**XMM-Newton observation of the persistent Be/NS X-ray binary pulsar RX J0440.9+4431**

N. La Palombara, L. Sidoli, P. Esposito, A. Tiengo, and S. Mereghetti

1 INAF, Istituto di Astrofisica Spaziale e Fisica Cosmica – Milano, via Bassini 15, 20133 Milano, Italy
e-mail: nicola@iasf-milano.inaf.it
2 INAF, Osservatorio Astronomico di Cagliari, località Poggio dei Pini, strada 54, 09012 Capoterra, Italy
3 IUSS-Istituto Universitario di Studi Superiori, viale Lungo Ticino Sforza 56, 27100 Pavia, Italy

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**ABSTRACT**

Many X-ray accreting pulsars have a soft excess below 10 keV. This feature was also detected in faint sources and at low luminosity levels, suggesting that it is an ubiquitous phenomenon. For the high luminosity pulsars \(L_X > 10^{36} \text{ erg s}^{-1}\), the fit to this component with thermal emission models usually provides low temperatures \(kT < \text{0.5 keV}\) and large emission regions \(R \geq \text{a few hundred km}\), hence it is referred to as a “soft” excess. Nevertheless, we previously found that in persistent, low-luminosity \(L_X \sim 10^{34} \text{ erg s}^{-1}\) and long-period \(P > 100 \text{ s}\) Be accreting pulsars the observed excess can be modeled with a rather hot \(kT_{\text{BB}} > \text{1 keV}\) black-body component of small area \(R_{\text{BB}} < \text{0.5 km}\), which can be interpreted as emission from the NS polar caps. In this paper, we present an analysis of an **XMM-Newton** observation of the Galactic Be pulsar RX J0440.9+4431, which is a poorly studied member of this class of sources. We find a best-fit period of \(P = 204.96 \pm 0.02 \text{ s}\), which implies an average pulsar spin-down over the past 13 years of \(P > 6 \times 10^{-9} \text{ s}^{-1}\). The estimated source luminosity is \(L_X \sim 8 \times 10^{35} \text{ erg s}^{-1}\), which is higher by a factor of less than ten compared to those obtained in the first source observations, but almost two orders of magnitude lower than those measured during the few outbursts that have been detected most recently. The source spectrum can be described with a power-law and black-body model, with \(kT_{\text{BB}} = 1.34 \pm 0.04 \text{ keV}\) and \(R_{\text{BB}} = 273 \pm 16 \text{ m}\), suggesting a polar-cap origin of this component. Our results support the classification of RX J0440.9+4431 as a persistent Be/NS pulsar, and confirm that the hot black-body spectral component is a common property of this class of sources.

**Key words.** X-rays: binaries -- accretion, accretion disks -- stars: emission line, Be -- pulsars: individual: LS V +44 17 -- X-rays: individuals: RX J0440.9+4431

1. Introduction

Most of the X-ray binary pulsars (XBPs) are high mass X-ray binaries (HMXRBs) in which a neutron star (NS) with magnetic field \(B \sim 10^{12} \text{ G}\) is accreting matter from a high-mass early-type star that is either an OB supergiant or a Be star. They can be persistently bright, with luminosities in excess of \(10^{34} \text{ erg s}^{-1}\), or transient sources characterized by quiescent phases, with emission around \(10^{34} \text{ erg s}^{-1}\) or less, interrupted by bright outbursts reaching \(L_X \sim 10^{36-38} \text{ erg s}^{-1}\) (Negueruela 1998; Reig 2007; Sidoli 2010).

In these sources, the X-ray spectra between 0.1 and 10 keV are usually described by a rather flat power-law, with a photon index of about one, but several XBPs have shown a marked “soft” X-ray excess above the main power-law component (see La Palombara & Mereghetti 2006, for a review). This excess is well-described by a thermal emission model (either blackbody, bremsstrahlung, or mekal) with low temperature \(kT_{\text{SE}} < 0.5 \text{ keV}\) and large emission area \(R_{\text{SE}} \geq \text{a few hundred km}\). This feature has been detected not only in the high-luminosity sources (with \(L_X \sim 10^{37-38} \text{ erg s}^{-1}\)) but also in several low-luminosity \(L_X \sim 10^{35-36} \text{ erg s}^{-1}\) XBPs observed in the Small Magellanic Cloud (SMC). In the case of 4U 0352+309 (Persei; La Palombara & Mereghetti 2006), 4U 0352+309/X Persei (La Palombara & Mereghetti 2007), and RX J1037.5-5647/LS 1698 (La Palombara et al. 2009). These three sources have a persistently low luminosity \(L_X \sim 10^{34-35} \text{ erg s}^{-1}\) and a long pulse period \(P > 100 \text{ s}\).

These properties suggest that the NS orbits the Be star in a wide and nearly circular orbit, continuously accreting material from the low-density outer regions of the circumstellar envelope; in the case of 4U 0352+309, this picture is supported by the long orbital period of 250.3 days (Delgado-Martí et al. 2001). For these sources, the detection of the thermal component was made easier by the small distance \((d \leq 5 \text{ kpc})\) and interstellar absorption \(N_{\text{H}} \sim 10^{21} \text{ cm}^{-2}\). We found that their soft excess can only be fitted with a black-body (other simple models being rejected) that contributes \(30\text{--}40\%\) of the total flux. Interestingly, in comparison with the other, more luminous sources, their black-body component is characterized by a higher temperature \(kT_{\text{BB}} > 1 \text{ keV}\) and a much smaller emission radius \(R_{\text{BB}} < 0.5 \text{ km}\). This hot BB spectral component sets these low-luminosity and long-period sources apart from all the other
pulsars, strongly suggesting that they form a distinct class. In their case, the thermal component could be produced by a different emission mechanism than in the high-luminosity pulsars. On the basis of the study of Hickox et al. (2004), it can be attributed to emission from the neutron-star polar caps. This idea is supported by the emission area of the black-body component, which is consistent with the estimated polar cap size, and the low energy part of the spectrum being clearly pulsed.

In this paper, we present the results of an XMM-Newton observation of RX J0440.9+4431, an example of this class of Be/NS pulsars. This system was discovered by the ROSAT Galactic plane survey (Motch et al. 1997) and identified with LS V+44 17, a moderately reddened (E(B−V) = 0.65 ± 0.05) B0.2 Ve star at ~3.3 kpc (Reig 2011). Thanks to observations with the PCA instrument on board RossiXTE, Reig & Roche (1999) performed the first detailed timing and spectral analysis, and discovered a pulsation with period P = 202.5 ± 0.5 s. Its spectrum was accurately fitted with different models (power-law, power-law plus black-body, two black-bodies, and cut-off power-law) and the measured flux implied that it has a luminosity of 3 × 10^35 erg s^{-1} between 3 and 30 keV. RX J0440.9+4431 was also detected in the hard X-ray range, and was reported (as source PBC J0440.9+4432) in the Palermo Swift-BAT hard X-ray catalogue (Cusumano et al. 2010), with a 15–150 keV flux of (2.0 ± 1.1) × 10^{-11} erg cm^{-2} s^{-1}, and in the catalogue obtained with the INTEGRAL/IBIS 7-year All-Sky Hard X-ray Survey (Krivonos et al. 2010a), with a 17–60 keV flux of (1.36 ± 0.22) × 10^{-11} erg cm^{-2} s^{-1}.

In the optical/IR waveband, the Hα line has a double-peak profile, varying from a symmetric shape to a completely distorted one on one side (V/R phases), with a correlation between the equivalent width of the Hα line and the infrared magnitudes such that as the EW(Hα) increases, the IR magnitudes become fainter. This long-term optical/IR variability is attributed to structural changes in the Be star's circumstellar disc, which alter the class of persistent, low-luminosity and long-period Be pulsars, strongly suggesting that they form a distinct class. In their case, the thermal component could be produced by a different emission mechanism than in the high-luminosity pulsars. On the basis of the study of Hickox et al. (2004), it can be attributed to emission from the neutron-star polar caps. This idea is supported by the emission area of the black-body component, which is consistent with the estimated polar cap size, and the low energy part of the spectrum being clearly pulsed.

2. Observations and data reduction

RX J0440.9+4431 was observed with XMM-Newton on 2011 March 18 (MJD = 55 638.417). The three EPIC cameras, i.e. one pn (Strüder et al. 2001) and two MOS (Turner et al. 2001), were operated in large window mode, with a time resolution of 48 ms for the pn camera and of 0.9 s for the two MOS cameras; the effective source exposure time was, respectively, of ~14 ks and ~17 ks. For all cameras the medium thickness filter was used. RX J0440.9+4431 was also observed for ~17 ks by the Reflection Grating Spectrometer (RGS), which was operated in spectroscopy mode (den Herder et al. 2001).

We used version 11.0 of the XMM-Newton Science Analysis System (SAS) to process the event files. After the standard pipeline processing, we searched for possible intervals of high instrumental background, with a negative result. EPIC source events were selected within a circular area, with an extraction radius of 30" for all the cameras; the corresponding background events were accumulated on large circular areas free of sources and with radii of 120", 50", and 60" for the pn, MOS1, and MOS2 cameras, respectively. We selected all the events in the energy range 0.15–12 keV, with pattern range 0–4 (i.e. mono- and bi-pixel events) for the pn camera and 0–12 (i.e. from 1 to 4 pixel events) for the two MOS. In all cases, the background contribution to the total count rate (CR) was negligible, resulting in a net CR of ~5.8 cts s^{-1} for the pn and ~1.8 cts s^{-1} for each of the two MOS. Although the source CR was very high, we checked with the SAS task epatplot that no event pile-up affected our data.

3. Timing analysis

For the timing analysis, we considered only the EPIC data. To measure the pulse period, we converted the event arrival times to the solar system barycenter and combined the three datasets. We measured the pulse period by a standard phase-fitting technique (Dall’Osso et al. 2003), obtaining a best-fit period of P = 204.96 ± 0.02 s. This result takes into account the effects of the source variability during the observation (Fig. 1); the individual pulses are indeed detected with high significance throughout the entire observation, even when the source is faint.

In Fig. 1 we report the background-subtracted light curves in the energy ranges 0.15–3.5 (soft), 3.5–12 (hard), and 0.15–12 keV (total), together with the hardness-ratio (HR) of the hard (H) to soft (S) light curves (computed as H/S); the two energy ranges were defined in order to obtain a comparable number of counts, while the time bin of 205 s, corresponding to one

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**Fig. 1.** Background-subtracted light curves of RX J0440.9+4431 in the energy ranges 0.15–3.5, 3.5–12, and 0.15–12 keV, with a time bin of 205 s (i.e. one pulse period).
pulse period was chosen to avoid the effects of the periodic pulsations. In both ranges, the average CR is \( \sim 4.5 \) cts s\(^{-1}\), with an increasing trend with time during the observation; moreover, the CR was highly variable over the short timescale, since there are CR variations of up to \( \sim 30\% \) between consecutive time bins. In addition the HR is characterized by a similar variability but, in this case, no long time-scale trend is observed; there is also no clear correlation with the source CR (Fig. 2), although the fit with a constant value HR = 1 is rejected (\( \chi^2/\text{d.o.f.} = 3.62/74 \)).

The XMM-Newton observation allowed us to investigate the pulse profile, for the first time, even at energies below 3 keV. In Fig. 3, we show the folded light curves in four different energy ranges, defined in order to obtain a comparable number of counts in each of them, together with the hardness ratio of the 3.4–10 keV energy ranges. The shape of the pulse profile is similar in the four ranges: in all cases, it shows a single broad peak, but it is impossible to fit it with a simple sinusoidal model; the measured pulsed fraction, defined as (CR\(_{\text{max}}\) – CR\(_{\text{min}}\))/(2 x CR\(_{\text{average}}\)), is \( \sim 55\% \) for all the energy ranges; the increasing part of the curve is more regular than the decreasing one, which is steeper at the beginning and flatter at the end. However, we note an energy dependence of the pulse profile around the CR minimum (phase \( \phi = 0.7 \)): the minimum CR value is reached at slightly later phases for increasing energies, and also the following CR increase is delayed; moreover, at the minimum egress the CR increases more suddenly at high energies than at the low ones. As a consequence, the HR of the hard to soft curves is highly variable in this phase interval: it first shows a sharp minimum just after the CR minimum, suddenly followed by a large peak.

4. Spectral analysis

For the EPIC source and background spectra, we adopted the same extraction parameters used for the light curves; we generated the applicable response matrices and ancillary files using the SAS tasks rmfgen and arfgen. We also considered the RGS data, using the source and background spectra and the response matrices obtained with the standard reduction pipeline. To ensure the applicability of the \( \chi^2 \) statistics, the EPIC and RGS spectra were rebinned with a minimum of 100 and 30 counts per bin, respectively; they were then fitted in the energy range 0.3–12 keV using XSPEC 12.4.0. In the following, all spectral uncertainties and upper limits are given at the 90% confidence level for one interesting parameter, and we assume a source distance of 3.3 kpc.

After checking that separate fits of the three EPIC cameras gave consistent results, we fitted them simultaneously to improve the quality of the statistics; we then checked that both RGS spectra were consistent with the EPIC ones, thus also included them in the spectral analysis; to this aim, we introduced a constant value HR\(_{\text{PL}}\) = 2.097/1083. Using an absorbed black-body (BB) model, we obtained \( N_{\text{H}} = (3.33 \pm 0.09) \times 10^{21} \) cm\(^{-2}\), which is \( \sim 58\% \) for all the energy ranges; the increasing part of the curve is more regular than the decreasing one, which is steeper at the beginning and flatter at the end. However, we note an energy dependence of the pulse profile around the CR minimum (phase \( \phi = 0.7 \)): the minimum CR value is reached at slightly later phases for increasing energies, and also the following CR increase is delayed; moreover, at the minimum egress the CR increases more suddenly at high energies than at the low ones. As a consequence, the HR of the hard to soft curves is highly variable in this phase interval: it first shows a sharp minimum just after the CR minimum, suddenly followed by a large peak.

In both cases, the fits of the spectrum were unacceptable, with large residuals, so we repeated the fit with a PL+BB model. In this way, we obtained a significant improvement (Fig. 4), with \( \chi^2/\text{d.o.f.} = 1.105/1081 \). The corresponding best-fit parameters are \( N_{\text{H}} = (7.3 \pm 0.4) \times 10^{21} \) cm\(^{-2}\), \( \Gamma = 0.85 \pm 0.07 \), and \( kT_{\text{BB}} = 1.34 \pm 0.04 \) keV. The PL normalization is \( f_{\text{nul}} = (1.8 \pm 0.2) \times 10^{-5} \) ph cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\) at 1 keV and the BB radius \( R_{\text{BB}} = 273 \pm 16 \) m. The absorbed flux in the energy range 0.3–12 keV is \( f_{\text{abs,X}} = 6.0 \pm 0.3 \times 10^{-11} \) erg cm\(^{-2}\) s\(^{-1}\), while the corresponding unabsorbed flux is \( f_{\text{unabs,X}} = 6.7 \times 10^{-11} \) erg cm\(^{-2}\) s\(^{-1}\), which implies a source luminosity \( L_x = 8.3 \times 10^{35} \) erg s\(^{-1}\). The BB component contributes to about 35% of the 0.3–12 keV source flux.

Neither the EPIC nor the RGS spectra have clear emission or absorption features. We also searched for narrow iron \( K_{\alpha} \) emission lines between 6 and 7 keV, with different widths between 0 and 0.5 keV. We found no evidence of these lines, with an upper limit on their equivalent widths of \( \sim 70 \) eV (90% c.l.) at most.
5. Phase-resolved spectroscopy

As shown in Fig. 3, the HR is characterized by large variations along the pulse, hence it is interesting to investigate the spin-phase resolved spectrum. To this aim, we first analyzed the background-subtracted spectra of the EPIC data in two different phase intervals, i.e. the soft (S, $\phi = 0.35 - 0.50$) and the hard (H, $\phi = 0.75 - 0.90$): in spite of the HR difference, they are characterized by a comparable CR in the total (0.15 – 12) energy range and, then, of photon counts in the accumulated spectra.

The independent fits of the two spectra with a single PL or BB model do not provide satisfactory results (in some cases they are rejected by the data), while the use of a PL+BB model significantly improves the spectral fit goodness; the best-fit parameters are reported in Table 1. Taking into account the estimated uncertainties, none of the spectral parameters vary significantly between the S and the H spectra: in all cases, they are characterized by comparable best-fit values.

We also investigated the spectral variability at the pulse minimum, where the HR shows an abrupt variation, by considering the spectrum of two narrow phase ranges at $\phi = 0.72$ and $\phi = 0.76$. Owing to the limited count statistics, it was impossible to perform a detailed spectral analysis, but we checked that the spectra in these regions are consistent with the best-fit models of the S and H phase intervals, respectively.

To investigate the relative variations in the two components with the period phase, we also simultaneously fitted the S and H spectra with the PL+BB model by assuming the same value of $N_H$, $\Gamma$, and $kT_{BB}$ for the two phase intervals. In this case, we obtained $N_H = (0.92 \pm 0.08) \times 10^{22}$ cm$^{-2}$, $\Gamma_{PL} = 1.48 \pm 0.17$, and $kT_{BB} = 1.67 \pm 0.05$ keV, with $\chi^2$/d.o.f. = 1.17/328. The corresponding normalization values are reported in Table 1 (Case I).

With these constraints on the model parameters, the spectral changes as a function of the phase are reproduced by the variations in the relative contribution of the two components. The values reported in Table 1 show that, with this assumption, the observed spectral variability is due to both components, since their flux varies by more than 50% between the two phases, even if in opposite directions: the PL flux decreases and the BB flux increases from the S to the H phase.

To confirm that the thermal component varies as a function of the rotational phase, we should prove that a constant BB component is rejected by the data. To this aim, we modified the test model by linking the BB parameters for the two spectra together, while both the photon-index $\Gamma$ and the normalization $I_{PL}$ of the PL component were able to vary independently in the two phase intervals. The resulting best-fit model implies that $N_H = (0.84 \pm 0.09) \times 10^{22}$ cm$^{-2}$, $kT_{BB} = 1.54 \pm 0.08$ keV, and $R_{BB} = 223^{+15}_{-17}$ m. The power-law parameters are shown in Table 2 (Case 2). Even with this model, we found a good quality fit ($\chi^2$/d.o.f. = 1.16/328), that is fully comparable to the previous case. This result suggests that it is possible to attribute the whole spectral variability to the PL component, and that a constant BB cannot be ruled out.

6. Discussion

Our XMM-Newton observation of RX J0440.9+4431 is the first of this source performed with a large X-ray telescope of the last generation, and has allowed us to investigate, for the first time, the timing and spectral properties of this pulsar at low X-ray energies below 3 keV. We have obtained a new measurement of the pulse period: $P = 204.96 \pm 0.02$ s. This value agrees with the period measurements obtained by the Gamma-ray Burst Monitor on-board the FERMI satellite since its launch in 2008, and collectively these data demonstrate that this source is characterized by a variable spin period, that is typical of wind-fed binary systems. On a longer timescale, our value is slightly larger than the previous value of 202.5 $\pm 0.5$ s found in 1998 by RossiXTE (Reig & Roche 1999): this period difference ($AP/P \approx 1\%$) is too large to be ascribed to orbital motion and implies that the average

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**Table 1.** Best-fit spectral parameters for the phase-resolved spectroscopy of RX J0440.9+4431, in the case of the independent fit of the two spectra.

<table>
<thead>
<tr>
<th>Phase interval</th>
<th>S</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_H \times 10^{22}$ cm$^{-2}$</td>
<td>0.76$^{+0.13}_{-0.14}$</td>
<td>0.69$^{+0.12}_{-0.11}$</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>1.12$^{+0.28}_{-0.24}$</td>
<td>0.89$^{+0.39}_{-0.42}$</td>
</tr>
<tr>
<td>$f_{PL}$a</td>
<td>2.76$^{+0.11}_{-0.14}$ (63%)</td>
<td>2.28$^{+0.30}_{-0.26}$ (44%)</td>
</tr>
<tr>
<td>$kT_{BB}$ (keV)</td>
<td>1.35$^{+0.17}_{-0.13}$</td>
<td>1.54$^{+0.12}_{-0.11}$</td>
</tr>
<tr>
<td>$R_{BB}$ (m)</td>
<td>237$^{+40}_{-37}$</td>
<td>247$^{+36}_{-27}$</td>
</tr>
<tr>
<td>$f_{BB}$a</td>
<td>1.63$^{+0.37}_{-0.05}$ (37%)</td>
<td>2.95$^{+0.99}_{-0.15}$ (56%)</td>
</tr>
<tr>
<td>$f_{rot}$a</td>
<td>4.39$^{+0.18}_{-0.42}$</td>
<td>5.23$^{+0.22}_{-1.25}$</td>
</tr>
<tr>
<td>$\chi^2$/d.o.f.</td>
<td>1.15/153</td>
<td>1.09/170</td>
</tr>
</tbody>
</table>

Notes. a) Absorbed flux in the energy range 0.3–12 keV, in units of $10^{-11}$ erg cm$^{-2}$ s$^{-1}$.
Table 2. Best-fit values for the black-body and power-law parameters, when the two spectra are fitted simultaneously with common values of $N_H$, $\Gamma$, and $kT_{BB}$ (Case 1) or with common values of $N_H$, $kT_{BB}$, and $R_{BB}$ (Case 2).

<table>
<thead>
<tr>
<th>Phase interval</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S</td>
<td>H</td>
</tr>
<tr>
<td>$N_H^a$</td>
<td>0.92$_{-0.08}^{+0.02}$</td>
<td>0.92$_{-0.07}^{+0.02}$</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>1.48$_{-0.11}^{+0.17}$</td>
<td>1.48$_{-0.13}^{+0.17}$</td>
</tr>
<tr>
<td>$f_{PL}^b$</td>
<td>3.37$^{+0.55}_{-0.66}$</td>
<td>2.24$^{+0.09}_{-0.04}$</td>
</tr>
<tr>
<td>$f_{BB}^c$</td>
<td>2.34$_{-0.20}^{+0.28}$</td>
<td>1.56$_{-0.04}^{+0.09}$ (54%)</td>
</tr>
<tr>
<td>$kT_{BB}$</td>
<td>1.67 $\pm 0.05$</td>
<td>1.67 $\pm 0.05$</td>
</tr>
<tr>
<td>$R_{BB}$</td>
<td>176$_{13}^{13}$</td>
<td>231$_{12}^{12}$</td>
</tr>
<tr>
<td>$f_{BB}^a$</td>
<td>2.02$_{-0.01}^{+0.06}$</td>
<td>3.47$_{-0.05}^{+0.06}$ (69%)</td>
</tr>
<tr>
<td>$f_{XRN}^2$</td>
<td>4.36$_{-0.16}^{+0.10}$</td>
<td>5.03$_{-0.14}^{+0.12}$</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>1.17</td>
<td>1.16</td>
</tr>
<tr>
<td>d.o.f.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes. (a) $\times 10^{32}$ cm$^{-2}$; (b) $\times 10^{-17}$ ph cm$^{-2}$ s$^{-1}$ keV$^{-1}$ at 1 keV; (c) absorbed flux in the energy range 0.3–12 keV, in units of $10^{-11}$ erg cm$^{-2}$ s$^{-1}$.

Assuming $A_V = 3.1 E(B-V)$ and the average relation $A_V = N_H \times 5.59 \times 10^{-22}$ cm$^{-2}$ between optical extinction and X-ray absorption (Predehl & Schmitt 1995), this implies that $N_H = 3.6 \times 10^{21}$ cm$^{-2}$, which is a factor of about two lower than our result. We note that the data used to calibrate the previous relation is characterized by a comparable dispersion, hence there is rough agreement between the two measurements.

We found evidence of a previously undetected thermal component, in addition to the main power-law: this thermal component has a high temperature ($kT = 1.34$ keV), a small emission area ($R = 273$ m), and contributes about 35% of the source flux below 10 keV. On the other hand, it was impossible to fit the $XMM$-Newton spectra with the two-black-body model used by Reig & Roche (1999). The RossiXTE spectrum showed a possible feature at ~6.2 keV, which might be a Fe-K emission line, but it was impossible to constrain its parameters, and only an upper limit of ~100 eV to the equivalent width (EQW) could be provided. In spite of the higher luminosity level, we found no evidence of the Fe-K emission line and derived an upper limit of ~70 eV (at 90% c.l.) to its EQW.

For its size and temperature, the $BB$ excess observed in $RX J0440.9+4431$ is similar to $BB$s detected by the persistent Be/NS XRBs, i.e. LS 1/61 235/RX J0146.9+6121 (La Palombara & Mereghetti 2006), X Persei/4U 0352+309 (Coburn et al. 2001; La Palombara & Mereghetti 2007), and LS 1698/RX J1037.5-5647 (Reig & Roche 1999; La Palombara et al. 2009): hence, this hot $BB$ spectral component is a common property of this type of sources. However, we note that a similar feature has also been observed in 3A 0535+262 (Orlandini et al. 2004; Mukherjee & Paul 2005), 4U 2206+54 (Masetti et al. 2004; Torrejón et al. 2004; Reig et al. 2009), and SAX J2103.5+4545 (Inam et al. 2004), which are other types of XRBs of low luminosity ($L_X \leq 10^{38}$ erg s$^{-1}$) and long pulse period ($P > 100$ s). Moreover, the same type of $BB$ excess has also been detected in the three supergiant fast X-ray transients (SFXTs) IGR J11215-5292 (Südi et al. 2007), IGR J08408-4503 (Südi et al. 2009), and XTE J1739-302 (Bozzo et al. 2010), only the first of which is a confirmed pulsar ($P = 187$ s). Finally, a hot $BB$ excess has also been detected in the SMC binary pulsar SXP 1062, a possible new persistent Be X-ray binary (Désert et al. 2011).
is shown, corresponding to different observations or flux levels. In most cases, the spectral parameters are within a narrow range of values, i.e. $kT_{BB} \sim 1–2$ keV and $R_{BB} < 200$ m. We emphasize that, in all these cases, the estimated total source X-ray luminosity is $\sim 10^{33}$ erg s$^{-1}$, with a 20–40% contribution of the black-body component. For RX J0440.9+4431, the BB radius is slightly larger ($R_{BB} \sim 270$ m), which is consistent with its total X-ray luminosity also being higher ($L_X \sim 8 \times 10^{33}$ erg s$^{-1}$). When observed at a high (i.e. $L_X \sim 10^{34}$ erg s$^{-1}$) luminosity level, RX J1037.5-5647 (point 2), 4U 0352+09 (point 4), SAX J2103.5+4545 (point 10), IGR J11215-5292 (asterisks), IGR J08408-4503 (cross), XTE J1739-302 (filled star), and SXP 1062 (empty diamonds). The continuous lines connect the black-body parameters corresponding to four different levels of luminosity (in erg s$^{-1}$).

References: 0 – this work; 1–La Palombara et al. (2009); 2 – Reig & Roche (1999); 3 – Coburn et al. (2001); 4 – La Palombara & Mereghetti (2001); 5 – Mukherjee & Paul (2005); 6 – La Palombara & Mereghetti (2006); 7 – Masetti et al. (2004); 8 – Torrejón et al. (2004); 9 – Reig et al. (2009); 10 – Inam et al. (2004); 11 – Sidoli et al. (2007); 12 – Sidoli et al. (2009); 13 – Bozzo et al. (2010); 14 – Hénault-Brunet et al. (2012).

In contrast to this sample of sources, several XBPs are characterized by a soft excess, since the fit of this component with a thermal emission model provides low temperatures ($kT < 0.5$ keV) and large emitting regions ($R > 100$ km). In Fig. 6, we report the luminosity and pulse period of both types of XBPs: the soft excess and the hot BB ones are reported as squares and circles, respectively. On the basis of their distribution in the $P - L_X$ diagram, these pulsars are divided into two distinct groups: the sources in the first group are characterized by high luminosity ($L_X \geq 10^{37}$ erg s$^{-1}$) and short pulse period ($P < 100$ s), and in most cases they are in close binary systems with an accretion disk; those in the second group have low luminosities ($L_X \leq 10^{36}$ erg s$^{-1}$) and long pulse periods ($P > 100$ s), since they have wide orbits and are wind-fed systems. While all the pulsars in the first group have a soft excess, both types of pulsars are present in the second group. In this case, the hot BB pulsars are the ones that, on average, are characterized by the lowest luminosities and the longest periods. This suggests that the hot BB spectral component is a common feature of the low-luminosity and long-period XBPs. However, in the second group of sources there is no clear separation between the two types of pulsars, since there is a partial overlap between the soft excess and the hot BB ones. Therefore, the origin of the spectral difference in pulsars with comparable values of luminosity and pulse period is unclear. Even if it were related to extremely different emission mechanisms operating in these sources, we cannot exclude that, at least in some cases, it is due to the degeneracy of spectral fitting in some spectra. On the basis of the X-ray spectrum it is often impossible to distinguish between a BB with a small radius and high temperature and one with a large radius and low temperature (see, e.g., Bozzo et al. 2010).

On the bases of our results and the emission models proposed by Hickox et al. (2004), in the case of RX J0440.9+4431 it also makes sense to attribute the observed spectral excess to the thermal emission from the NS polar cap, in agreement with what has already been suggested for the other persistent Be pulsars. To verify this hypothesis, we assume that the source is in the “accretor” state, with matter accretion onto the NS surface. Assuming $M_{NS} = 1.4 M_\odot$ and $R_{NS} = 10^6$ cm, the source luminosity $L_X = 8.3 \times 10^{34}$ erg s$^{-1}$ implies an accretion rate $\dot{M} = 4.5 \times 10^{14}$ g s$^{-1}$ and, adopting $B_{NS} = 10^{12}$ G, a magnetospheric radius $R_m = 10^7$ cm (Campana et al. 1998). In this case, based on the relation $R_{col} \sim R_{NS} (R_{NS}/R_m)^{0.5}$ (Hickox et al. 2004), we would obtain $R_{col} \sim 320$ m. This value, which is an estimate of the expected size of the polar cap, is remarkably similar to the estimated black-body emitting radius ($R_{BB} \sim 270$ m), hence it strongly supports the idea of a polar-cap origin for the observed BB emission. If this description were correct, we would expect to observe some variability in the thermal component along the pulse phase. The phase-resolved spectral analysis confirmed the spectral variability along the pulse, but this can be attributed to the PL component, since a constant BB component is fully compatible with the spectral data. The lack of variability of the BB component does not contradict the idea of a polar-cap origin, as anisotropic radiation can appear to be steady along the pulse for some geometrical configurations of the hot spots on the NS surface (Beloborodov 2002). The phase dependence of the non-thermal component is likely due to the anisotropy of the Comptonized radiation of the accretion
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Note added in proof. While this article was in its publication phase, we became aware of the paper of Tsygankov et al. (2012) reporting the discovery of a cyclotron absorption line in the high-energy X-ray spectrum of RX J0440.9+4431. This paper is based instead on data obtained with the INTEGRAL, Swift, and RXTE observatories during the 2010 April and September outbursts of the X-ray pulsar. Although the source during this time interval was significantly brighter than during our XMM-Newton observation, most of the timing and spectral results described in that paper are in good agreement with our results.

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