# Observation of blackbody excess in persistent Be/NS binary pulsars


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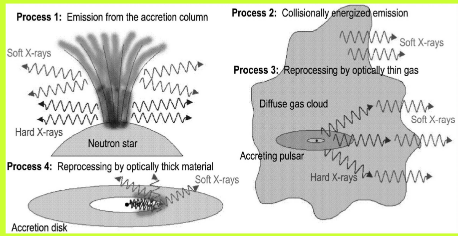
## ABSTRACT

The spectra of many X-ray accreting pulsars show a *soft* excess below 10 keV. This feature has been detected also in faint sources and at low luminosity levels, suggesting that it is an ubiquitous phenomenon. In the case of the high-luminosity pulsars ($L_X > 10^{36}$ erg/s), the fit of this component with thermal emission models usually provides low temperatures (kT < 0.5 keV) and large emission regions (R > 100 km); for this reason, it is referred to as a *soft* excess. In the latest years we have performed an observation campaign with XMM-Newton of persistent, low-luminosity ($L_X \sim 10^{34}$ erg/s) and long-period (P > 100 s) Be accreting pulsars, which were previously poorly studied at soft X-ray energies. Instead of the typical soft excess of the brighter sources, in this case we detected a different feature: the observed spectra show a ***hard*** excess which can be modeled with a rather hot (kT > 1 keV) blackbody component of small area (R < 0.5 km), which can be interpreted as emission from the NS polar caps.


## Scientific context

Most X-ray binary pulsars (XBPs) are High Mass X-Ray Binaries (HMXRBs) in which a Neutron Star (NS) with a magnetic field B ~ $10^{12}$ G accretes matter from a high-mass early-type star, either an OB supergiant or a Be star. The X-ray spectra of both subgroups are generally described by a rather flat power-law between 0.1 and 10 keV (photon index ~ 1) with a high-energy cutoff, but several of the brightest XBPs (with $L_X \sim 10^{37-38}$ erg $s^{-1}$) have also a marked soft X-ray excess above the main component. The same type of feature has been detected also in several fainter sources (with $L_X \sim 10^{35-36}$ erg $s^{-1}$) of the Small Magellanic Cloud, where the observations are unaffected by the high interstellar absorption along the Galactic plane. Only in a few cases this low-energy component unambiguously showed coherent pulses, and a variety of simple models (both thermal and non-thermal) have been proposed to fit this feature. Hickox et al. (2004) has suggested that the presence of a soft spectral component could be a very common, if not an ubiquitous, feature intrinsic to X-ray pulsars. It can be due to different emission processes (as shown in the below figure), mainly depending on the source luminosity; therefore it is very interesting to investigate the presence and the characteristics of this feature also in the faint XBPs.




Hickox et al. (2004)

## Source characteristics

We have analyzed the *XMM-Newton* observations of four persistent Be binary pulsars in the Galactic plane:

- RX J0146.9+6121 (La Palombara & Mereghetti, 2006)
- 4U 0352+309 (La Palombara & Mereghetti, 2007)
- RX J1037.5-5647 (La Palombara et al., 2009)
- RX J0440.9+4431 (La Palombara et al., 2011, in preparation)

According to the classification proposed by Reig & Roche (1999) for the persistent Be binary pulsars, these sources are characterized by:

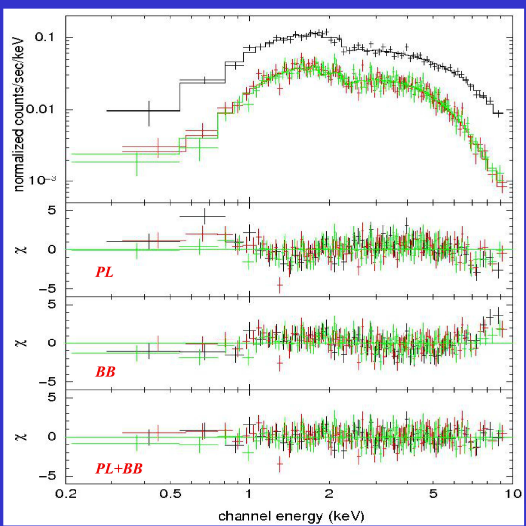
- persistent low luminosity ($L_X \sim 10^{34-35}$ erg $s^{-1}$) with small fluctuations
- no outbursts and absence of any transient behavior
- long pulse periods ($P_{spin}$ > 100 s)
- missing or very weak Iron line at 6.4 keV

Since $P_{spin} \sim P_{orb}^2$ (Corbet 1986), the above properties suggest that in these systems the Be star orbits the NS in a wide and nearly circular orbit, continuously accreting material from the low-density outer regions of the circumstellar envelope; for 4U 0352+309, this suggestion has been confirmed by the discovery of an orbital period of 250.3 days (Delgado-Marti et al. 2001), while for RX J0440.9+4421 an orbital period of ~ 155 days has been recently estimated (Tsygankov et al. 2011).

| X-ray source | RX J0146.9+6121 | 4U 0352+309 | RX J1037.5-5647 | RX J0440.9+4431 |
|---|---|---|---|---|
| Optical counterpart | LS I +61° 235 | X Persei | LS 1698 | BSD 24-491 |
| Spectral type | B0 IIIe | O9.5 IIIe | B0 III-V | B0.2 Ve |
| Distance (kpc) | ~ 2.5 | ~ 1 | ~ 5 | ~ 3.2 |
| Pulse period (s) | 1396.1 | 839.3 | 853.4 | 204.96 |

## Spectral analysis

In all cases the fit of the source spectrum with a single-component emission model, either a power-law (*PL*) or a blackbody (*BB*), leaves large residuals. On the other hand, the use of a *PL+BB* model provides a significant improvement of the fit quality.




In all cases the blackbody component is characterized by a high temperature (kT > 1 keV) and a small emission radius (R < 0.5 km) and contributes for ~ 30-40 % of the total flux. Moreover, we found no evidence for a Fe K emission line, and it was only possible to set an upper limit (UL) on the equivalent width (EQW) of a possible Iron line.

| X-ray source | 4U 0352+309 | RX J0146.9+6121 | RX J1037.5-5647 | RX J0440.9+4431 |
|---|---|---|---|---|
| $L_X$ (0.3-10 keV, erg $s^{-1}$) | ~$1.4 \times 10^{35}$ | ~$1.5 \times 10^{34}$ | ~$1.2 \times 10^{34}$ | ~$6.6 \times 10^{34}$ |
| Photon index Γ | 1.48 ± 0.02 | 1.34 ± 0.05 | 0.51(+0.17/-0.29) | 0.86 ± 0.07 |
| $T_{BB}$ (keV) | 1.42 ± 0.03 | 1.11 ± 0.06 | 1.26(+0.16/-0.09) | 1.33 ± 0.04 |
| $R_{BB}$ (m) | 361 ± 3 | 140 ± 15 | 128(+13/-21) | 265(+16/-15) |
| Flux PL (%) | ~ 61 | ~ 76 | ~ 58 | ~ 66 |
| Flux BB (%) | ~ 39 | ~ 24 | ~ 42 | ~ 34 |
| UL EQW Fe (keV, 90 % c.l.) | ~ 0.1 | ~ 0.15 | ~ 0.2 | ~ 0.07 |

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**a BB component of high temperature and small size is a possible additional common property of persistent BeXRBs**

Based on the emission models proposed by Hickox et al. (2004), the low luminosity of these binary pulsars suggests that the observed BB component is due to thermal emission from the NS polar cap.

Assuming $M_{NS} = 1.4\ M_{SUN}$, $R_{NS} = 10^6$ cm and $B_{NS} = 10^{12}$ G, we can estimate:

- the accretion rate: $dM/dt = LR_{NS}/(GM_{NS})$
- the magnetic dipole momentum: $\mu = B_{NS}R_{NS}^3/2$
- the magnetospheric radius: $R_m = \{\mu^4/[2GM(dM/dt)^2]\}^{1/7}$
- the accretion column radius: $R_{col} \sim R_{NS}(R_{NS}/R_m)^{1/2}$

In this way, we obtained the following values for the polar-cap radius:

| X-ray source | 4U 0352+309 | RX J0146.9+6121 | RX J1037.5-5647 | RX J0440.9+4431 |
|---|---|---|---|---|
| Polar cap radius (m) | ~ 330 | ~ 230 | ~ 200 | ~ 270 |

The polar cap radius are comparable to the estimated radius of the BB emission

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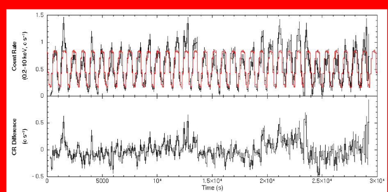
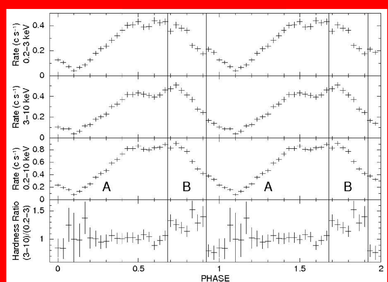
***the observed thermal component can be attributed to the emission from the NS polar caps.***

## Timing analysis

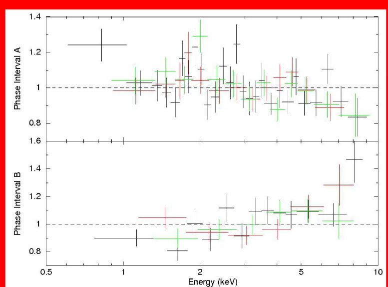
In the *top panel* of the below figure, which reports the background-subtracted light-curve of RX J1037.5-5647, the pulsed emission of the source is clearly evident. The same curve also shows that the pulsed fraction $(CR_{max} - CR_{min})/(2 \times CR_{average})$ is rather high (> 70 %). In the *bottom panel* we report the difference between the curve of the whole *XMM-Newton* observation (*black*) and the *average* curve (*red*), which is obtained by assuming that all the pulses are equal to the average folded light curve: it shows that there are significant differences between the individual pulses, although there is no evidence for a large source variability on long timescales.




The folded light-curve shows that the pulse profile is energy dependent, while there is no simple correlation between the count rate and the hardness ratio between the hard (E > 3 KeV) and the soft (E < 3 keV) energy bands.

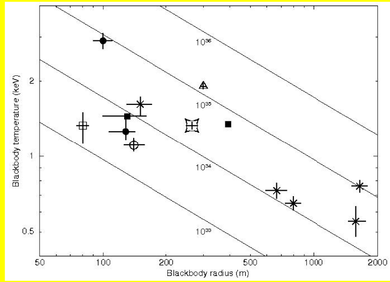



To study the source behavior in more detail, we analyzed the background-subtracted spectra in the two phase intervals A and B. In the below figure we report the ratios of the two spectra to the renormalized average model spectrum. The data show that the spectra of phase intervals A and B are, respectively, softer and harder than the phase-averaged one, which implies a spectral variability along the pulse phase.



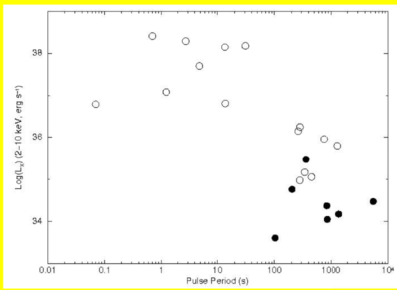

## Comparison with other X-ray binary pulsars

In the case of 4U 0352+309 and RX J1037.5-5647, a BB excess above the main power-law component has been detected also by observations performed with the *RossiXTE* telescope (Coburn et al., 2001; Reig & Roche 1999). Moreover, a similar feature has been found also in the non-persistent, low-luminosity binary pulsars 3A 0535+262 (Mukherjee & Paul 2005), 4U 2206+54 (Torrejon et al. 2004) and SAX J2103.5+4545 (Inam et al. 2004). To compare the results obtained in all the performed observations, in the below figure we report the corresponding best-fit *BB* radius and temperature (different simbols refer to different sources), together with lines showing four different levels of the *BB* luminosity.




The figure shows that, for sources with $L_{BB} \leq 10^{34}$ erg $s^{-1}$, the *BB* parameters are clustered in a narrow range of values, since $T_{BB}$ = 1-2 keV and $R_{BB}$ ~ 100 m. On the other hand, for larger values of the *BB* luminosity the previous parameters are spread over a wide range of values.

An X-ray excess has also been observed in several other, more luminous binary pulsars. In contrast to the previous low-luminosity sources, in their case the fit of this excess with a thermal emission model provided low temperatures ($T_{BB}$ < 0.5 keV) and large emitting radii ($R_{BB}$ > 100 km): for this reason, this feature is usually described as a ***soft*** excess.




In the previous figure we report the luminosity and pulse period of the XBPs with a detected thermal excess. They are divided in two well distinct groups: the sources in the first group are characterized by high luminosity ($L_X > 10^{37}$ 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 ($L_X < 10^{36}$ erg $s^{-1}$) and long pulse periods (P > 100 s), since they have wide orbits and are wind fed systems. Among the sources of the second group of XBPs, the seven pulsars previously discussed (reported as *filled circles*) are the ones that have, at the same time, the lowest luminosities and the longest periods; in their case the blackbody component has a higher temperature ($kT_{BB}$ > 0.5 keV) and a much smaller emission radius ($R_{BB}$ < 2 km), therefore these low-luminosity and long-period pulsars are very similar also from the spectral point of view. Their hot BB spectral component separates them from all the other pulsars, strongly suggesting that **they form a distinct and well defined class of binary pulsars**.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