THE INFRARED COUNTERPART TO THE ANOMALOUS X-RAY PULSAR 1RXS J170849−400910

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Received 2002 November 17; accepted 2003 April 16; published 2003 April 25

ABSTRACT

We report the discovery of the likely IR counterpart to the anomalous X-ray pulsar (AXP) 1RXS J170849−400910 based on the Chandra High Resolution Camera (imaging detector) X-ray position and the deep optical/IR observations carried out from ESO telescopes and the Canada-France-Hawaii Telescope during 1999–2002. Within the narrow uncertainty region, we found two relatively faint $(K' = 20.0$ and $K' = 17.53)$ IR objects. Based on their color and position in the $J-K'$ versus $J-H$ diagram, only the brighter object is consistent with the known IR properties of the counterparts to other AXPs. No variability was detected for this source, which is similar to what is observed in the case of 4U 0142+614. Like in other AXPs, we found that the IR flux of 1RXS J170849−400910 is higher than expected for a simple blackbody component extrapolated from the X-ray data. If confirmed, this object would be the fourth IR counterpart to a source of the AXP class and would make the IR excess a likely new characteristic of AXPs.

Subject headings: infrared: stars — pulsars: general — pulsars: individual (1RXS J170849−400910) — stars: neutron — X-rays: stars

1. INTRODUCTION

Anomalous X-ray pulsars (AXPs) are thought to be solitary magnetic rotating neutron stars with either a standard magnetized field or one that is larger than $10^{14}$ G (magnetars), although the binary system scenario with a very low mass companion is not completely ruled out by current observational data (for a review, see Israel, Mereghetti, & Stella 2002b, Mereghetti et al. 2002, and references therein). Different production mechanisms for the observed X-ray emission have been proposed, involving either accretion or dissipation of magnetic energy. The magnetar model, originally proposed by Duncan & Thompson (1992) to explain soft gamma-ray repeaters (SGRs), appears to be successful at interpreting most of the properties of AXPs. In fact, AXPs have been linked to SGRs (which are thought to be magnetars, i.e., neutron stars powered by their strong magnetic fields) because of similar timing properties, namely, periods and positive period derivatives (Duncan & Thompson 1992; Thompson & Duncan 1993, 1996). What differentiates the two classes of objects is unclear. The similarity in the spin parameters would not be sufficient by itself to differentiate AXPs and SGRs from other groups of pulsars with very different emission properties. Conversely, a very high magnetic field strength (if at all) cannot be the sole factor governing whether or not a neutron star is a magnetar, a radio pulsar, or in a binary system (Camilo et al. 2000). The possible connection of AXPs with SGRs has gained more credibility with the recent detection of SGR-like X-ray bursts from two AXPs (Kaspi & Gavriil 2002; Gavriil, Kaspi, & Woods 2002) that also showed IR variability. For 1E 2259+586, IR variability of the likely counterpart has been detected a few days after a strong bursting activity seen with the Rossi X-Ray Timing Explorer (Kaspi, Gavriil, & Woods 2002; G. L. Israel et al. 2003, in preparation). Similarly, the variability of the IR counterpart to 1E 1048.1−5937 is thought to be related to X-ray variability (Israel et al. 2002a), although no simultaneous X-ray/IR observations were available. The magnetar scenario does not make any prediction (yet) on the optical/IR emission seen in AXPs. If AXPs are powered by accretion via a disk, analogous to the X-ray bursts observed in low-mass X-ray binaries, it is expected that the effects of the X-ray bursts’ activity in AXPs (and SGRs) propagate toward longer wavelengths, e.g., via reprocessing in the disk (see Middleditch & Nelson 1976 and Lawrence et al. 1983). Evidence for flattening (or excess) of the flux distribution in the IR band (with respect to a simple blackbody component forced to be consistent with both the X-ray and optical data) has been reported in three AXPs, namely, 1E 2259+586, 1E 1048.1−5937, and 4U 0142+614 (Hulleman et al. 2001; Wang & Chakrabarty 2002; G. L. Israel et al. 2003, in preparation). The spectral flattening and variability of the IR emission of AXPs are potentially important diagnostics for the study of these enigmatic objects and their possible connections with other classes of pulsars.

1RXS J170849−400910 was discovered by the ROSAT mission during the All Sky Survey program (Voges et al. 1996), but only a few years later, ~11 s pulsations were discovered by ASCA (Sugizaki et al. 1997). Both the period derivative ($\dot{P} \sim 2 \times 10^{-11}$ s s$^{-1}$) and the optical upper limits inferred for its counterpart were found to be consistent with those of AXPs (Israel et al. 1999). The source is radio-quiet (i.e., no pulsations...
were detected in the radio band; Israel et al. 2002b) and a stable rotator comparable to radio pulsars (Gavriil & Kaspi 2002). It is also the only AXP for which X-ray spectral variations as a function of the pulse phase have been detected and determined to be associated with variations of the pulse profile (similar to those observed in “standard” accretion-powered X-ray binary systems; G. L. Israel et al. 2003, in preparation). Finally, 1RXS J170849–400910 represents the only AXP for which a spectral signature, thought to be due to resonant cyclotron absorption, has been detected, confirming the presence of a relatively high magnetic field (Rea et al. 2003).

In this Letter, we present the results obtained from Chandra, ESO, and Canada-France-Hawaii Telescope (CFHT) observations of 1RXS J170849–400910 in the X-ray, optical, and IR bands. We identified the likely IR counterpart to this AXP based on positional coincidence and unusual IR colors. The overall (from X-ray to IR) energy distribution is also presented and discussed in the light of the IR excess detected in 1RXS J170849–400910 and other AXPs.

2. CHANDRA OBSERVATIONS

The field of 1RXS J170849–400910 was observed during Chandra Cycle 2 with the High Resolution Camera–Imager (HRC-I; Zombeck et al. 1995) on 2001 September 23 for an effective exposure time of 9870 s. Data were reduced with CIAO, version 2.2, and analyzed with standard software packages for X-ray data (CIAO, XIMAGE, XRONOS, etc.). The observation was carried out with a nominal aspect solution, and the latest calibration files were used. Only one source was detected in the HRC-I (see Israel et al. 2002a for details on the detection algorithms). The source has the following coordinates: R.A. = 17°08′46″87, decl. = −40°08′52″44 (equinox J2000), with an uncertainty circle radius of 0″7 (90% confidence level; consistent with the ROSAT HRI positions in Israel et al. 1999). Photon arrival times were extracted from a circular region with a radius of 1″5, including more than 90% of the source photons, and corrected to the barycenter of the solar system. A coherent pulsation at a period of 11.0011 ± 0.0005 s (90% confidence level) was detected, confirming that the source is indeed 1RXS J170849–400910.

We also carried out a spatial profile analysis for the X-ray emission from a region of 7″ radius centered on the source position. The spatial profile was found to be in good agreement with the expected Chandra point-spread function (PSF) for an on-axis source (see Israel et al. 2002a). Unfortunately, the high X-ray background in the 1RXS J170849–400910 field prevented a more sensitive search for diffuse emission at larger radii.

3. OPTICAL/IR OBSERVATIONS

Most of the optical/IR data were obtained with the 3.6 m ESO telescope (La Silla, Chile) equipped with the ESO Faint Object Spectrograph and Camera (EFOSC2; a CCD with 2048 × 2048 pixels, a 0″157 pixel scale, and a 5″2 × 5″2 field of view [FOV]) in the optical band and with the 3.5 m New Technology Telescope (NTT; La Silla, Chile) equipped with the Son of ISAAC (SOFI; Hawaii HgCdTe 1024 × 1024 array; 0″292 pixel scale and 4″9 × 4″9 FOV) in the near-IR band. Additional IR data were obtained at the 3.6 m CFHT (Mauna Kea, Hawaii) equipped with the Adaptive Optics Bonnette (AOB; Hawaii HgCdTe 1024 × 1024 array; 0″035 pixel scale and 36″ × 36″ FOV).

Optical Johnson R-filter deep images were obtained with EFOSC2 on 1999 September 15–16 with effective exposure times of 1500 s (with seeing of 0″8). Standard reduction packages were used in the analysis of the optical data (DAOPHOT II; Stetson 1987) in order to obtain the photometry of each stellar object in the images. A limiting magnitude (3σ confidence level) of R ∼ 26.5 was reached.

Images in the J and H bands were initially acquired with SOFI on 2001 May 26 with 1920 s (J) and 2400 s (H) of effective exposure time (with seeing of 0″4–0″6). Observations yield a limiting magnitude of 22.7 (J) and 22.6 (H; 3σ confidence level). SOFI Ks images were obtained on 2002 February 19 (seeing 0″3). The exposure time was 3000 s, and a limiting magnitude of Ks ∼ 21.4 was reached. In all these cases, single 5 s long exposure images were taken for each filter with offsets of 40″ in order to sample and subtract the variable IR background. Finally, H and K′ images were obtained with AOB on 2002 August 17 with effective an exposure time of 2700 s (for each filter; with seeing of 0″4–0″5). Thanks to the adaptive optics, we obtained a source PSF of ~0″12 yielding a limiting magnitude of 23.1 (H) and 21.8 (K′). During the latter run, single 60 s long exposure images were taken with random offsets in the 4″–10″ range. Standard IR software packages were used for sky frame subtraction and image co-addition (ECLIPSE and IRDR; Devillard 1997 and Sabbey et al. 2001).

To register the Chandra coordinates of 1RXS J170849–400910 on our optical/IR images, we computed the image astrometry using, as a reference, the positions of stars (about 20 for ESO instruments) selected from the Guide Star Catalog, version 2.2 (GSC2.2), which has an intrinsic absolute accuracy of about 0″2–0″4 (depending on the magnitude and sky position of the stars). After taking into account the uncertainties of the source X-ray coordinates (0″7), the rms error of our astrometry (0″12), and the propagation of the intrinsic absolute uncertainties on the GSC2.2 coordinates (we assumed a value of 0″3), we estimated the final accuracy attached to the 1RXS J170849–400910 position to be about 0″8. Figure 1 shows a region of 28″ × 20″ around the 1RXS J170849–400910 position in the K′-band CFHT image (with 90% confidence level ROSAT and Chandra uncertainty circles superposed). In the inset, we show the close-
up of the region around the Chandra position with the counterpart candidates marked.

The 3.6 m ESO optical R-band data show that no object is consistent with the Chandra position of 1RXS J170849–400910 down to a limiting magnitude of about 26.5. On the other hand, two relatively faint objects are detected in the IR images carried out at the CFHT (marked with A and B in Fig. 1). The latter two sources have the following IR magnitudes as inferred from X-ray observations. The rectangle, which includes the position of object A, represents the most probable region of the diagram where the IR counterpart to 1RXS J170849–400910 would lie, based on the known IR counterparts to AXPs.

Fig. 2.—Color-color diagram obtained for all the objects detected within a radius of about 30″ around the Chandra position of 1RXS J170849–400910. The proposed counterpart is marked with the letter A. Several evolutionary star sequences are also shown for comparison, for different values of $A_V$; 0, 2, 4, 6, and 11.2 (thin solid lines; the latter value obtained by assuming total Galactic absorption), and $A_V = 7.8$ (thick solid line; assuming $N_H = 1.4 \times 10^{22}$ cm$^{-2}$ as inferred from X-ray observations). The rectangle, which includes the position of object A, represents the most probable region of the diagram where the IR counterpart to 1RXS J170849–400910 would lie, based on the known IR counterparts to AXPs.

4. DISCUSSION

The proposed IR counterpart to 1RXS J170849–400910 is by far the brightest one among those of AXPs: $K' = 21.7$, $K = 20.0$, and $K_J = 19.4$ for 1E 2259+586, 4U 0142+614, and 1E 1048.1–5937, respectively (Hulleman et al. 2001; G. L. Israel et al. 2003, in preparation; Wang & Chakrabarty 2002). We note that the relatively large X-ray–to–IR unabsorbed flux ratio of about 500 is lower than that obtained for other AXPs. However, 1RXS J170849–400910 is also the most luminous AXP in the 0.5–10 keV band with an unabsorbed luminosity of $\geq 4 \times 10^{38}$ ergs s$^{-1}$ (assuming a distance $\geq 5$ kpc). In order to characterize the broadband energy distribution of the source, we plotted the IR–X-ray data of 1RXS J170849–400910 in Fig. 3. X-ray fluxes have been inferred by using the phase-averaged spectral parameters obtained with BeppoSAX data (Israel et al. 2001; Rea et al. 2003). Two different values of the extinction have been used for model fitting purposes: $A_V = 7.8$ and 11.2 (triangles and circles, respectively), corresponding to the $N_H$ inferred from the X-ray spectra and the Galactic absorption in the direction of the source, respectively.

The blackbody component detected in the X-rays ($kT \sim 0.45$ keV; Israel et al. 2001; Rea et al. 2003) cannot account for the (relatively high) IR flux. Similarly, the power-law com-
ponent, if extrapolated to IR wavelengths, would imply a much higher IR flux level that is not observed; a cutoff must therefore occur in the UV/optical bands. Regardless of the exact position of the cutoff, we note that the X-ray–to–IR emission of 1RXS J170849–400910 cannot be fitted with a simple spectral component (similar to the case of 4U 0142+614 and 1E 2259+586; Hulleman, van Kerkwijk, & Kulkarni 2000; Hulleman et al. 2001).

The magnetar model does not account for the observed IR emission or IR variability of AXPs, and no predictions can be verified. Therefore, we discuss the above observational findings in the context of models based on fossil disks (Chatterjee, Hernquist, & Narayan 2000; Alpar 2001) since they make clear predictions for the IR emission. However, up to now the latter models are unable to account for the bursts seen in AXPs and SGRs. In the case of a fossil disk, the IR emission arises mainly from two components: viscous dissipation and the reprocessing of X-ray flux impinging on the disk from the pulsar (Perna, Hernquist, & Narayan 2000; Perna & Hernquist 2000; Alpar 2001). Specifically, at IR wavelengths and based on the X-ray luminosity of 1RXS J170849–400910, the dominant emission component is expected to be X-ray irradiation. The models we considered have been computed for a distance of 5 kpc, and the observed X-ray luminosity as an input parameter, but since the disk luminosity scales almost linearly with the X-ray luminosity, the result is nearly independent of the distance. As for the X-ray spectrum, in the accretion model (with magnetic fields of ~10^{12} G), one would expect the emission to be roughly a blackbody produced in a region (polar cap) much smaller than the area of the star. Current X-ray data are consistent with this but are not good enough to allow a firm discrimination with respect to the X-ray spectrum of a magnetar, in which case one would expect the area of the emitting region to be consistent with the whole surface of the star (Perna et al. 2001).

In Figure 3, we show disk models obtained with the inner and the outer radius of the disk, r_{in} and r_{out}, and the inclination left free to vary (note, however, that the inclination only scales the fluxes while r_{in} and r_{out} modify the shape of the model and the flux peak position; see Perna et al. 2000 for details). The best fit was obtained for a small truncated disk, with r_{in} and r_{out} equal to 10^{11} and 5 \times 10^{11} cm, respectively (dotted line in Fig. 3). However, this solution would not be able to explain the X-ray emission from AXPs, being that the value of r_{in} is larger than the corotation radius (~8 \times 10^{10} cm), which is the characteristic value of r_{in} in order to have accretion on the neutron star surface and, at the same time, spin-down. Therefore, we fixed r_{in} to the corotation radius for two different values of extinction. The results of the fit are shown in Figure 3 (dashed-dotted and solid lines, respectively). Values of r_{out} = 10^{12} and 8 \times 10^{11} cm were obtained for A_{V} = 7.8 and 11.2, respectively (fallback compact disks; Menou, Perna, & Hernquist 2001). In both cases, the J measurement is lower than the model expectations (2 \sigma). The above solution might also be applied to the case of an accretion disk formed by mass transfer from a (light) companion, although in this case an (unknown) amount of IR flux should also originate from the star surface. We note that IR flattening has also recently been discovered for 4U 0142+614, likely during an X-ray bursting activity phase of 1E 1048.1–5937 (Wang & Chakrabarty 2002; G. L. Israel et al. 2003, in preparation). The IR flattening or excess might represent a new important property shared by AXPs. The IR emission of AXPs in the magnetar scenario remains to be addressed through detailed modeling. However, we note that the presence of a disk would not be necessarily in contrast with the magnetar scenario. Three AXPs are associated with supernova remnants and are likely embedded in dense regions. Therefore, a “hybrid” scenario in which a magnetar irradiates a fossil disk (the matter of which is not accreting in this case) might not be unreasonable, although it should be confirmed through additional future observations and its consistency checked through theoretical studies. In conclusion, we note that none of the proposed theoretical models (at least in their present form) seem to be able to easily account simultaneously for the IR, optical, and X-ray emission of AXPs.

This work is supported through CNAAS, ASI, CNR, and MURST-COFIN grants. The authors thank Olivier Hainaut, Leonardo Vanzi (NTT Team), Olivier Lai (CFHT Team), and Hank Donnelly (Chandra Team).

REFERENCES

Alpar, M. A. 2001, ApJ, 554, 1245
Bono, G., Caputo, F., Cassisi, S., Castellani, V., Marconi, M. 1997, ApJ, 479, 279
Bono, G., Caputo, F., Cassisi, S., Marconi, M., Piersanti, L., & Tornambé, A. 2000, ApJ, 543, 955
Camilo, F., Kaspi, V. M., Lyne, A. G., Manchester, R. N., Bell, J. F., D’Amico, N., McKay, N. P. F., & Crawford, F. 2000, ApJ, 541, 367
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Chatterjee, P., Hernquist, L., & Narayan, R. 2000, ApJ, 534, 373
Devillard, N. 1997, Messenger, 87, 19
Duncan, R. C., & Thompson, C. 1992, ApJ, 392, L9
Fitzpatrick, E. L. 1999, PASP, 111, 63
Gavriil, F. P., & Kaspi, V. M. 2002, ApJ, 567, 1076
Gavriil, F. P., Kaspi, V. M., & Woods, P. M. 2002, Nature, 419, 142
Hulleman, F., Tennant, A. F., van Kerkwijk, M. H., Kulkarni, S. R., Kouvouliotou, C., & Patel, S. K. 2001, ApJ, 563, L49
Hulleman, F., van Kerkwijk, M. H., & Kulkarni, S. R. 2000, Nature, 408, 689
Israel, G. L., Covino, S., Stella, L., Campaña, S., Habel, F., & Mereghetti, S. 1999, ApJ, 518, L107
Israel, G. L., et al. 2002a, ApJ, 580, L143
Israel, G. L., Mereghetti, S., & Stella, L. 2002b, Mem. Soc. Astron. Italiana, 73, 465
Israel, G. L., Oosterbroek, T., Stella, L., Campaña, S., Mereghetti, S., & Parmar, A. N. 2001, ApJ, 560, L65
Kaspi, V. M., & Gavriil, F. P. 2002, IAU Circ. 7924
Kaspi, V. M., Gavriil, F. P., & Woods, P. M. 2002, IAU Circ. 7926
Lawrence, A., et al. 1983, ApJ, 271, 793
Menou, K., Perna, R., & Hernquist, L. 2001, ApJ, 559, 1032
Mereghetti, S., Chiarfone, L., Israel, G. L., & Stella, L. 2002, in Proc. 270th WE-Heraeus Seminar on Neutron Stars, Pulars, and Supernova Remnants, ed. W. Becker, H. Lesch, & J. Trümper (MPE Rep. 278; Garching: MPE), 29
Middleditch, J., & Nelson, J. 1976, ApJ, 208, 567
Perna, R., & Hernquist, L. 2000, ApJ, 544, L57
Perna, R., Hernquist, L., & Narayan, R. 2000, ApJ, 541, 344
Perna, R., Heyl, J. S., Hernquist, L. E., Juett, A. M., & Chakrabarty, D. 2001, ApJ, 557, 18
Predehl, P., & Schmitt, J. H. M. M. 1995, A&A, 293, 889
Rea, N., Israel, G. L., Stella, L., Oosterbroek, T., Mereghetti, S., Angelini, L., Campana, S., & Covino, S. 2003, ApJ, 586, L65
Sabby, C. N., McMahon, R. G., Lewis, J. R., & Irwin, M. J. 2001, in ASP Conf. Ser. 238, Astronomical Data Analysis Software and Systems X, ed. F. R. Harnden, Jr., F. A. Primini, & H. E. Payne (San Francisco: ASP), 317
Stetson, P. B. 1987, PASP, 99, 191
Sugizaki, M., Nagase, F., Torii, K., Kinugasa, K., Asanuma, T., Matsuoka, K., Koyama, K., & Yamauchi, S. 1997, PASJ, 49, L25
Thompson, C., & Duncan, R. C. 1993, ApJ, 408, 194
———. 1996, ApJ, 473, 322
Voges, W., et al. 1996, IAU Circ. 6420
Wang, Z.-X., & Chakrabarty, D. 2002, ApJ, 579, L33
Zombeck, M. V., Chappell, J. H., Kenter, A. T., Moore, R. W., Murray, S. S., Fraser, G. W., & Serio, S. 1995, Proc. SPIE, 2518, 96