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RXTE observations of RX J0146.9+6121: a new X-ray outburst of the Be/X-ray pulsar

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Abstract. RXTE observations of the Be/X-ray binary pulsar RX J0146.9+6121 in July 1997 revealed the begin of a new X-ray outburst, the second observed after its discovery in August 1984 by EXOSAT. The flux increased by nearly a factor of five within one week reaching 3.2 10^{-10} erg cm^{-2} s^{-1}. The corresponding X-ray luminosity for a distance of 2.5 kpc is an order of magnitude brighter than the level observed between 1994 and 1996 by ASCA and ROSAT. The neutron star spin period was measured to 1404.2 $\pm$ 1.2 s indicating the start of a spin-up phase as expected for increased matter accretion onto the neutron star during outburst. A combined spectral analysis of ASCA and RXTE data revealed an exponential cutoff in the power-law spectrum at 4 keV.

Key words: stars: emission-line, Be – stars: individual: RX J0146.9+6121 – stars: neutron – X-rays: stars

1. Introduction

RX J0146.9+6121, the X-ray pulsar with the longest known spin period of nearly 25 min, was first recognized in EXOSAT ME observations of 4U 0142+61 as hard X-ray transient in outburst (White et al. 1987) which contributed to the collimated X-ray flux of the 8 s pulsar. Using the imaging capabilities of the ROSAT PSPC detector it was possible to identify RX J0146.9+6121 as Be/X-ray binary (Motch et al. 1991; Coe et al. 1993; Motch et al. 1997) and verify that the pulsations were caused by this X-ray source close to 4U 0142+61 (Hellier 1994). The X-ray luminosity of RX J0146.9+6121 during the outburst in August 1984 as seen by EXOSAT approached 10^{36} erg s^{-1} while ROSAT and ASCA observations between 1994 and 1996 always found the source at a low level of 2 10^{34} erg s^{-1} (Haberl et al. 1998).

The pulse period decreased from 1455 s in August 1984 to 1412 s in February 1993. The period decrease then nearly stopped at a period of 1407 s in February 1996 in agreement with the picture of increased spin-up of the neutron star only during periods of enhanced accretion via a disk during outbursts. In this respect RX J0146.9+6121 resembles X Persei, another long period X-ray pulsar (837 s; Haberl et al. 1998).

In the present paper we describe the results of recent X-ray observations of RX J0146.9+6121 obtained with the Rossi X-ray Timing Explorer (RXTE) which found the source steadily increasing in luminosity indicating the begin of a new outburst.

2. The observations

RX J0146.9+6121 was observed by RXTE in 1997 on July 4 (15:58 - 18:37 UT), July 6 (15:32 - 18:30) and July 10, 20:05 - July 11, 06:19. We present here the results obtained from the PCA instrument (Jahoda et al. 1996). The standard data selection filters were applied with a minimum elevation angle of 10 degrees and a maximum offset of 0.02 degrees from the nominal pointing direction. This yields a total net exposure of 27760 s (2752 s, 5040 s and 19968 s for the three observation intervals, respectively). To improve the signal to noise ratio we used only data from the top layer anodes of the detectors. To reduce the contribution of 4U 0142+61 to the X-ray signal the satellite pointing was offset from the position of RX J0146.9+6121 resulting in 2.4% and 15.0% collimator efficiency for 4U 0142+61 and RX J0146.9+6121, respectively.

Fig. 1 shows the PCA light curve obtained from the complete observation and the last part of the observation is enlarged with higher time resolution in Fig. 2. Superimposed onto a general increase in intensity towards the end of the observation are intensity variations up to a factor of 7 caused by the X-ray pulsations.

A time-folding analysis was applied to the data corrected to the solar system barycenter and a period of 1404.2 ± 1.2 s was derived. The light curve folded with this period is shown in Fig. 3. The pulse profile is similar to that observed by ASCA and ROSAT, but shows more substructure due to the higher signal to noise ratio. The pulsed fraction is with 69 $\pm$ 4% consistent with the values derived from ASCA and ROSAT observations (Haberl et al. 1998).

Hardness ratios obtained by dividing the count rates from different energy bands (2 - 4 keV, 4 - 6.2 keV and 6.2 - 20 keV)

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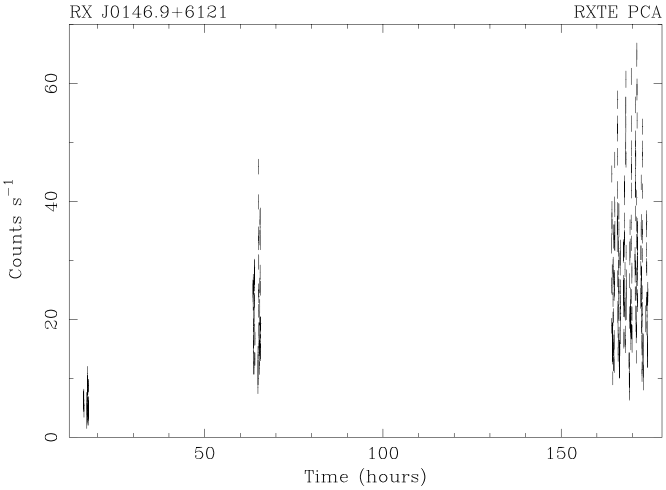

Fig. 1. Background subtracted 2 − 20 keV light curve of RX J0146.9+6121 starting on July 4, 1997 at 15:58:24 UT. Each point is integrated over 64 s

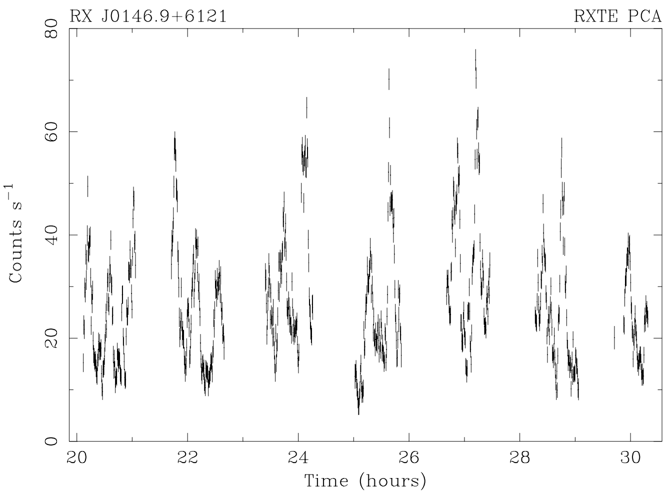

Fig. 2. The last part of the light curve from Fig. 1 with a time resolution of 32 s. Start time is July 10, 1997 at 20:05:20 UT

do not indicate spectral changes during the X-ray pulse. The hardness ratios also do not vary significantly throughout the observation, i.e. no spectral changes with X-ray intensity are visible. Therefore average energy spectra were extracted from the three observation periods individually and for the complete observation, with the latter shown in Fig. 4. In model fits to the spectra the contribution of 4U 0142+61 was taken into account by adding a power-law (photon index 3.67) and blackbody (kT 0.386 keV) component with fixed parameters as derived from an ASCA observation of 4U 0142+61 by White et al. (1996). Since 4U 0142+61 shows little intensity variations in the 1 - 10 keV band we assumed the same intensity as during the ASCA observation (a 0.5 − 10 keV flux of 1.3 10^{-10} erg cm^{-2} s^{-1}) and corrected for collimator efficiency. With this assumption 4U 0142+61 contributes only ∼3% to the observed flux (see Fig. 4).

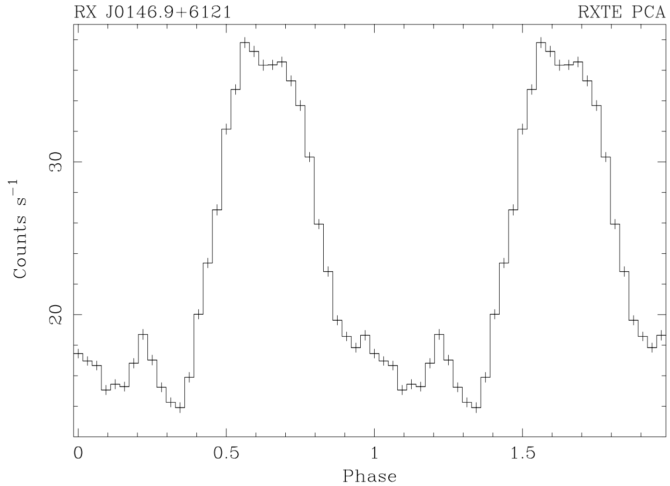

Fig. 3. Pulse profile of RX J0146.9+6121 obtained in the 2 − 20 keV band by folding the light curve with a period of 1404.22 s

A power-law model for RX J0146.9+6121 yields acceptable fits to the spectra of the three observation intervals with reduced χ^2 values of 0.98, 1.20 and 1.36, respectively. The flux in the 0.5 - 10 keV band corrected for collimator efficiency increased from 7.1 10^{-11} erg cm^{-2} s^{-1} to 2.8 10^{-10} erg cm^{-2} s^{-1} within 6 days. Apart from the intensity no variations of the derived spectral parameters within the errors are found, compatible with the insignificant hardness ratio changes. For further spectral investigations the average spectrum of the complete observation was used. The best power-law fit yields a photon index of 2.20 ± 0.07 and photo-electric absorption of the spectrum by a column density of 8.8 ± 0.8 10^{22} H cm^{-2}. The average flux is 2.5 10^{-10} erg cm^{-2} s^{-1}. A fit with a power-law with exponential high energy cutoff improves the χ^2 from 64.6 (56 degrees of freedom; dof) to 54.6 (54 dof) with a cutoff energy of ∼3.8 keV and a folding energy of ∼11.3 keV. This model yields a power-law index of 1.4, more within the range typically observed from Be/X-ray pulsars (Nagase 1989). The best fit model is plotted in Fig. 4 as histogram.

To constrain the cutoff model parameters a combined fit of the ASCA GIS (from Haberl et al. 1998) and RXTE PCA spectra was performed. This extends the covered energy band to 0.8 - 25 keV. Since the RXTE observations do not indicate any change of spectral slope with intensity we assume the photon index to be the same during the two observations with different instruments. The fits for both power-law and cutoff power-law are unacceptable if also the absorbing column density is assumed to be the same and therefore the N_H was allowed to vary independently. A power-law fit then yields χ^2_r of 1.45 while the power-law with high energy cutoff improves the fit to a χ^2_r of 1.10. The best fit model is shown in Fig. 5 and the parameters are summarized in Tab. 1. The comparison of the spectral parameters of the ASCA and RXTE spectra shows that the absorption column density increased considerably between the two observations from a value consistent with interstellar absorption (Motch et al. 1997; Haberl et al. 1998) to nearly 5 10^{22} H cm^{-2}. This indicates a large amount of additional absorbing matter intrinsic to the

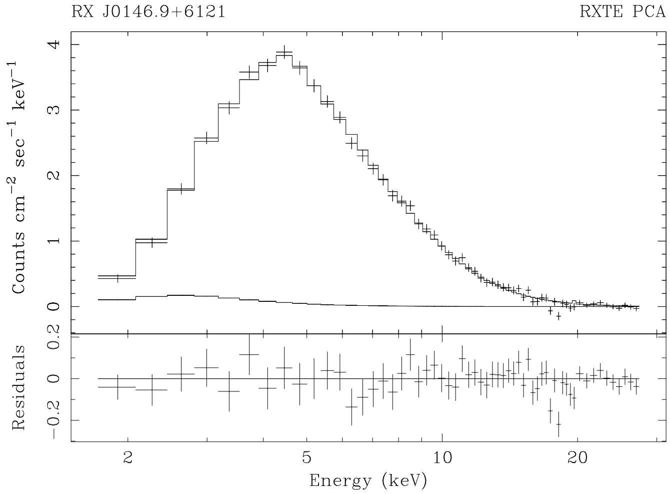

Fig. 4. Average X-ray spectrum over the complete RXTE observation. The best fit power-law model with high-energy cutoff (see text) is plotted as upper histogram and the residuals are shown in the lower panel. The contribution of 4U 0142+61 is indicated by the lower histogram

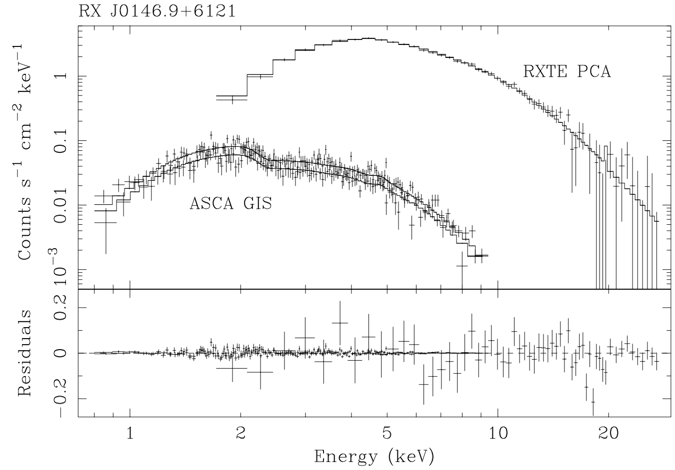

Fig. 5. Simultaneous fit of a power-law with high-energy cutoff model to the ASCA and RXTE spectra of RX J0146.9+6121. The model is plotted as histogram and the residuals are shown in the lower panel

Table 1. Combined spectral fit of a power-law model with high energy cutoff to the ASCA GIS and RXTE PCA spectra.

Parameter	value	confidence$^{(1)}$
Photon index	1.20	0.93 – 1.34
Cutoff energy (keV)	4.0	3.1 – 4.6
Folding energy (keV)	9.1	6.8 – 10.9
N_H ASCA (10^{22} H cm^{-2})	0.78	0.56 – 0.94
N_H RXTE (10^{22} H cm^{-2})	4.9	4.2 – 5.7
χ^2	338	
Degrees of freedom	306	
$F_x{}^{(2)}$ ASCA (10^{-11} erg cm^{-2} s^{-1})	3.7	
$F_x{}^{(2)}$ RXTE (10^{-11} erg cm^{-2} s^{-1})	26.0	
$L_x{}^{(3)}$ ASCA (10^{34} erg s^{-1})	3.41	
$L_x{}^{(3)}$ RXTE (10^{34} erg s^{-1})	34.5	

$^{(1)}$ 90% range, assuming one parameter of interest ($\chi^2 \pm 2.71$)
$^{(2)}$ 0.5 – 10.0 keV
$^{(3)}$ 0.5 – 10.0 keV, distance = 2.5 kpc, corrected for absorption

system in July 1997. The average X-ray luminosity (corrected for absorption) during the July 1997 RXTE observation was a factor of 10 higher than during the ASCA observation in Sept. 1994.

3. Discussion

We observed RX J0146.9+6121 during the begin of a new X-ray outburst, the second since its discovery in 1984. The average X-ray luminosity in the 0.5 – 10 keV energy band was a factor of 10 higher in July 1997 compared to the quiescent level between 1994 and 1996 as observed by ASCA and ROSAT. The latter X-ray observations are presented in Haberl et al. (1998). The analysis of the X-ray spectra reveals a large increase of absorbing column density from very little system-intrinsic absorption (the N_H is consistent with the interstellar absorption of $\sim$7 10^{21} H cm^{-2} derived from the optical, Motch et al. (1997)) during quiescence to more than 4 10^{22} H cm^{-2} during the new outburst. An even higher absorption of $\sim$4 10^{23} H cm^{-2} is indicated by the EXOSAT observation during the first outburst of RX J0146.9+6121 when the highest luminosity was observed. This supports the idea that the X-ray outbursts are powered by enhanced accretion of stellar wind material from the Be star. The decrease in pulse period since the last ASCA and ROSAT observations may indicate that a new accretion disk has formed around the neutron star or that the accretion via a permanent disk has substantially increased, providing angular momentum to spin up the star.

RX J0146.9+6121 shows no dependence of the X-ray spectrum on intensity. This is evident from the RXTE observation when the X-ray luminosity increased by a factor of five and also from the very similar pulse profile in different PCA energy bands between 2 – 20 keV. The ROSAT and ASCA observations of RX J0146.9+6121 during its quiescent state increase the range of pulse-averaged intensity variations to a factor of 10 and cover together energies from 0.1 – 20 keV, but no significant change in the pulse profile was seen. The EXOSAT ME spectrum, although contaminated by 4U 0142+61, further strengthens the case of no spectral variations with X-ray intensity as the derived photon index of 2 for a simple power-law (White et al. 1987) is consistent with the values derived from the later ASCA and RXTE observations.

The constant shape of the X-ray spectrum justifies a combined fit of the ASCA and RXTE spectra revealing an exponential cutoff at 4 keV in the continuum spectrum. This cutoff is already indicated in the RXTE spectrum only, but the spectrum does not extend sufficiently below the cutoff energy to usefully constrain the cutoff parameters. High energy cutoffs are common in the spectra of accreting X-ray pulsars but typically at energies of 10 – 20 keV. It is remarkable that the two X-ray pulsars with the longest spin periods, namely X Persei and RX J0146.9+6121, exhibit the lowest cutoff energies of 2 keV (Schlegel et al. 1993; Haberl 1994) and 4 keV, respectively. If the cutoff energy is an indicator of the magnetic field strength of the neutron star as previously proposed (see the discussion in Haberl et al. 1998) it suggests a factor of 10 lower field strength for X Persei and RX J0146.9+6121 compared to typical X-ray pulsars.

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