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THE PULSE-PHASE–DEPENDENT SPECTRUM OF THE ANOMALOUS X-RAY PULSAR 1RXS J170849−400910

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ABSTRACT

We report on the results of a 50 ks *BeppoSAX* observation of 1RXS J170849−400910, one of the five (plus a candidate) known anomalous X-ray pulsars (AXPs). The *BeppoSAX* data are consistent with a power-law + blackbody spectral decomposition, making 1RXS J170849−400910 the fourth source of this class for which such a spectral decomposition was found. The inferred power-law slope and blackbody temperature are $\Gamma \sim 2.6$ and $kT_{BB} \sim 0.46$ keV, respectively. We find that the pulse profile is significantly energy-dependent, a remarkable feature for an AXP. By using the power-law + blackbody decomposition, we detect a significant variation in at least one spectral parameter, the power-law photon index, as a function of the pulse phase. This is the first significant detection of a spectral parameter variation in an AXP. The implications of these results are briefly discussed.

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

1. INTRODUCTION

More than 20 years after the discovery of pulsations from 1E 2259+586, the nature of anomalous X-ray pulsars (AXPs) is still an open issue. Although we can be reasonably confident that AXPs are magnetic rotating neutron stars, their energy production mechanism is still uncertain. It is also unclear whether they are solitary objects or whether they are in binary systems with very low mass companions (for a review, see Israel, Mereghetti, & Stella 2001 and references therein). Different production mechanisms for the observed X-ray emission have been proposed, involving either the accretion or the dissipation of magnetic energy. Among the properties that distinguish AXPs from known magnetic ($\geq 10^{12}$ G) accreting X-ray pulsars found in high- and low-mass X-ray binaries are (1) spin periods in a narrow range (∼6–12 s), (2) very soft and absorbed X-ray spectra, (3) relatively stable spin-period evolutions, with long-term spin-down trends, and (4) flat distributions in the Galactic plane and three clear associations with supernova remnants. There are currently five ascertained members of the AXP class plus one likely candidate.

The relatively bright source 1RXS J170849−400910 was discovered early in the *ROSAT* mission (Voges et al. 1996); in 1997, however, this source attracted much attention because of the *ASCA* discovery of ∼11 s pulsations (Sugizaki et al. 1997). Based on the pulse period and the unusually soft X-ray spectrum, the source was tentatively classified as an AXP candidate. This interpretation was confirmed through *ROSAT* High Resolution Imager (HRI) observations that provided the first measurement of the period derivative $\dot{P} \sim 2 \times 10^{-11}$ s s^{-1} (Israel et al. 1999a). The source 1RXS J170849−400910 is one of the two AXPs for which a phase-coherent timing solution was obtained by a systematic monitoring program with the *Rossi X-Ray Timing Explorer* (*RXTE*) Proportional Counter Array (Kaspi, Chakrabarty, & Steinberger 1999). The source was found to be a quite stable rotator with phase residuals of only ∼1%, i.e., comparable to or smaller than those measured for most radio pulsars. However, in 1999 September, the *RXTE* satellite detected a sudden spin-up event from 1RXS J170849−400910 that was interpreted as a "glitch" similar to those observed in the Vela pulsar and other young radio pulsars (Kaspi, Lackey, & Chakrabarty 2000).

A search for optical counterparts in the field of 1RXS J170849−400910 was carried out by Israel et al. (1999a). These authors, based on two refined *ROSAT* HRI positions, were able to rule out a massive early-type companion (a distant and/or absorbed OB star would appear more reddened). However, the images were taken from a 1.5 m telescope and were not deep enough to constrain any other proposed theoretical scenario such as a low-mass companion, a residual disk, or a magnetar.

An association between 1RXS J170849−400910 and the supernova remnant G346.6−0.2 located ∼12′ away was proposed by Marsden et al. (2001). However, as discussed by Gaensler et al. (2001), such an association appears to be unlikely. An image at 1.4 GHz showed the presence of an arc of diffuse emission ∼8′ away from 1RXS J170849−400910 (Gaensler et al. 2001), which was interpreted as a previously unknown supernova remnant (G346.5−0.1). Also, in this case, there are no convincing arguments for a physical association between G346.5−0.1 and 1RXS J170849−400910. No radio emission was detected from 1RXS J170849−400910, with upper limits of 3 mJy on the continuum (5 σ at 1.4 GHz; Gaensler et al. 2001).

In this Letter, we report the results obtained from a *BeppoSAX* observation of 1RXS J170849−400910 that took place before the glitchlike event detected by *RXTE* (part of the results presented in this Letter was reported in Israel et al. 2001). A two-component spectrum, i.e., a power-law plus a blackbody, was found. Moreover, the *BeppoSAX* observation revealed a significant energy-dependent pulse profile. Pulse-phase spectroscopy (PPS) shows that, in the context of the blackbody + power-law spectral decomposition, this effect is likely connected to a photon-index variation. This observation therefore provided the first evidence for pulse-phase–related

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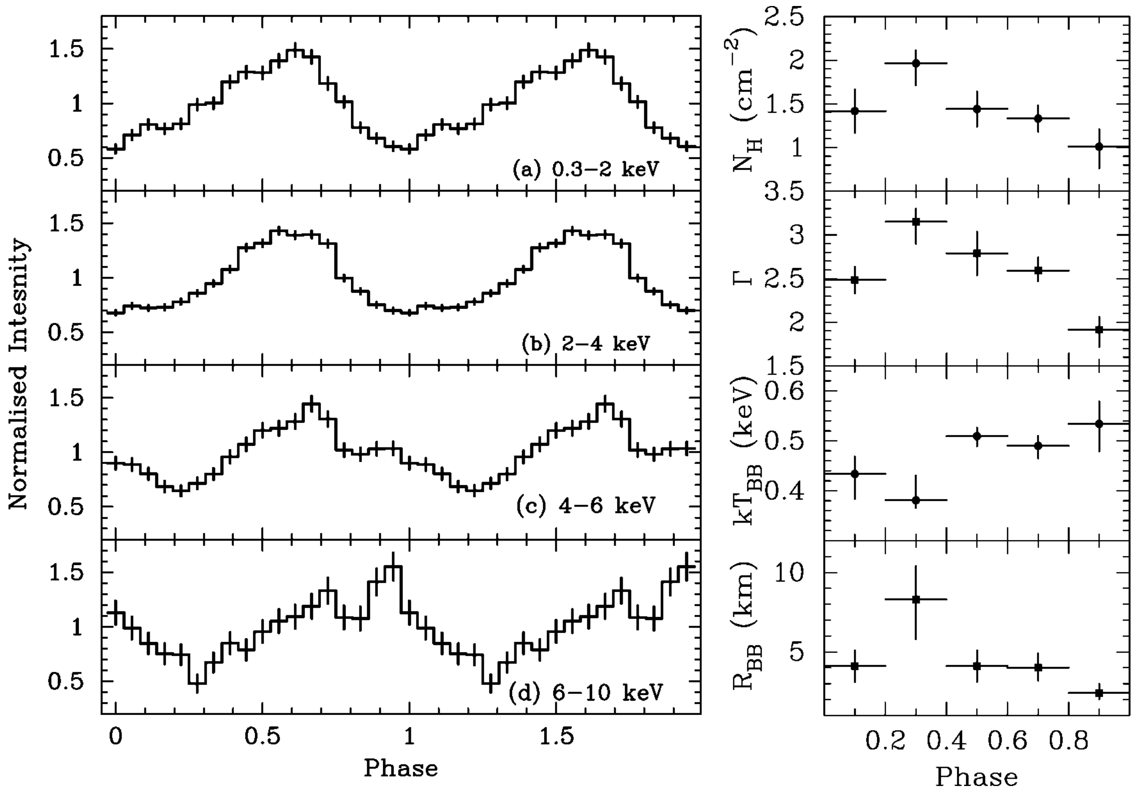

FIG. 1.—(*a–d*) 1RXS J170849−400910 MECS and LECS light curves folded to the best period ($P = 10.99915$ s) for four different energy intervals. For clarity, two pulse cycles are shown. Zero phase was (arbitrarily) chosen to correspond to the minimum in the 0.3–2 keV folded light curve. The results of the PPS are shown for selected free parameters (*right panels*; the absorption column in units of 10^{22}). Phase intervals refer to those shown in the left panel.

spectral variations in an AXP. The implications of these results are also briefly discussed.

2. OBSERVATIONS

BeppoSAX observed 1RXS J170849−400910 between 1999 March 31 (14:27 UT) and April 1 (22:50 UT) with imaging Narrow Field Instruments: the Low-Energy Concentrator Spectrometer (LECS; 0.1–10 keV; Parmar et al. 1997; 26 ks effective exposure time) and the Medium-Energy Concentrator Spectrometer (MECS; 1.3–10 keV; Boella et al. 1997; 52 ks effective exposure time).

3. RESULTS

3.1. *Timing Analysis*

The arrival times of the 0.1–10 keV photons from 1RXS J170849−400910 were corrected to the barycenter of the solar system, and a 1 s binned light curve was accumulated. The MECS counts were used to accurately determine the pulse period. The data were divided into 12 time intervals, and for each interval, the relative phase of the pulsations was determined. These phases were then fitted with a linear function giving a best-fit period of 10.99915 ± 0.00002 s. The background-subtracted light curves, folded at the best period in different energy ranges (Fig. 1, *left panels*) show an energy-dependent profile. In particular, the phase interval of the minimum in the energy interval 0.3–2 keV folded light curve corresponds to a maximum in the 6–10 keV folded light curve. Moreover, the pulsed fraction (the semiamplitude of the modulation divided by the mean source count rate) decreases from ∼40% to ∼30% from the lowest to the highest energy band.

3.2. *Spectral Analysis*

Pulse-height analyzer (PHA) spectra were obtained from the *BeppoSAX* position (R.A. = $17^h08^m48^s$, decl. = $-40°08'58''$; equinox 2000; 90% confidence level radius of 22″) of 1RXS J170849−400910 using an extraction radius of 4′ and 8′ for the MECS and LECS, respectively. Background subtraction was performed using both standard blank-field exposures and background regions taken from the observation of 1RXS J170849−400910 far from the position of the AXP, ending up with similar results. The PHA spectra were rebinned in order to have more than 40 counts in each bin such that minimum χ^2 fitting techniques could be reliably used. All those bins that were consistent with containing zero counts after background subtraction were rejected. Moreover, the analysis of the MECS and LECS spectra was restricted to the 1.8–10 and 0.1–5 keV ranges, respectively, where the calibration of response files is more accurate. A constant factor free to vary within a predetermined range was applied in the fitting to account for known normalization differences between LECS and MECS.

A simple power-law model did not fit the data well (with a reduced χ^2 of 1.24 for 204 degrees of freedom [dof]). All the other single-component models that we tried produced even worse results. A much better fit (see Fig. 2) was obtained by including, in addition to the power law, a soft thermal component and a blackbody (with a reduced χ^2 of 1.00 for 202 dof). This model was successfully fitted to the spectra of three other AXPs. An *F*-test shows that the inclusion of the

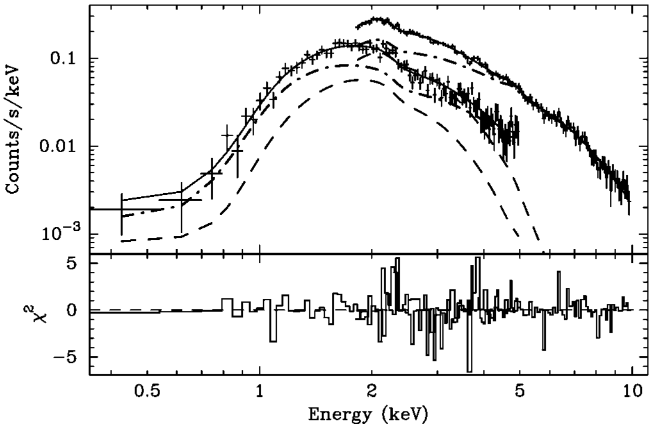

FIG. 2.—LECS and MECS energy spectra of 1RXS J170849−400910. The residuals (in units of χ^2) of the best fit are also shown (see the text for details). The power-law and blackbody components are shown with dot-dashed and dashed lines, respectively.

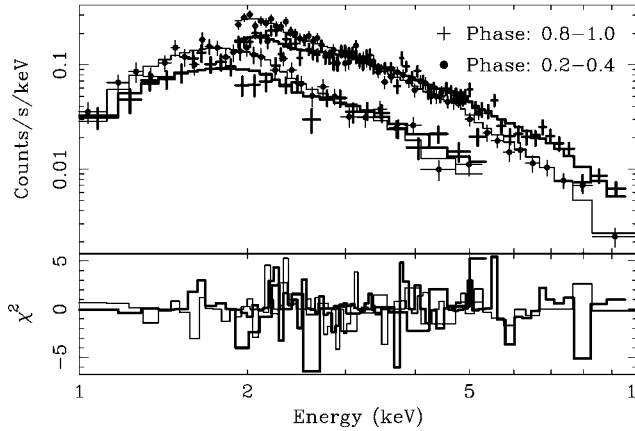

FIG. 3.—LECS and MECS spectra of 1RXS J170849−400910 for two selected phase intervals, 0.2–0.4 and 0.8–1.0 keV, as reported in Fig. 2. The power-law photon-index variation is clearly evident.

blackbody component is highly significant (with a probability of ~6 σ). The best fit was obtained for an absorbed [N_H = (1.42 ± 0.15) × 10^{22} atoms cm^{-2}] power law with a photon index of $\Gamma = 2.6 \pm 0.2$ and a blackbody component with a temperature of $kT_{BB} = 0.46 \pm 0.03$ keV (with a 90% confidence level reported; see Table 1). The unabsorbed 0.5–10 keV flux was 1.3×10^{-10} ergs s^{-1} cm^{-2}. The blackbody component accounts for about 36% of the total absorbed flux in the same band. Figure 2 shows the spectral shape and components of 1RXS J170849−400910 as determined by *BeppoSAX*.

We also tried to fit the spectra using different spectral decompositions. Among these, we find a relatively good fit (with a reduced χ^2 of 1.10 for 202 dof) with a two-blackbody model (see Table 1). It is also worth mentioning that in this case, we obtained a soft component (i.e., a blackbody) with a characteristic temperature similar to that inferred with the power-law + blackbody model.

The data from the High Pressure Gas Scintillation Proportional Counter and the Phoswich Detector System did not provide any useful information on 1RXS J170849−400910. In fact, due to the large fields of view of these instruments, the relatively short exposure time (~25 ks), and the steep spectrum of 1RXS J170849−400910, the source was not detected.

3.3. *Phase-resolved Spectroscopy and Pulse Profiles*

PPS was carried out with the MECS and LECS data. A set of five phase-resolved spectra (with phase boundaries 0.0, 0.2, 0.4, 0.6, and 0.8) were accumulated. After rebinning and background subtraction, these were then fitted with the power-law + blackbody model described in § 3.1. Due to the small number of photons in the LECS spectra, we removed all the PHA channels below 1 keV. Initially, the blackbody temperature was fixed at its phase-averaged best-fit value, and only the power-law parameters and blackbody normalization were allowed to vary, giving a cumulative (over the whole set of spectra) reduced χ^2 of 1.10 for 466 dof. The fits were then repeated with the power-law component fixed and the blackbody parameters free to vary, resulting in a reduced χ^2 of 1.32 for 466 dof for the best fit. Then all the parameters were varied and fitted together. In the latter case, the best fit gave a reduced χ^2 of 1.04 for 456 dof. An *F*-test shows that the freeing of the blackbody and power-law phase-averaged parameters is highly significant (the reduction in χ^2 has a formal probability of 9×10^{-4} and 1×10^{-19} for the blackbody and power-law parameters, respectively). In the right panels of Figure 1 and in Figure 3, the results of the PPS are shown for the most interesting parameters and phase intervals.

TABLE 1
BEPPOSAX PHASE-AVERAGED FIT OF 1RXS J170849−400910

Spectral Parameter	PL	PL + BB	BB + BB
N_H ($\times 10^{22}$ atoms cm^{-2})	1.88 ± 0.08	1.42 ± 0.15	0.9 ± 0.1
Γ	3.28 ± 0.05	2.62 ± 0.17	…
PL flux ($\times 10^{-11}$ ergs s^{-1} cm^{-2})	4.26	3.30	…
kT_{BB} (keV)	…	0.46 ± 0.03	0.50 ± 0.02
	…	…	1.54 ± 0.06
BB radius (km)	…	4.0 ± 0.4	4.4 ± 0.2
	…	…	0.30 ± 0.02
BB flux ($\times 10^{-11}$ ergs s^{-1} cm^{-2})	…	1.2	2.8 ± 1.3
	…	…	1.7
χ^2/dof	1.24	1.00	1.10
L_X ($\times 10^{35}$ ergs s^{-1})	8.5	3.6	2.0

NOTE.—Fluxes and luminosities refer to the 0.5–10 keV band. Fluxes are not corrected for the interstellar absorption. Flux uncertainties are about 10%. The source luminosities were derived by setting $N_H = 0$ and assuming a distance of 5 kpc. PL = power law; BB = blackbody.

A check was performed by fitting the power-law photon-index values obtained in each phase intervals with a constant (see right panels of Fig. 1). This set an ∼3 σ significant variation in the power-law photon-index parameter. Statistical uncertainties prevent a firm detection of variations in the other parameters (see right panels of Fig. 1).

The upper two panels of Figure 4 show the pulsed fraction versus energy during the *BeppoSAX* observation for the first two harmonics. These values were obtained by fitting the corresponding light curves with two sinusoidal functions. Note that definitions of the pulsed fraction that involve the maximum and the minimum of the folded light curve should be used with care since they are dependent on the binning time and, therefore, the presence of unusually low or high data points. The sinusoidal fit, when feasible, is less sensitive to these data points. The first harmonic decreases from ∼36% to ∼26% as the energy increases from 0.5–2 to 6–10 keV. A constant value of ∼10% is inferred for the second harmonic. The last two panels refer to the ratio between the power law and the total absorbed fluxes (i.e., the blackbody + power-law spectral model; *third panel*) and the ratio between the blackbody and the power-law unabsorbed fluxes (*lowest panel*). From the comparison of these quantities, we can infer that (1) there is evidence for a decrease of the first harmonic pulsed fraction at energies above 5 keV, although the statistics are poor, (2) there is evidence for an anticorrelation between the power-law component and the first harmonic pulsed fraction (see first and third panels), and (3) there is evidence for a direct correlation between the latter and the blackbody component (see first and fourth panels).

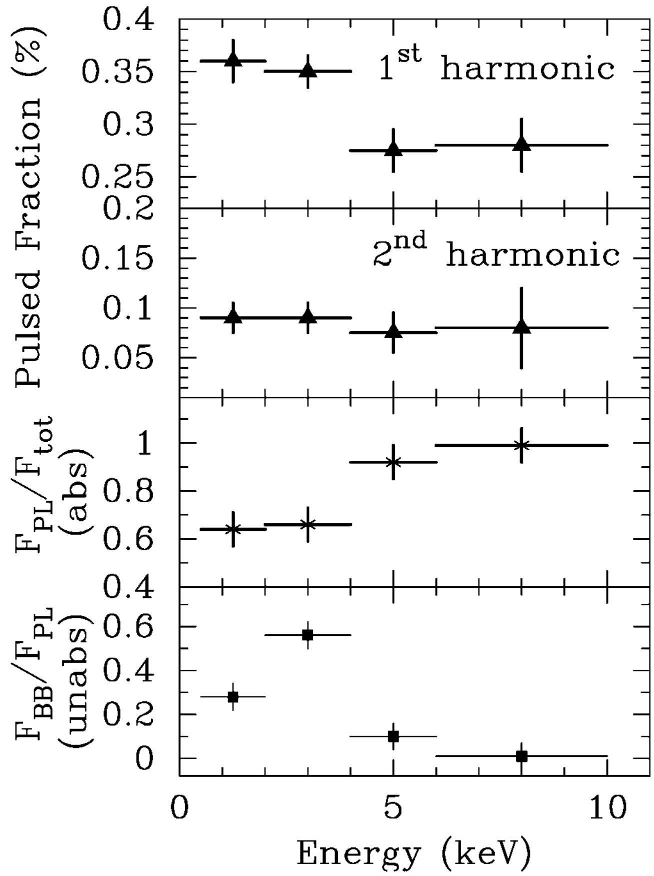

FIG. 4.—Pulsed fraction of the first two harmonics of 1RXS J170849−400910 as a function of the energy (*upper two panels*), together with the power-law–to–total absorbed flux ratio and the blackbody–to–power-law unabsorbed flux ratio (*lower two panels*). See text for details.

4. DISCUSSION

The 0.1–10 keV *BeppoSAX* spectrum of 1RXS J170849−400910 is well modeled by the sum of a (absorbed) relatively steep power law and a low-energy blackbody. Therefore, 1RXS J170849−400910 is the fourth AXP, after 4U 0142+614 (White et al. 1996; Israel et al. 1999b), 1E 2259+586 (Corbet et al. 1995; Parmar et al. 1998), and 1E 1048.1−5937 (Oosterbroek et al. 1998), for which such a spectral decomposition has been detected. We note that these sources are also the ones for which good spectral data are available. This possible decomposition for 1RXS J170849−400910 was first suggested by Sugizaki et al. (1997), although it was not statistically significant using the *ASCA* data. The comparison between the *BeppoSAX* and *ASCA* observations reveal that the source has remained nearly at the same (absorbed) flux level (∼4.4 × 10^{-11} and ∼4.3 × 10^{-11} ergs cm^{-2} s^{-1} in the 0.8–10 keV band for *BeppoSAX* and *ASCA*, respectively). Also, the spectral parameters (in the blackbody + power-law model) are similar to those found by *ASCA* with the exception of the temperature of the blackbody, which is higher in *BeppoSAX*: this is not unusual since *BeppoSAX* instruments have a higher sensitivity below 1 keV, allowing a better evaluation of the absorption column and, therefore, of the blackbody-component parameters.

We also tried to fit the spectrum of 1RXS J170849−400910 with other models. Among these, we used two blackbodies. Such a decomposition is in agreement with accreting, magnetic field decay and cooling models that have been invoked to account for the main physical mechanism(s) responsible for the X-ray emission of AXPs (see also Thompson & Duncan 1993 and Heyl & Hernquist 1997). Two (or more) concentric regions with different temperatures are in fact expected: the innermost corresponding to the polar caps of the neutron star (which is also the hottest) and a larger area around the magnetic caps characterized by a lower temperature (see also DeDeo, Psaltis, & Narayan 2001, Özel, Psaltis, & Kaspi 2001, and Perna et al. 2001). Regardless the origin of the emission from these regions, we note that the size of the blackbodies is always smaller than the neutron star surface, even for an unrealistic distance to the AXP of ∼15 kpc, with the smallest region (R_{BB} ∼ 0.3 km) also being the hottest (kT ∼ 1.5 keV). The results of a more detailed and systematic spectral and timing study of the AXPs observed by *BeppoSAX* will be reported elsewhere.

An analysis of the pulse shape of 1RXS J170849−400910 as a function of energy (in the 0.3–10 keV band) reveals a prominent variation, with the minimum at low energies corresponding to the maximum at high energies (see also Fig. 1). Correspondingly, the PPS detected a significant variation for at least one spectral component, the power-law photon index, as a function of phase. The peak in the pulse profile at the highest energy also corresponds to the lowest value of the photon index, similar to what was observed in accreting X-ray pulsars (Makishima et al. 1999 and references therein). Although energy-dependent changes in the pulse shape were already observed for 4U 0142+614 (White et al. 1996; Israel et al. 1999b; Paul et al. 2000), the variations of 1RXS J170849−400910 are also accompanied by a nearly total phase reversal between the low-energy band and the high-energy band and are likely due to a changing power-law slope (as suggested by Sugizaki et al. 1997 and Gavriil & Kaspi 2001, who also find similar pulse-shape variations in *RXTE* data). We note that in the past, the lack of any conspicuous change in the pulse profiles as a function of energy and/or pulse-phase–resolved spectra of AXPs was used to argue against the possibility that these sources are accreting X-ray objects. We finally note that the pulse fraction as a function of energy shown in Figure 4 is not in disagreement with that recently reported by Özel et al. (2001), who used a different definition of the fractional contribution (and assumed only one harmonic) to the pulsations.

So far, 1RXS J170849−400910 is the only AXP for which a sudden spin-up was observed (Kaspi et al. 2000). This was interpreted as a glitch similar to that observed in Vela and other young radio pulsars. However, we note that glitches could in principle be detected also in accreting (spinning-down) X-ray sources with a sufficiently high magnetic field strength (in analogy with the known characteristics of radio pulsars) if they are in a low noise level phase, as indeed AXPs are known to be. A way to distinguish, in the near future, whether 1RXS J170849−400910 experienced a radio pulsar-like glitch or, perhaps, an accreting X-ray pulsar-like spin-up behavior would be to accurately monitor the period history after the event. We note that the lack of the recovery of the $\dot{P}$-value to the pre-event one (in contrast to the known behavior of glitches observed in radio pulsars) would argue against "magnetar" models, at least in the current formulation, while its detection might not be conclusive for any model (magnetar or accretion).

The source 1RXS J170849−400910 is also the first AXP for which spectral changes as a function of pulse phase have been significantly detected. These spectral/timing properties make 1RXS J170849−400910 an especially interesting AXP to study. More sensitive and/or higher throughput observations of 1RXS J170849−400910 might yield important additional information on the spectral changes causing the pulse-shape variations and extend the energy range over which the source is detected above 10 keV.

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REFERENCES

Boella, G., et al. 1997, A&AS, 122, 327
Corbet, R. H. D., Smale, A. P., Ozaki, M., Koyama, K., & Iwasawa, K. 1995, ApJ, 443, 786
DeDeo, S., Psaltis, D., & Narayan, R. 2001, ApJ, 559, 346
Gaensler, B. M., Slane, P. O., Gotthelf, E. V., & Vasisht, G. 2001, ApJ, 559, 963
Gavriil, F. P., & Kaspi, V. M. 2001, ApJ, submitted (astro-ph/0107422)
Heyl, J., & Hernquist, L. E. 1997, ApJ, 489, L67
Israel, G. L., Covino, S., Stella, L., Campana, S., Haberl, F., & Mereghetti, S. 1999a, ApJ, 518, L107
Israel, G. L., Mereghetti, S., & Stella, L. 2001, Mem. Soc. Astron. Italiana, in press
Israel, G. L., et al. 1999b, A&A, 346, 929
Kaspi, V. M., Chakrabarty, D., & Steinberger, J. 1999, ApJ, 525, L33
Kaspi, V. M., Lackey, J. R., & Chakrabarty, D. 2000, ApJ, 537, L31
Makishima, K., Mihara, T., Nagase, F., & Tanaka, Y. 1999, ApJ, 525, 978
Marsden, D., Lingenfelter, R. E., Rothschild, R. E., & Higdon, J. C. 2001, ApJ, 550, 397
Oosterbroek, T., Parmar, A. N., Mereghetti, S., & Israel, G. L. 1998, A&A, 334, 925
Özel, F., Psaltis, D., & Kaspi, V. M. 2001, ApJ, in press (astro-ph/0105372)
Parmar, A. N., et al. 1997, A&AS, 122, 309
Parmar, A. N., Oosterbroek, T., Favata, F., Pightling, S., Coe, M. J., Mereghetti, S., & Israel, G. L. 1998, A&A, 330, 175
Paul, B., Kawasaki, M., Dotani, T., & Nagase, F. 2000, ApJ, 537, 319
Perna, R., Heyl, J. S., Hernquist, L. E., Juett, A. M., & Chakrabarty, D. 2001, ApJ, 557, 18
Sugizaki, M., Nagase, F., Torii, K., Kinugasa, K., Asanuma, T., Matsuzaki, K., Koyama, K., & Yamauchi, S. 1997, PASJ, 49, L25
Thompson, C., & Duncan, R. C. 1993, ApJ, 408, 194
Voges, W., et al. 1996, IAU Circ. 6420
White, N. E., Angelini, L., Ebisawa, K., Tanaka, Y., & Ghosh, P. 1996, ApJ, 463, L83