A Gemini Observation of the Anomalous X-ray Pulsar 1RXS J170849-400910

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Abstract

The anomalous X-ray pulsars (AXPs) represent a growing class of neutron stars discovered at X-ray energies. While the nature of their multi-wavelength emission mechanism is still under debate, evidence has been recently accumulating in favor of their magnetar nature. Their study in the optical and infrared (IR) wavelengths has recently opened a new window to constrain the proposed models. We here present a brief overview of AXPs and our Gemini-South observation of 1RXS J170849-400910, which is a relatively bright AXP discovered with ROSAT and later found to be an 11 s X-ray pulsar by ASCA. The observation was taken with the near-IR imager Flamingos in J (1.25 µm), H (1.65 µm), and Ks (2.15 µm). We confirm the recent detection by Israel et al. (2003) of a source coincident with the Chandra source (candidate ‘A’). Our derived magnitudes of J = 20.6 (0.2), H = 18.6 (0.2), and Ks = 17.1 (0.2) are consistent with those derived by Israel et al. (2003), and indicate that if this source is indeed the IR counterpart to 1RXS J170849-400910, then there is no evidence of variability from this AXP. However, given the lack of IR variability and the relatively high IR to X-ray flux of this source when compared to the other AXPs, we conclude that this source is unlikely the counterpart of the AXP, and that the other source (candidate ‘B’) within the Chandra error circle should not be ruled out as the counterpart. Further monitoring of these sources and a deep observation of this complex field are needed to confirm the nature of these sources and their association with the AXP.

Key words: ISM: individual (1RXS J170849-400910), Stars: Neutron, ISM: Supernova Remnants, X-Rays: ISM

1 Introduction

The ‘Anomalous X-ray Pulsars’ (AXPs) represent a growing class of pulsars whose X-ray luminosities (∼10^{34}-10^{36} erg s^{-1}) can not be accounted for by their spin-down power nor by conventional binary accretion models, thus
the name ‘anomalous’. Currently, we know of 8 AXPs, one of which is a transient AXP (XTE 1810-197) and two are AXP candidates (CXOU J0110043.1-721134 and AX 1845-0258). Typified by 1E2259+586, the first AXP discovered in the SNR CTB 109 (Gregory & Fahlman, 1980), AXPs share the following properties:

1. they are slow X-ray rotators (when compared to the rotation-powered Crab-like pulsars) with periods constrained to the narrow range of 5–12 seconds, and unlike the accretion-powered pulsars, they spin down;
2. their large spin-down rates and the association of three of them with SNRs indicate a young age ($10^3$–$10^5$ years, see Table 1);
3. they lack a detectable companion star and have a small scale height above the Galactic Plane;
4. they have soft X-ray spectra (compared to the Crab-like and accretion-powered pulsars) characterized by a two-component blackbody+power law;
5. they do not have radio counterparts; but half the sample has faint optical and/or IR counterparts (see Table 1).

The two competing models proposed to describe the emission mechanism from these sources have been the accretion and ‘magnetar’ models.

In the accretion model, typical high-mass X-ray binaries are ruled out based on the AXPs’ relatively low X-ray luminosities, soft X-ray spectra, lack of Doppler shifts associated with binary orbital motion, and the absence of bright optical counterparts. However, models which involve accretion from a fossil disk, established from matter falling back onto the neutron star following its birth, have not been ruled out and have been favored by some authors (Chatterjee et al., 2000; Alpar, 2001; Marsden et al., 2001). These accretion models are particularly successful in explaining the period clustering of AXPs and their persistent X-ray emission. However, they are problematic in explaining the bursts energetics and the optical pulsations from 4U 0142+614 (Kern & Martin, 2002); see however Ertan & Cheng (2004) who argue that the observed optical pulsed emission from 4U 0142+614 can be explained within the disk model.

Evidence has been recently accumulating in favor of the ‘magnetar’ model, which was proposed to explain the properties of their relatives, the Soft Gamma-Ray Repeaters (SGRs). In this model (Duncan & Thompson, 1992; Thompson & Duncan, 1995; Colpi et al., 2000), AXPs and SGRs have inferred magnetic fields of $\sim10^{14}$–$10^{15}$ G, at least two orders of magnitude higher than the Crab and an order of magnitude larger than the quantum critical field. Their large spin-down torques are provided by the magnetic dipole radiation. The super-Eddington bursts result from the release of magnetic energy through instabilities from inside the neutron star. The persistent thermal X-rays were suggested to be due to the surface heating by magnetic field decay, while the nonthermal X-rays could be due to acceleration of particles by the Alfvén waves on the neutron star surface. The magnetar model has been successful in explaining most of the AXPs properties, including the period clustering of these sources when the
magnetic field decays significantly on a timescale of $\sim 10^4$ years (Colpi et al., 2000). However, the emission at optical and IR wavelengths is yet to be further explored in the light of the recent observations (see §2).

2 Optical and IR Observations:

As of today, 4(5) AXPs have been recently detected in the optical or IR. In Table 1, we summarize their properties including their spin periods, their dipole magnetic fields ($B \sim 3.2 \times 10^{19} (P \dot{P})^{0.5}$ Gauss), their spin down ages ($\tau = P/2 \dot{P}$), their association with SNRs, and the magnitudes of their proposed counterparts. Optical and IR observations have been recently driving a wealth of theoretical modeling in order to understand their emission mechanisms at those wavelengths.

In the accretion model, energy is dissipated by viscous processes in the accretion disks. Perna et al. (2000) computed the theoretical predictions for the optical and IR emission from the accretion model established by fallback following a supernova explosion (Chatterjee et al., 2000). While the predicted magnitudes are brighter than the observed values, Perna et al. (2000) noted that the discrepancy could be explained by the sensitivity of the predicted fluxes (especially in the optical regime) to the value of the inner part of the disk, and that the emission at the near-IR wavelengths should originate from the outermost regions of the disk. Perna et al. (2000) also argued that the spin-down rate from accretion models is identical to that predicted by the magnetar model. Therefore, the ability to distinguish between the two models lies in searching for disk emission at wavelengths longer than X-rays. Mereghetti et al. (2002) noted that the geometry and size of the disks are too uncertain to definitely rule out the accretion model.

In the magnetar model, there hasn’t been much theoretical prediction of the optical/IR emission; and it is only recently that Özel (2004) argued that, in the magnetar model, the IR emission can not be due to thermal emission from the neutron star surface, but that it is synchrotron emission from the magnetosphere. In this model, the IR to X-ray flux is expected to be correlated with the spin-down energy of the AXP. However, Rea et al. (2004) found that the IR emission from XTE 1810-197 does not follow this general trend.

It is likely that ‘hybrid’ models which involve a neutron star with a magnetar field strength in the higher multipoles, and a dipole field in the $10^{12}$ G interacting with a fallback disk, are more realistic in explaining all AXP properties (Eksi & Alpar 2003). The higher multipole magnetic field would explain the bursting properties of the AXPs, and the AXP period clustering and X-ray/IR correlation can be explained in the accretion model. This ‘hybrid’ model has been recently supported by the IR observations of XTE 1810-197 (Rea et al. 2004).
3 1RXS J170849-400910

3.1 Previous observations

1RXS J170849-400910 was first discovered with the ROSAT X-ray satellite (Voges et al., 1996), and later found to be an 11 s pulsar with ASCA (Sugizaki et al., 1997). This AXP is one of the brightest AXPs with an X-ray luminosity of $\sim 2 \times 10^{35}$ erg s$^{-1}$ at a distance of 5 kpc.

This source lies in a complex region of the sky and in the neighborhood of the supernova remnant G346.5–0.1. The association between the AXP and the SNR is however unlikely (Gaensler et al., 2001). No radio counterpart to 1RXS J170849-400910 has been found and a $5\sigma$ upper limit of 3 mJy was placed (Israel et al., 2003; Gaensler et al., 2001). Recent Chandra observations have located the source at $\alpha=17^{h} 08^{m} 46.87, \delta=-40^{o} 08^{\prime} 52.44$ (J2000) with an uncertainty circle radius of 0.8 (90% confidence level) consistent with the ROSAT HRI observation (Israel et al., 2003).

BeppoSAX observations of 1RXS J170849-400910 reported on the first detection of an absorption line near 8.1 keV, which if interpreted as a proton cyclotron line, would imply a magnetic field value of $B=1.6 \times 10^{15}$ G. This value is higher but not inconsistent with the magnetic field derived from the spin-down of the source ($B \sim 4.6 \times 10^{14}$ Gauss), a magnetar-strength value. While no bursting activity has been yet reported from this AXP, it was observed to glitch (Dall’Osso et al., 2003; Kaspi & Gavriil, 2003).

Recently, optical and IR observations were performed with the 3.6 m ESO telescope in La Sille, Chile. Additional IR data were obtained with the 3.6 m CFHT (Mauna Kea, Hawaii). While there was no optical detection within the Chandra circle down to a limiting magnitude in R of 26.5, two faint objects were detected in the IR (Israel et al., 2003). The two sources, named A & B, have the following magnitudes: $K'=17.53 \pm 0.02$, $H=18.85 \pm 0.05$, $K_s=17.3 \pm 0.1$\footnote{K$_s$ was reported as 18.3 in Israel et al. (2003), however the magnitudes in K and K$_s$ should be similar and so we corrected for the typo (Israel, private communication).} for object A; and $K'=20.0 \pm 0.08$, $H=20.43 \pm 0.07$ for object B. Israel et al. (2003) argue that object A is most likely the counterpart of 1RXS J170849-400910.

3.2 The Gemini observation:

This Gemini observation was part of an approved Gemini program to search for and study the IR counterparts of AXPs. Due to unfortunate problems with the Near Infrared Imager (NIRI) in both cycles 2001B and 2002B, the Gemini-North observations of AXPs 1E 2259+586, 1E 1841-045, and AX J1845-0258 did not take place.

1RXS J170849-400910 was however observed using the Gemini-South FLAMIN-
GOS I near-IR (1–2.5 μm) multi-object spectrograph and imager, built at the University of Florida. On 2002, July 11-12, 40 individual 45 s images in the Ks (1.99 – 2.30 μm) filter were obtained for a total exposure time of 1,800 s. On 2002, July 12-13, 37 individual 60 s images in the H (1.49–1.78 μm) filter for a total exposure time of 2,220 s and 25 individual 90 s images in the J (1.15–1.33 μm) filter for a total exposure time of 2,250 s were obtained. July 12-13 had photometric weather. The images have a scale of 0.078 arcsec pixels with a field of view of 2.6′×2.6′.

The individual images were sky-subtracted, flat-fielded and then combined using the Gemini IRAF package following the standard reduction techniques for FLAMINGOS data. The FWHM of the combined observations is 0.5″–0.6″ for both nights.

The Persson IR standard stars (Persson et al., 1998) S754 and S294 were observed on July 2002, 11-12, and S279 was observed on 2002, July 12-13. These data were reduced as described above and used for calibration. Photometry were obtained using DAOPHOT II (Stetson, 1987). The limiting magnitude was found to be 19.3 (Ks), 21.3 (H), and 22.0 (J).

4 Results and Discussion:

As shown in Fig. 1, we confirm Israel et al. (2003) detection of candidate ‘A’, an IR source located within the 0.8″ uncertainty region of the position of 1RXS J170849-400910, as determined by the Chandra X-ray observation.

Table 1 displays the magnitudes and colour indices for candidate ‘A’ and compares them with those found by Israel et al. (2003). It should be noted that the resolution of the Gemini data is such that candidates ‘A’ and ‘B’ are not resolved and therefore the colour indices determined for candidate ‘A’ could be contaminated slightly, but not significantly, by candidate ‘B’. Using CFHT, Israel et al. (2003) measured the H magnitude of both candidates ‘A’ and ‘B’ to be 18.85 +/- 0.05 and 20.43 +/- 0.07, respectively. The combined magnitude given these two measurements would be 18.6 and therefore we estimate the contamination in magnitude to be 0.2-0.3. This is consistent with the difference in magnitudes between the Israel et al. (2003) measurement and ours (Table 2).

While IR variability seems to be a common property of AXPs, Israel et al. (2003) reported no variability in 1RXS J170849-400910 for the observations taken 1999 September 15-16, 2001 May 26, & 2002 February 19. As well, our Gemini magnitudes agree with those of Israel et al. (2003) in the J, H, and Ks bands, within error (Table 2). We conclude that there is also no evidence of variability between the Israel et al. observations and ours.

While the absence of IR variability could be explained by the (so far) no detection of bursts from this AXP, we believe that a more likely interpretation of the absence of IR variability over ~3 years is that candidate ‘A’ is not the true counterpart to the AXP. Unless 1RXS J170849-400910 is an anoma-
lous AXP, this conclusion is further supported by the very small X-ray to IR flux ratio (∼500) compared to that observed for all other AXPs (>1000). We therefore conclude that candidate ‘B’ or other fainter (undetected) stars in this crowded field should not be ruled out as a potential counterpart to 1RXS J170849-400910. Future deep observations and simultaneous monitoring in the IR and X-rays are needed to confirm our conclusions.

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References

Alpar, M. A. 2001, On Young Neutron Stars as Propellers and Accretors with Conventional Magnetic Fields, ApJ, 554, 1245–1254.
Chatterjee, P., Hernquist, L., & Narayan, R. 2000, An Accretion Model for Anomalous X-Ray Pulsars, ApJ, 534, 373–379.
Colpi, M., Geppert, U., Page, D. 2000, Period Clustering of the Anomalous X-Ray Pulsars and Magnetic Field Decay in Magnetars, ApJ, 529, L29–L32.
Dall’Osso, S. et al. 2003, The Glitches of the Anomalous X-Ray Pulsar 1RXS J170849.0-400910, ApJ, 599, 485–497.
Duncan, R. C. & Thompson, C. 1992, Formation of very strongly magnetized neutron stars - Implications for gamma-ray bursts, ApJ, 392, L9–L13.
Durant, M., van Kerkwijk, M. & Hullemann, F. 2003, Optical and Infrared Observations of Anomalous X-ray Pulsars, in "Young Neutron Stars and Their Environments" (IAU Symposium 218, ASP Conference Proceedings), eds F. Camilo and B. M. Gaensler (astro-ph/0309801).
Eksi, K. Y., & Alpar, M. A. 2003, Can Thin Disks Produce Anomalous X-Ray Pulsars?, ApJ, 599, 450–456.
Ertan, Ü, & Cheng, K. S. 2004, On the Infrared, Optical, and High-Energy Emission from the Anomalous X-Ray Pulsar 4U 0142+61, ApJ, 605, 840–845.
Gaensler, B., Slane, P., Gotthelf, E., Vasisht, G. 2001, Anomalous X-Ray Pulsars and Soft Gamma-Ray Repeaters in Supernova Remnants, ApJ, 559, 963–972.
Gregory, P. C., & Fahlman, G.G. 1980, An extraordinary new celestial X-ray source, Nature, 287, 805-806.
Hulleman, F., van Kerkwijk, M. H., & Kulkarni, S. R. 2000, An optical counterpart to the anomalous X-ray pulsar 4U0142+61, Nature, 408, 689–692.
Hulleman, F. et al. 2001, A Possible Faint Near-Infrared Counterpart to the Anomalous X-Ray Pulsar 1E 2259+586, ApJ, 563, L49–L52.
Israel, G. L. et al. 2003, The Infrared Counterpart to the Anomalous X-Ray Pulsar 1RXS J170849-400910, ApJ, 589, L93–L96.
Israel, G.L. et al. 2004, Accurate X-Ray Position of the Anomalous X-Ray Pulsar XTE J1810-197 and Identification of Its Likely Infrared Counterpart, ApJ, 603, L97–L100.
Kaspi, V. M. & Gavriil, F. 2003, A Second Glitch from the “Anomalous” X-Ray Pulsar 1RXS J170849.0-4000910, ApJ, 596, L71–L74.
Kaspi, V. M. et al. 2003, A Major Soft Gamma Repeater-like Outburst and Rotation Glitch in the No-longer-so-anomalous X-Ray Pulsar 1E 2259+586, ApJ, 588, L93–L96.
Kern, B. & Martin, C. 2002, Optical pulsations from the anomalous X-ray pulsar 4U0142+61, Nature, 417, 527–529.
Özel, F. 2004, A Model for the Optical/IR Emission from Magnetars, ApJL, submitted (astro-ph/0404144).
Marsden, D., Lingenfelter, R. E., Rothschild, R. E., & Higdon, J. C. 2001, Nature versus Nurture: The Origin of Soft Gamma-Ray Repeaters and Anomalous X-Ray Pulsars, ApJ, 550, 397–409.
Mereghetti, S., Chiarlone, L., Israel, G.L., & Stella, L. 2002, The Anomalous X-ray Pulsars, in Proceedings of the 270. WE-Heraeus-Seminar, Bad Honnef, Eds. W. Becker, H. Lesch and J. Trümper (astro-ph/0205122).
Persson, S. E., Murphy, D. C., Krzeminski, W., Roth, M., & Rieke, M. J. 1998, A New System of Faint Near-Infrared Standard Stars, AJ, 116, 2475–2488.
Perna, R., Hernquist, L., & Narayan, R. 2000, Emission Spectra of Fallback Disks around Young Neutron Stars, ApJ, 541, 344–350.
Rea, N. et al. 2004, Correlated Infrared and X-ray variability of the transient Anomalous X-ray Pulsar XTE J1810-197, A&A, 425, L5–L8.
Stetson, P. B. 1987, DAOPHOT – A computer program for crowded-field stellar photometry, PASP, 99, 191–222.
Sugizaki, M. et al. 1997, Discovery of an 11-s X-Ray Pulsar in the Galactic-Plane Section of the Scorpius Constellation, PASJ, 49, L25–L30.
Thompson, C. & Duncan, R. C. 1995, The soft gamma repeaters as very strongly magnetized neutron stars - I. Radiative mechanism for outbursts, MNRAS, 275, 255–300.
Voges, W. et al. 1996, ROSAT All-Sky Survey Bright Source Catalogue, IAUC, 6420, 2.
Wang, Z. & Chakrabarty, D. 2002, The Likely Near-Infrared Counterpart to the Anomalous X-Ray Pulsar 1E 1048.1-5937, ApJ, 579, L33–L36.
| AXP             | P   | B    | τ    | SNR? | optical/IR counterpart[^s]                  |
|-----------------|-----|------|------|------|--------------------------------------------|
|                 | s   | 10^{14} G | 10^{3} yrs |      |                                            |
| XTE1810-197     | 5.54| 2.6  | 7.6  | –    | I>24.3, H=21.3–22.0                        |
|                 |     |       |      |      | K_s=20.3–20.8[^1]                          |
| 1E 1048.1-5937  | 6.45| 5.0  | 2.7  | –    | I=26.6, J=21.7, H=20.8                    |
|                 |     |       |      |      | K_s=19.4–21.2[^2]                          |
| AX 1845-0258    | 6.97| ?    | ?    | G29.6+0.1 | –                             |
| 1E 2259+586     | 6.98| 0.59 | 230  | CTB 109 | J, I, R>23.8, 25.6, 26.4                |
|                 |     |       |      |      | K_s=20.4–21.7[^3]                          |
| CXOU 0110043.1-721134 | 8.0 | ?    | ?    | –    | –                                          |
| 4U 0142+615     | 8.69| 1.3  | 72   | –    | R=24.98[^4]                              |
| 1RXS J170849-400910 | 11.0| 4.6  | 9.4  | –    | (see Table 2)[^5]                        |
| 1E 1841-045     | 11.8| 7.0  | 4.6  | Kes 73 | –                                          |

[^s]: The references that follow correspond to the optical and infrared observations
[^1]: Israel et al. (2004); Rea et al. (2004)
[^2]: Wang & Chakrabarty (2002); Durant, van Kerkwijk & Hulleman (2003)
[^3]: Hulleman et al. (2001); Kaspi et al. (2003)
[^4]: Hulleman et al. (2000)
[^5]: Israel et al. (2003) and this work.

Table 1
Summary of AXPs and their proposed optical/IR counterparts.
| magnitude/reference | this work | Israel et al. (2003) |
|---------------------|-----------|---------------------|
| J                   | 20.6±0.2  | 20.9±0.1            |
| H                   | 18.6±0.2  | 18.85±0.05          |
| −                   | 18.6±0.1  |                     |
| K_s                 | 17.1±0.2  | 17.3±0.1 (a)        |
| K'                  | 17.53±0.02|                     |
| J-H                 | 2.0±0.4   | 2.3±0.2             |
| J-K_s (a)           | 3.5±0.4   | 3.6±0.2             |
| J-K'                | 3.4±0.1   |                     |
| H-K_s (a)           | 1.5±0.4   | 1.6±0.2             |
| −                   | 1.3±0.2   |                     |
| H-K'                | 1.32±0.07 |                     |
| −                   | 1.1±0.1   |                     |

(a) after correcting for the typo in Israel et al. (2003); see text for details.

Table 2
Infrared magnitudes of candidate ‘A’.
Fig. 1. (Left): Colour image composed of J, H, and Ks filter images coloured as shown at right. Circles shown represent 90% error circles from ROSAT (9′′-radius) and Chandra (0.8′′-radius) as in the figure from Israel et al. (2003). (Right): Individual filter images. White arrow points to the position of AXP Candidate ‘A’ (Israel et al. 2003).
This figure "Fig1-medres.jpg" is available in "jpg" format from:

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