioning that accretion scenarios would be hard-pressed to explain the spin-down age of at least one member of Table 1, the ~ 2000 yr of the pulsar in Kes 73 (see Table 1; Gotthelf & Vasisht, 1997). First, it is difficult for accretion torques to spin-down a pulsar to 12 s in $\sim 10^3$ yr from initial periods $P_i \lesssim 10^2$ ms unless, of course, the pulsar were born a very slow rotator, which is quite interesting in its own right. Secondly, if the pulsar were rotating near its equilibrium period, as in the Ghosh & Lamb (1979) scenario, the spin-down time of $P/2\dot{P} \sim 3900$ yr is inconsistent with the luminosity implied accretion rate, $\dot{M} \simeq 10^{-11} M_\odot \, \mathrm{yr}^{-1}$ (assuming the pulsar has a standard dipolar field $\simeq 10^{12}$ G); these usually lie in range 10^4–10^5 yr.

In conclusion, further X-ray observations are required to secure the classification of the 7-s pulsar to the growing family of AXPs – by measuring the long term stability of the X-ray flux, secular trends in the pulse period including Doppler modulation, the lack of which will firm up the likelihood against an accreting binary hypothesis. Indeed, if AXPs are akin to SGRs then they could display sporadic hard X-ray transients, although such behavior is yet to be observed. Infrared observations to search for a possible counterpart to AX J1845 − 0258 could be carried out in spite the somewhat crude localization; we mention that past optical/IR searches for counterparts have been unsuccessful. Furthermore, radio observations to uncover an associated supernova remnant could be pursued. The high foreground absorption could easily cloak the soft X-ray emission of an aged, few $\times 10^4$ yr-old, remnant. We find it remarkable that the period of AX J1845 − 0258 agrees so well with that of 1E 2259 + 586, although at present we believe this is sheer coincidence.

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