XMM-Newton observation of the Be/neutron star system RX J0146.9+6121: a soft X-ray excess in a low luminosity accreting pulsar

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ABSTRACT

We report on the XMM-Newton observation of the Be/neutron star X-ray binary system RX J0146.9+6121, a long period (~23 m) pulsar in the NGC 663 open cluster. The X-ray luminosity decreased by a factor of two compared to the last observation carried out in 1998, reaching a level of \( \sim 1 \times 10^{34} \text{ erg s}^{-1} \), the lowest ever observed in this source. The spectral analysis reveals the presence of a significant excess at low energies over the main power-law spectral component. The soft excess can be described by a black-body spectrum with a temperature of about 1 keV and an emitting region with a radius of \( \sim 140 \text{ m} \). Although the current data do not permit us to ascertain whether the soft excess is pulsed or not, its properties are consistent with emission from the neutron star polar cap. This is the third detection of a soft excess in a low luminosity (~1 \( \times 10^{34} \text{ erg s}^{-1} \)) pulsar, the others being X Per and 3A 0535+262, suggesting that such a spectral component, observed to date in higher luminosity systems, is a common feature of accreting X-ray pulsars. The results of these three sources indicate that, in low luminosity systems, the soft excess tends to have a higher temperature and a smaller surface area than in the high luminosity ones.

Key words. stars: individual: RX J0146.9+6121 – X-rays: binaries

1. Introduction

High Mass X-Ray Binaries (HMXRBs) are binary systems consisting of a neutron star (NS) or, less frequently, a black hole, accreting matter from a high mass early type star. Based on the nature of the mass donor star, either a supergiant of O/B spectral type or a Be star, HMXRBs can be divided in two subgroups showing different variability properties. HMXRBs with supergiant companions tend to be persistent sources, although some of them display high and low states with X-ray flux varying by a large factor (~100 or more). On the other hand, neutron star Be X-ray binaries (BeXRBs) are generally transient sources, due to the long term variability of the equatorial discs surrounding Be stars and/or the orbital eccentricity. For both subgroups, when the compact object is a NS, the X-ray spectra are well described by a rather flat power-law between 0.1 and 10 keV (photon index ~1) followed by a high-energy cutoff.

With the advent of imaging X-ray satellites a large number of BeXRB systems has been discovered in the Small Magellanic Cloud (Haberl & Sasaki 2000; Israel et al. 2000; Yokogawa et al. 2003; Macomb et al. 2003; Sasaki et al. 2003; Haberl & Pietsch 2004). The observation of these sources, unaffected by the high interstellar absorption present in the Galactic plane, makes it possible to study in detail their X-ray spectra, extending down to energies of a few hundred eV. This has allowed investigators to discover that most of them have a marked soft excess above the power-law model (Nagase 2002; Haberl & Pietsch 2005).

RX J0146.9+6121 is a BeXRB hosting a neutron star characterized by a rotational period of about 23 min, among the longest observed in X-ray pulsars. The pulsations were discovered with non-imaging instruments on board EXOSAT and initially attributed to a different nearby source (White et al. 1987). Subsequent observations clarified the picture (Mereghetti et al. 1993; Hellier 1994) and led to the optical identification of RX J0146.9+6121 with the B0 Ie star LS 1+61° 235 (Coe et al. 1993). This star is a member of the open cluster NGC 663 (Tapia et al. 1991; Fabregat et al. 1996; Pignolli et al. 2001) for which a distance in the range between 2 and 2.5 kpc has been derived (Kharchenko et al. 2005; Pandey et al. 2005). In the following we adopt \( d = 2.5 \text{ kpc} \). Due to its relatively short distance, RX J0146.9+6121 is not much absorbed and is therefore a good target to investigate the properties of the soft X-ray emission in a Galactic source. Here we present the results of a recent observation obtained with the XMM-Newton satellite, providing the most sensitive observation of this source ever obtained below 2 keV.

2. Observations and data reduction

RX J0146.9+6121 was observed by XMM-Newton between 22:40 UT of 2004 January 14 and 10:20 UT of 2004 January 15. Since the main target was the NGC 663 open cluster, RX J0146.9+6121 was detected at an off-axis angle of 9.3°. The three EPIC instruments, i.e. the pn camera (Strüder et al. 2001) and the MOS1 and MOS2 cameras (Turner et al. 2001), were active and operated in Full Frame mode. For all of them, the Medium thickness filter was used.
We used version 6.1 of the XMM-Newton Science Analysis System (SAS) to process the event files. After the standard pipeline processing of the data, we looked for possible periods of high instrumental background, due to flares of soft protons with energies less than a few hundred keV. We found that the first ~15 ks of the observation were affected by a soft-proton contamination. However, since RX J0146.9+6121 was detected with a count-rate (~1 cts s⁻¹) much higher than that of the background, the soft-protons during the bad time intervals have a negligible effect on the source spectral and timing analysis (their count rate in the source extraction area is less than 0.01 cts s⁻¹). Hence for our analysis we used the data of the whole observation, corresponding to exposure times of 35.4 and 41.2 ks in the pn and MOS cameras, respectively.

3. Timing analysis

During our observation some flux changes on an ~hour timescale were present, as shown by the background subtracted light curve plotted in Fig. 1. This is based on the data in the 0.15–10 keV range obtained from the three EPIC cameras. A bin size of 1.4 ks, corresponding to one spin period, has been chosen to avoid the effects due to the periodic pulsations. Variations up to ~20% around the average level of ~1.9 cts s⁻¹ are evident.

To obtain a measure of the pulse period, we converted the times of arrival to the solar system barycenter and performed a folding analysis using the source events of three cameras. By fitting the χ² versus trial period curve with the appropriate sinc function as described in Leahy (1987), we derived a period of 1396.14 ± 0.25 s. In Fig. 2 we show the folded light curves in four energy intervals (0.3–2, 2–4.5, 4.5–7 and 7–10 keV) chosen to allow a direct comparison with the light curves previously derived with RossiXTE data (Mereghetti et al. 2000). The pulse profile, characterized by a broad peak, is clearly energy-dependent, with the maximum shifting from phase ~0.4–0.5 at $E < 2$ keV to phase ~0.6 at $E > 7$ keV.

The hardness ratio (HR) between the light curves above and below 2 keV, reported in Fig. 3, is characterized by a slow and regular increase from its minimum to its maximum value, followed by a rather irregular decrease. This plot, where we have divided the pulse period in ten phase intervals, shows that there is not a simple correlation between the hardness and the total count rate: we observe the same HR value at completely different count rate levels, but also very different HR values for the same count rate. This indicates that the spectral hardness of RX J0146.9+6121 does not depend in a simple way on its flux level.

4. Spectral analysis

For the source spectra we used an extraction radius of 30″ around the source position in the case of the MOS2 and pn cameras; for the MOS1 camera the extraction radius was reduced to 15″, since the source was imaged close to a CCD gap. We checked with the SAS task epatplot that no event pile-up affected our data, then we accumulated all the events with pattern range 0–4 (i.e. mono- and bi-pixel events) and 0–12 (i.e. from 1 to 4 pixel events) for the pn and the two MOS cameras, respectively. The background spectra were accumulated on large circular areas with no sources and radius of 210″ and 120″ for the MOS1 and the MOS2 camera, respectively. For the pn camera...
Fig. 4. Top panel: pn spectrum of RX J0146.9+6121 with the best-fit power-law (dashed line) plus black-body (dotted line) model. Middle panel: residuals (in units of σ) between data and model in the case of the single power-law. Bottom panel: residuals in the case of the power-law plus black-body.

The background spectrum was extracted from a circular region of the same radius and at the same CCD rows of the source region. We generated ad hoc response matrices and ancillary files using the SAS tasks rmfgen and arfgen. All spectra were rebinned with a minimum of 30 counts per bin and fitted in the energy range 0.3–10 keV using XSPEC 11.3.2.

After checking that separate fits of the three spectra gave consistent results, we fitted the spectra from the three cameras simultaneously in order to increase the count statistics and to reduce the uncertainties. The fit with an absorbed power-law yielded $N_H = (6.24 \pm 0.14) \times 10^{21}$ cm$^{-2}$ and photon index $\Gamma = 1.36 \pm 0.02$, but with large residuals and $\chi^2$/d.o.f. = 1.283/1480.1. The addition of a blackbody component improved the fit quality significantly (Fig. 4): we obtained $N_H = (5.09^{+0.24}_{-0.23}) \times 10^{21}$ cm$^{-2}$ and $\Gamma = 1.34^{+0.05}_{-0.06}$ and $kT_{BB} = 1.11^{+0.07}_{-0.06}$ keV, with $\chi^2$/d.o.f. = 1.036/1478. The emission surface of the thermal component has a radius $R_{BB} = 140^{+17}_{-14}$ m for $d = 2.5$ kpc. The unabsorbed flux in the energy range 0.3–10 keV is $f_X \sim 2 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, about 24% of which is due to the blackbody component.

We also attempted to fit the soft part of the spectra with other emission models, such as mekal, thermal bremsstrahlung and broken power-law. In all these cases the results were worse than those obtained with the blackbody model, since the reduced chi-squared was higher, the residuals were larger and/or the best-fit parameter values were unrealistic.

We did not find significant evidence for emission lines. By adding Gaussian components at various energies to the above model, we estimated upper limits of the order of 150 eV for the equivalent width of lines in the 6–7 keV energy range.

5. Phase-resolved spectroscopy

Prompted by the results described above, we performed a phase-resolved spectroscopy in order to study in more detail the source behavior. We defined phase 0 by matching the folded light curve to that observed in 1996 with RossiXTE and extracted the background subtracted spectra for the same four phase intervals used

Table 1. Best-fit spectral parameters for the phase-resolved spectroscopy of RX J0146.9+6121, in the case of the independent fit of the four spectra. Errors are at a 90% confidence level for a single interesting parameter. $N_H$ and $kT_{BB}$ are measured in units of $10^{21}$ cm$^{-2}$ and keV, respectively.

| Parameter | Phase Interval |
|-----------|----------------|
| $N_H$     | A   | B   | C   | D   |
|           | 4.8^{+4.4}_{-2.5} | 5.4^{+4.4}_{-3.0} | 5.0^{+5.0}_{-0.7} | 3.6^{+6.5}_{-0.5} |
| $\Gamma$  | 1.47^{+0.19}_{-0.20} | 1.39^{+0.09}_{-0.08} | 1.31^{+0.35}_{-0.23} | 1.06^{+0.11}_{-0.21} |
| $kT_{BB}$ | 0.98^{+0.08}_{-0.12} | 1.05^{+0.10}_{-0.09} | 1.34^{+0.17}_{-0.18} | 1.21^{+0.21}_{-0.16} |

\begin{table}[h]
\begin{tabular}{lcccc}
\hline
| Parameter | A   | B   | C   | D   |
|-----------|-----|-----|-----|-----|
| $R_{BB}$  | 76  | 130 | 121 | 87  |
| $F_{PL}$  | 2.24^{+0.07}_{-0.03} | 3.25^{+0.05}_{-0.03} | 1.32^{+0.03}_{-0.06} | 0.89^{+0.01}_{-0.03} |
| $f_{TOT}$ | 2.04 | 3.42 | 1.77 | 1.06 |
| $f_{BB}$  | 1.69 | 2.46 | 1.00 | 0.67 |
| $f_{BB}$  | 0.35 | 0.96 | 0.77 | 0.39 |
|            | (17%) | (28%) | (44%) | (37%) |
\hline
\end{tabular}
\end{table}

\begin{itemize}
\item $a$ Unabsorbed flux in the energy range 0.3–10 keV, in units of $10^{-11}$ erg cm$^{-2}$ s$^{-1}$.
\item $b$ Radius of the blackbody component (in metres) for a source distance of 2.5 kpc.
\item $c$ Intensity of the power-law component in units of $10^{-13}$ ph cm$^{-2}$ s$^{-1}$ keV$^{-1}$ at 1 keV.
\item $d$ Unabsorbed flux in the energy range 0.3–10 keV, in units of $10^{-14}$ erg cm$^{-2}$ s$^{-1}$.
\end{itemize}

in Mereghetti et al. (2000) and indicated in Fig. 2. The first step was to fit all of them with the best-fit power law plus blackbody model of the phase averaged spectrum, leaving only the relative normalization factors free to vary. The ratios of the four spectra of each instrument to these renormalized average models show significant residuals and clearly demonstrate the spectral variability as a function of the pulse phase.

We then fitted the four spectra independently. In all cases, the absorbed power-law model was not satisfactory, while the addition of a blackbody component significantly improved the fit. Therefore we used this model for all the spectra, leaving all the parameters free to vary: the results are reported in Table 1.

In order to investigate the relative variations of the two components with the period phase, we also simultaneously fitted the four spectra forcing common values for $N_H$, $\Gamma$ and $kT_{BB}$. In this case we obtained $N_H = (5.8 \pm 0.1) \times 10^{21}$ cm$^{-2}$, $\Gamma = 1.60 \pm 0.02$ and $kT_{BB} = 1.36^{+0.04}_{-0.03}$ keV, with $\chi^2$/d.o.f. = 1.117/1989; the corresponding normalization values are reported in Table 2. In this interpretation the spectral changes as a function of the phase are reproduced by the variations in the relative contribution of the two components.

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1 Errors are at a 90% confidence level for a single interesting parameter.
However, the above results do not necessarily imply that the soft component is pulsed. In fact an acceptable fit ($\chi^2$/d.o.f. = 1.097/1989) can also be obtained by imposing that the blackbody component parameters be the same in the four spectra, as shown in Table 3.

The above results are summarized in Fig. 5, where we show the pulse-phase dependence of the black-body temperature, the power-law photon index and the unabsorbed flux of the two components for both fits. Since they have a similar statistical quality, we can neither confirm nor deny that the thermal component is variable.

### 6. Discussion

The *XMM-Newton* data described here were obtained almost 6 years after the latest X-ray observation of RX J0146.9+6121, which was performed by *BeppoSAX* on 1998 February 3 (Mereghetti et al. 2000). Therefore it is interesting to compare our results with those obtained in the past. In Fig. 6 we show the long term evolution of the source spin period and luminosity since the time of the *EXOSAT* discovery in 1984. If we exclude the first observation, when the source was in outburst, the linear fit of all the periods gives a spin-up at an average rate of $P = -(4.6^{+0.1}_{-0.2}) \times 10^{-8}$ s$^{-1}$, similar to that measured until 1998. This result suggests that during the 6 years between the *BeppoSAX* and the *XMM-Newton* observations, the momentum transfer onto the neutron star has proceeded with no major changes. The flux detected by *XMM-Newton* corresponds to a luminosity of $\sim 1.5 \times 10^{34}$ erg s$^{-1}$, a factor $\sim 2$ lower than the minimum level observed in the previous years, indicating that, after the outburst of July 1997 (Haberl et al. 1998), RX J0146.9+6121 has been continuously fading.

Comparison with the *RossiXTE* results reported in Fig. 2 of Mereghetti et al. (2000) shows that, despite the luminosity variation, the shape of the pulse profiles in the energy interval common to the two instruments (2–10 keV) has not changed. The *XMM-Newton* data also confirm that, above 2 keV, there is a significant spectral softening in the initial rising part of the pulse (phase interval A).

The main advantage of the data reported here, with respect to previous observations of this source, is the better coverage of the energy range below 2 keV. In comparison to the *BeppoSAX* results, the phase averaged spectroscopy gives a smaller hydrogen column density: $N_H = (5.09^{+0.25}_{-0.23}) \times 10^{21}$ cm$^{-2}$ instead of
with a long pulse period. The soft excesses of these sources have similar properties, since they tend to have a higher temperature (>1 keV) and a smaller emission radius (∼0.1 km) compared to the soft excesses observed in high luminosity systems, which have a temperature of about 0.1 keV and an emission radius of a few hundred km. In these three low luminosity systems the soft excess contributes 25–35% of the total flux (Coburn et al. 2001; Mukherjee & Paul 2005). Also in the case of X Per and 3A 0535+262 this excess has been attributed to the emission from the polar caps.

7. Conclusions

We have reported the analysis of the data collected by XMM-Newton in a ~42 ks observation of the Be/neutron-star X-ray pulsar RX J0146.9+6121. The unabsorbed flux corresponds to a source luminosity $L_X \approx 1 \times 10^{34}$ erg s$^{-1}$ in the $2–10$ keV energy range, about 50% lower than the lowest level ever observed from this source, indicating a monotonic source fading over long time scales.

Thanks to the high effective area of XMM-Newton also at low energies, we could perform the first accurate spectral study below 2 keV for this source. In the phase-averaged spectrum we have revealed the presence of a significant soft excess over the primary power-law component; this excess can be described by a black-body with $kT_{BB} \sim 1$ keV, while any attempt to fit it with a different emission model was unsuccessful.

The phase-resolved spectroscopy has confirmed the large spectral variability along the pulse period already observed above 2 keV. Unfortunately, with the current data, it is not possible to derive compelling results on the phase variability of the soft excess component. Although the emission below 2 keV is clearly pulsed and the low energy part of the spectrum varies with the phase, we have shown that such variations can be explained equally well by changes in the blackbody component or in the power law component alone.

Clearly the relatively small distance and low interstellar absorption toward RX J0146.9+6121 plays a role in the possibility of detecting a soft excess in such a low luminosity pulsar. Comparison with other X-ray binary pulsars shows that, so far, a soft excess has been detected only in much brighter sources. The data reported here support the hypothesis that a soft

Fig. 7. Total X-ray luminosity of the sources of Table 4 as a function of the interstellar absorption.
### Table 4. Orbital and spectral parameters for XBPs with a detected soft excess.

| Source      | flux in (0.3–10) keV | Flux in (0.064–7) keV | Flux in LE 0.09 s-1 | Source of flux in LE 0.09 s-1 |
|-------------|----------------------|-----------------------|---------------------|-----------------------------|
| RX J0146.9−6121 |                     |                       |                     |                             |
| SE model    |                      |                       |                     |                             |
| XSE model   |                      |                       |                     |                             |
| XMM−Newton observation of RX J0146.9−6121 | | | | |

ORbital and spectral parameters for XBPs with a detected soft excess (SE).
thermal component is a ubiquitous emission feature of this class of sources. In this sense, it would be very interesting to use the large collecting area of XMM-Newton in long observations of the faintest and longest period Be binaries, both in the SMC and in the Milky Way, such as, for example, the persistent low luminosity systems RX J0440.9+4431 and RX J1037.5-5647 (Reig & Roche 1999).

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