Astron. Astrophys. 330, 189–194 (1998)

ASTRONOMY AND ASTROPHYSICS

X-ray observations of the slowest known Be/X-ray pulsars RX J0146.9+6121 and X Persei

F. Haberl[1], **L. Angelini**[2,3], **C. Motch**[4], **and N.E. White**[2]

[1] Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstrasse, D-85748 Garching, Germany
[2] Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[3] University Space Research Association
[4] Universite Louis Pasteur, Observatoire Astronomique de Strasbourg, 11 rue de l'Universite, F-67000 Strasbourg, France

Received 28 July 1997 / Accepted 1 September 1997

Abstract. We present ASCA and ROSAT observations of the Be/X-ray binary pulsars RX J0146.9+6121 and X Persei between 1994 and 1996. Measuring the neutron star spin period and X-ray luminosity of X Persei shows that the episode of low X-ray luminosity and monotonic spin-down since 1978 continued to at least August 1995. ASCA and ROSAT HRI observations of RX J0146.9+6121 detected the pulsar with the longest known neutron star spin period at low luminosities after the X-ray outburst seen by EXOSAT in August 1984. The large spin period decrease seen between 1984 and 1993 has nearly stopped at a period of 1407.3 s in February 1996. We discuss that the X-ray outburst behaviour of X Persei with respect to its Be star phase changes observed in the optical can be caused by an asymmetry in the matter distribution around the Be star.

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

1. Introduction

The low galactic latitude X-ray source RX J0146.9+6121 was discovered by Motch et al. (1991) from the ROSAT all-sky survey and identified with the Be star LS I +61 235 (VES 625). Further infrared and optical observations (Coe et al. 1993, Motch et al. 1997) confirmed the source as member of the Be/X-ray binaries, systems in which a compact object – generally a neutron star – accompanies a Be star in a wide eccentric orbit. After ROSAT PSPC observations in February 1993 revealed the pulse period of 1412 s (Hellier 1994) it was clear that RX J0146.9+6121 was responsible for the 25 min modulation in the X-ray flux seen in EXOSAT observations of the 8 s pulsar 4U 0142+61 (White et al. 1987). RX J0146.9+6121 is located only 24′ away from this Uhuru source, well inside the collimator response of the EXOSAT ME instrument.

Send offprint requests to: F. Haberl (fwh@mpe-garching.mpg.de)

The pulse period of 1412 s seen from RX J0146.9+6121 exceeds the 837 s observed from X Persei. These are far the longest known spin periods from a neutron star in an X-ray binary. X Persei, a O9.5 IIIe star (Slettebak 1982) has long been known as Be/X-ray binary. Recent optical observations revise the spectral classification to B0 V and the distance to 700±300 pc (Lyubimkov et al. 1997, Roche et al. 1997). After an X-ray outburst which peaked in 1975 and lasted probably more than 5 years the source shows an episode with modest X-ray luminosity of a few 10^{34} erg s^{-1} and spin-down with $\dot{P}/P \sim 1.6\ 10^{-4}$ y^{-1} since 1978 (for a review of the optical, IR and X-ray data see Roche et al. 1993) at least until the ROSAT observation in August 1992 reported by Haberl (1994).

In this paper we present new X-ray observations of RX J0146.9+6121 obtained with ASCA and ROSAT between 1990 and 1996 and ROSAT observations of X Persei from February and August 1995. We detected X Persei again at its low-level intensity, further extending the X-ray low-state. The X-ray behaviour of RX J0146.9+6121 suggests large similarities of the two Be/X-ray binary systems.

2. X-ray observations of RX J0146.9+6121

2.1. ASCA

RX J0146.9+6121 was observed in the $1-10$ keV band with ASCA (see Tanaka et al. 1994) on September 18, 1994 from 21:35 UT through 10:00 UT on the following day. The prime target of the observation was the 8 s pulsar 4U 0142+61 (White et al. 1996). The observation was arranged to include both sources in the 40′ field of view (FOV) of the two gas imaging spectrometers, GIS2 and GIS3. RX J0146.9+6121 was located at off-axis angles of ∼17′ and ∼13′ for GIS2 and GIS3, respectively. To avoid telemetry saturation the solid-state imaging spectrometer, SIS, did not include RX J0146.9+6121. The standard data selection filters were applied with a minimum elevation angle of 5 degrees, a cutoff rigidity of 6 GeV/c and rejection of events when the satellite was crossing the South Atlantic Anomaly.

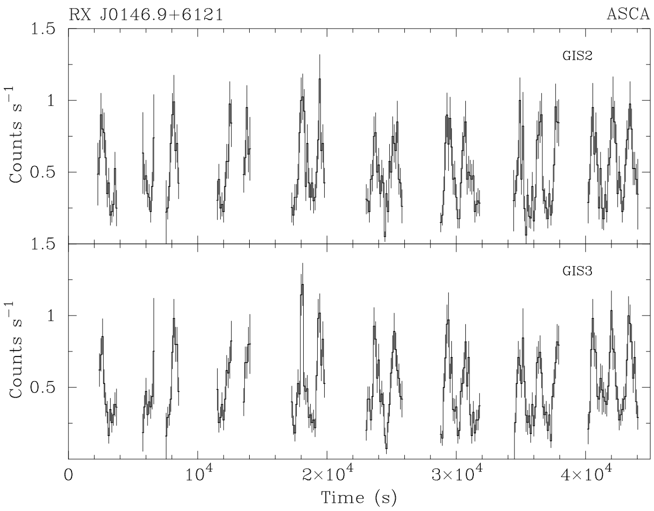

Fig. 1. 0.8 − 10 keV light curves of RX J0146.9+6121 from the ASCA GIS2 and GIS3 detectors starting on Sep. 18, 1994 at 22:18:54 UT. Each point is integrated over 120 s

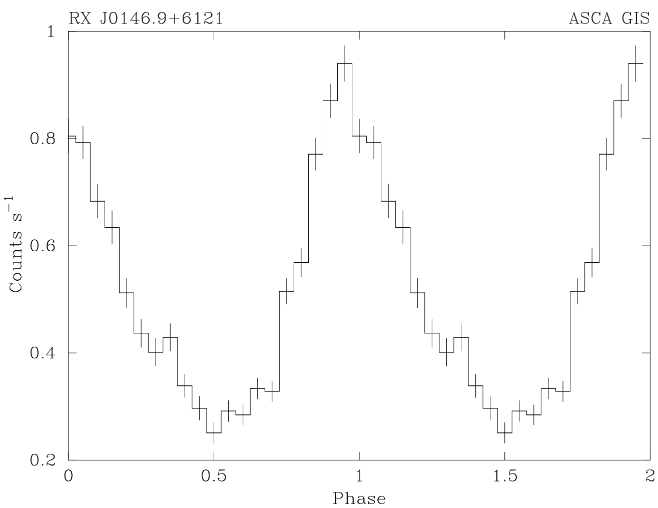

Fig. 2. Pulse profile of RX J0146.9+6121 obtained in the 0.8 − 10 keV energy band by folding the GIS2 and GIS3 combined data with a period of 1407.4 s. Two periods are plotted for clarity versus arbitrary phase

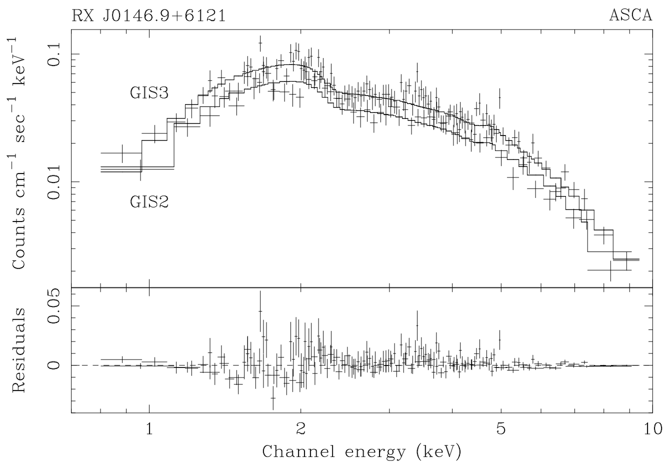

Fig. 3. ASCA GIS2 and GIS3 spectra (upper panel) plotted together with the best fit power-law model as histogram. Residuals are shown in the lower panel

This yields a total exposure of 19839 s and 19855 s for GIS2 and GIS3, respectively. Source events were extracted within a $6'$ radius centered on the source positions and the background estimated from identically sized regions located in a source-free area of the GIS images. The vignetting corrected average count rate in the energy band 0.8 − 10 keV was 0.528 ± 0.012 and 0.510 ± 0.009 counts s^{-1} for GIS2 and GIS3, respectively. Fig. 1 shows the light curves obtained by GIS2 and GIS3 where the $\sim$24 minute pulsations are directly visible. A pulse arrival time analysis was applied as described in White et al. (1996) and a period of 1407.4 ± 3.0 s was derived. The semi-amplitude of the modulation is 66 ± 3% in the 0.8 − 10 keV energy range (Fig. 2) and does not change significantly with energy.

Energy spectra were extracted from the GIS2 and GIS3 data and re-binned to have at least 30 counts in each channel. Power-law, bremsstrahlung and blackbody single-component models including photoelectric absorption were simultaneously fit to the two spectra. The uncertainties in the relative detector efficiencies were accounted for by including and fitting a relative normalization parameter. Acceptable fits with a similar reduced χ^2 of 1.1 were obtained with the power-law model, with a photon index of 1.46 ± 0.08 and absorption of (1.00 ± 0.15) 10^{22} H cm^{-2}, and the bremsstrahlung model, with a temperature of 24^{+12}_{-8} keV and a column density of (0.91 ± 0.1) 10^{22} H cm^{-2}. The blackbody model gives a reduced χ^2 of 1.4 with a column density of 0.0. From optical observations a E(B-V) of 1.09 is derived (Motch et al. 1997) yielding a column density of 6.3 − 7.4 10^{21} H cm^{-2} to RX J0146.9+6121. The power-law and bremsstrahlung model suggest some system intrinsic absorption while the blackbody model can be rejected as unrealistic. Fig. 3 shows the GIS2 and GIS3 spectra and the residuals to the best fit power-law model. No iron line was detected with an upper limit of 90 eV for the equivalent width of a narrow line at 6.4 keV. The flux in the 0.5 − 10 keV band estimated using the power-law model is 3.9 10^{-11} erg cm^{-2} s^{-1}.

Assuming that the spectral shape of RX J0146.9+6121 between the ROSAT PSPC and ASCA observations did not change, we performed a simultaneous fit by allowing only the relative normalisation to vary. The absorbed power-law still gives an acceptable fit with reduced χ^2 of 1.17. The absorption is 8.6 10^{21} H cm^{-2} and the photon index is 1.39. The intensity in the PSPC spectrum is only 3% lower than the average derived for the GIS spectra, which is well within the errors. An absorbed power-law with exponential high-energy cutoff was fit to see if the spectral shape might be similar to that of X Persei measured by BBXRT and ROSAT PSPC (Schlegel et al. 1993, Haberl 1994). Such a model also fits the 0.1 − 10 keV spectrum of RX J0146.9+6121 with a reduced χ^2 of 1.10. Formally the two more free parameters are not required but the model can not be excluded. The best fit yields N_H = 6.0 10^{21} H cm^{-2}, photon

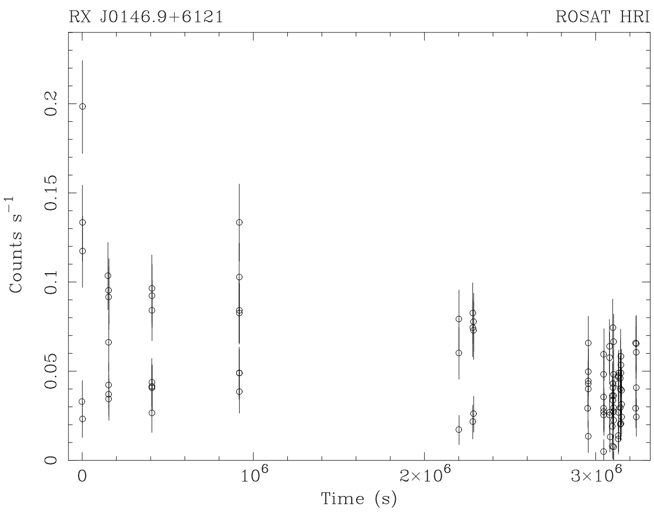

Fig. 4. ROSAT HRI light curve of RX J0146.9+6121 obtained in Jan./Feb. 1996. Each point represents an average over 300 s

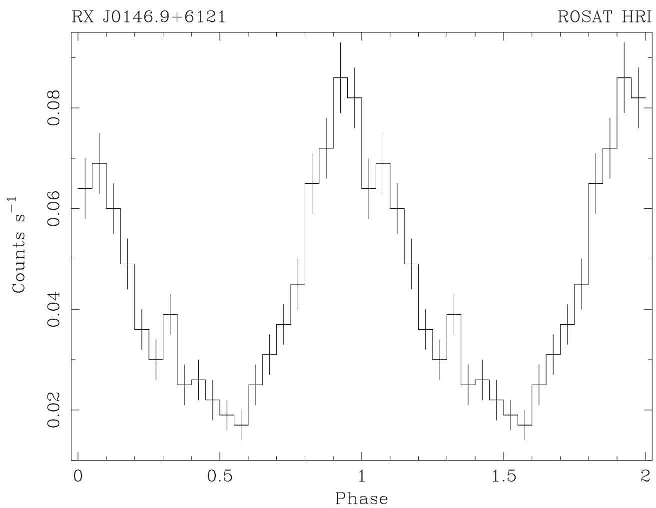

Fig. 5. Pulse profile of RX J0146.9+6121 obtained from the ROSAT HRI observation. The light curve is folded with 1407.28 s and plotted as in Fig. 2

index 0.69, cutoff energy ∼2 keV and folding energy 5.7, all very similar to the parameters found from X Persei.

2.2. ROSAT

RX J0146.9+6121 was observed by ROSAT in the 0.1 − 2.4 keV energy band using the High Resolution Imager (HRI) as focal instrument between January 21 and February 28, 1996. The ROSAT mission is outlined by Trümper (1983) and the HRI is described by David et al. (1993). The total net exposure of 38.7 ksec was distributed unevenly over the 39 days with no observations from February 2−15 and 18−23.

The source was detected in the ROSAT HRI observation with an average count rate of 0.046 ± 0.001 counts s^{-1} and intensity variations between 0.005 and 0.2 counts s^{-1}, mainly caused by the X-ray pulsations. The light curve with a time resolution of 300 s is plotted in Fig. 4. Assuming a power-law spectrum as derived from the PSPC observation (Hellier 1994) the PSPC to HRI count rate conversion factor is 2.9. This reveals an intensity decrease by about a factor of two between the PSPC and HRI observation. This could be caused by an overall intensity decline or also by increased absorption.

A pulse arrival time analysis was applied by splitting the HRI data into nine parts. Due to the long time span of the HRI observation the period can be determined accurately to 1407.28 ± 0.02 s. The folded light curve, shown in Fig. 5, has a semi-amplitude modulation of 62 ± 7% similar to the ROSAT PSPC and the ASCA observation. The pulse profiles obtained from the HRI and the GIS observations are nearly identical and further illustrate the energy independence and no changes with time. Small features on the decline part of the pulse peak are visible in the profiles of both instruments. The energy independence excludes absorption dips as origin and suggests some minor intensity peaks superimposed on the major pulse.

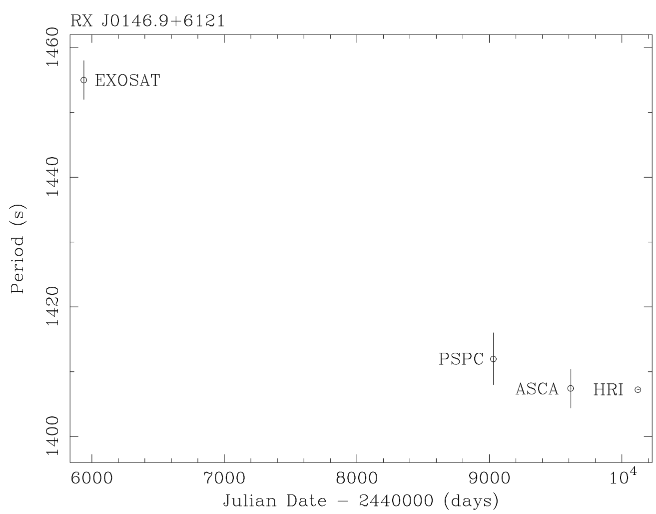

Fig. 6. Pulse period history of RX J0146.9+6121 from August 1984 to February 1996

2.3. History of pulse period and luminosity

The pulse period history of RX J0146.9+6121 between the EXOSAT measurement in August 1984 and the ROSAT HRI point from February 1996 is summarized in Fig. 6. The last two period measurements show that the large average period decrease of 5 s yr^{-1} between 1984 and 1993 has slowed down considerably.

The decrease in the spin-up rate of RX J0146.9+6121 is accompanied by a fading in X-ray luminosity. Re-fitting the ROSAT PSPC spectrum with a power-law with the photon index fixed at the value derived from the ASCA spectrum yields a reduced χ^2 of 1.2. The absorption is $(0.84 \pm 0.07)\ 10^{22}$ H cm^{-2}, somewhat higher than the value derived by Hellier (1994), but consistent with the ASCA value. We therefore adopt the power-law index of 1.46 for the spectrum of RX J0146.9+6121 to calculate 0.5 − 10.0 keV luminosities for comparison of the different

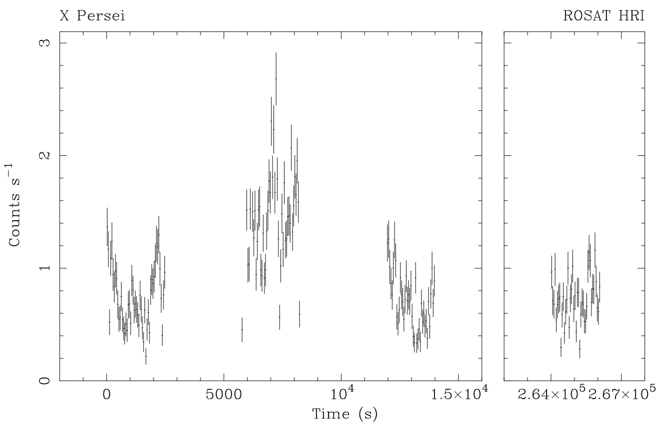

Fig. 7. HRI light curve of X Persei from August 16–20, 1995 with a time binning of 50 s. Note the gap of nearly 3 days between the last two observation intervals

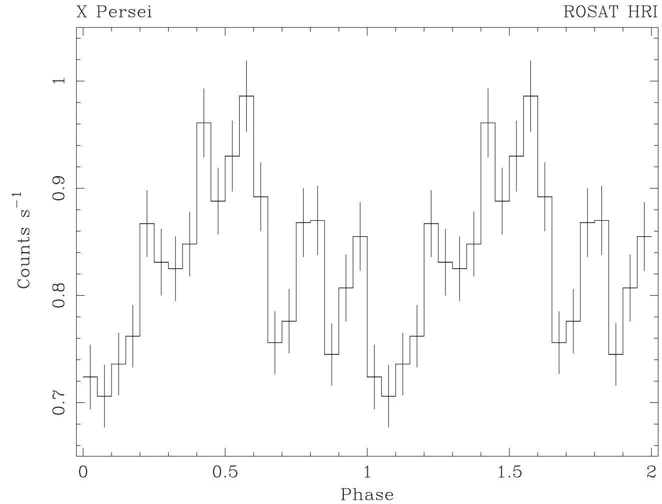

Fig. 8. Pulse profile of X Persei obtained by combining the two HRI observations half a year a part and assuming a constant $\dot{P}$ of 2.4 10^{-9} s^{-1}

observations assuming a distance of 2.5 kpc. This is the distance of the open cluster in which RX J0146.9+6121 is located (Tapia et al. 1991). The luminosities corrected for absorption are 3.4 10^{34} erg s^{-1}, 4.0 10^{34} erg s^{-1} and 1.8 10^{34} erg s^{-1} for the ROSAT PSPC, ASCA and ROSAT HRI observations, respectively. For the HRI observation no spectral change relative to the PSPC observation was assumed.

During the ROSAT all-sky survey RX J0146.9+6121 was scanned for about 3 days around August 1, 1990, 2.5 years before the ROSAT pointed observation. The average count rate during the total net exposure of 539 s was a factor of 1.8 below the count rate seen during the pointed observation (Motch et al. 1997), i.e. at an intensity level comparable to the HRI observation. Again assuming the same spectrum as during the pointed PSPC observation the luminosity was about 1.9 10^{34} erg s^{-1}.

3. ROSAT HRI observations of X Persei

X Persei was re-observed by ROSAT using the HRI as focal plane detector on February 28, 1995 between 05:31 and 10:14 UT for a net exposure time of 7743 s and from August 16, 1995 23:32 UT to August 20, 1995 01:28 UT for 9829 s. The average count rates were 0.84 ± 0.01 counts s^{-1} and 0.85 ± 0.01 counts s^{-1}, respectively. The light curve of the August observation is shown in Fig. 7. The temporal behaviour is similar to the PSPC observation in 1992 (Haberl 1994) with the pulse modulation on top of factor $\sim$2 variations with time scales of around 2 hours. Assuming the power-law spectrum best representing the PSPC spectrum (photon index 0.64 and N_H = 1.4 10^{21} H cm^{-2}), an average HRI count rate of 1.0 counts s^{-1} is expected. The lower observed HRI count rate may be caused by higher absorption as it was e.g. observed during the BBXRT observation (N_H = 2.5 10^{21} H cm^{-2}, Schlegel et al. 1993) or by a lower intrinsic X-ray intensity. Thus, unless the X-ray spectrum has changed dramatically, the X-ray luminosity is in the range 3–4 10^{34} erg s^{-1} (2–10 keV using a distance of 1300 pc for comparison with previous measurements), at the same level X Persei was always detected after its outburst in 1975 (Roche et al. 1993, Haberl 1994).

A timing analysis of the X Persei HRI observations performed in the same way as for RX J0146.9+6121 yields a pulse period of 837.2 ± 0.1 s for the August 1995 observation. The observation from February 1995 was too short and did not cover a long enough base line to constrain the period. The new HRI measurement further continues the spin-down episode of X Persei with $\dot{P}/P \sim 1.5\ 10^{-4}$ y^{-1}.

To improve the statistics of the pulse profile the two HRI observations were combined by assuming a constant $\dot{P}$ value of 2.4 10^{-9} s s^{-1} as it was observed between the PSPC and the second HRI observation. The profile is shown in Fig. 8. Although the statistical quality is still low the profile is consistent with that obtained from the PSPC observation.

4. Discussion

X-ray observations of the 1400 s pulsar RX J0146.9+6121 from ASCA and ROSAT between 1994 and 1996 show the source to be at a low luminosity around 2 10^{34} erg s^{-1} (0.5 – 10 keV, 2.5 kpc). This is a factor of 20 fainter than the outburst luminosity seen by EXOSAT in August 1984. A large decrease in pulse period from 1455 s to 1412 s occured between 1984 and 1993 (Hellier 1994). During the ASCA and ROSAT observations, September 1994 and February 1996, the period was measured to be 1407.4 s and 1407.3 s, respectively. The last X-ray observations suggest that the spin period of the neutron star in RX J0146.9+6121 has reached a relatively constant value of 1407 s for an X-ray luminosity of a few 10^{34} erg s^{-1}. This period is unlikely the Kepler period at the inner accretion disk which is bounded by the neutron stars magnetosphere to be in accretion equilibrium, as it would imply a magnetic field strength of 8 10^{13} G for a standard 1.4 $M_\odot$ neutron star with 10 km radius. This is much higher than magnetic field strength values derived from cyclotron features seen in the X-ray spectra of X-ray pulsars which only in the case of A0535+26 may reach 10^{13} G (Grove et al. 1995). For more typical values of B around 10^{12} G the equilibrium period for a luminosity of 2 10^{34} erg s^{-1} is expected to be around 40 s, far from the observed period.

The monotonic spin-down episode in X Persei indicates that any accretion disk is transitory, only forming during outbursts. Standard accretion disk theory then predicts (e.g. Frank et al. 1992) spin-up as was observed from X Persei during the outburst. The long spin period indicates that the episodes of spin-down dominate the spin period changes and the increased accretion via a disk during rare outbursts does not bring the spin into equilibrium. If a similar scenario is valid for RX J0146.9+6121, the low – still slightly decreasing – X-ray luminosity and the much reduced spin-up observed in the last years suggests that the accretion disk has dissipated and that it may also enter an episode of low X-ray luminosity and spin-down.

Evolutionary considerations suggest that Be – neutron star binary systems are formed from close binaries of massive stars (van den Heuvel 1983). X Persei and RX J0146.9+6121 are probably systems with long orbital periods of the order of several hundreds of days. A 580 day period claimed for X Persei (Hutchings et al. 1974) could however not be confirmed. One such long orbital period system is PSR B1259−63, a 47 ms pulsar in a 1237 day orbit around a Be star. If the neutron stars in X Persei and RX J0146.9+6121 were born with similar short spin period and their present long spin periods are due to spin-down they must be older systems.

The ASCA spectrum of RX J0146.9+6121 is the first measured broad band spectrum (0.8 – 10 keV) without confusion by the close pulsar 4U 0142+61. It is consistent with a power-law with photon index 1.5 which is relatively steep for X-ray pulsars (typical 0.8 – 1.5, Nagase 1989). X Persei, the other long period pulsar, also shows a steep spectrum with a photon index of 0.8 and an exponential cutoff above 2.2 keV. This cutoff-model was suggested by BBXRT data (Schlegel et al. 1993) and the break confirmed by the flatter ROSAT PSPC spectrum in the 0.1 – 2.4 keV range (Haberl 1994). Combining the ROSAT PSPC and the ASCA GIS spectra of RX J0146.9+6121 in a simultaneous model-fit shows that the spectrum can also be represented by a power-law with exponential cutoff as in the case of X Persei. The power-law index, cutoff and folding energy (0.69, 2 keV and 5.7 keV, respectively) are consistent within the errors with those found from X Persei.

It has been suggested that the cutoff seen in the power-law spectra of X-ray pulsars is related to the magnetic field strength of the neutron star. Observed cyclotron line energies E_0 and cutoff energies E_c are correlated with $E_0 \sim 2\,E_c$ (Makishima & Mihara 1992, see also White et al. 1993). This would suggest field strengths of a few 10^{11} G for X Persei and RX J0146.9+6121 (if there is a break in the spectrum), one order of magnitude lower than for typical X-ray pulsars which show cutoff energies of 10 – 20 keV. However, no cyclotron features have been directly seen in the spectra of X Persei and RX J0146.9+6121. At these relatively low magnetic fields strengths the distortion of the spectrum from the neutron star surface will be much reduced, and the spectrum should resemble a blackbody (White et al. 1996). A luminosity dependence of the cutoff energy seen from EXO 2030+375 also indicates that the cutoff energy may not provide a reliable measure of the surface magnetic field strength (Reynolds et al.1993).

RX J0146.9+6121 and X Persei show persistent low-level X-ray flux after their outbursts with little variations. Both sources have similar luminosities in the 2 – 10 keV band (RX J0146.9+6121 $\sim$ 1.2–2.9 10^{34} erg s^{-1}, X Persei $\sim$ 0.7–2.5 10^{34} erg s^{-1}). For RX J0146.9+6121 a distance of 2.5 kpc is used, the distance to the open cluster RX J0146.9+6121 is probably associated with (Tapia et al. 1991). Motch et al. (1997) give 2.9 kpc but Reig et al. (1997) derive a spectral type and luminosity class of B1V, more consistent with 2.5 kpc. We use a revised distance estimate for X Persei of 700 pc (Lyubimkov et al. 1997, Roche et al. 1997). This relatively constant X-ray luminosity needs to be explained in the framework of stellar wind accretion.

X Persei is well observed in the optical and large changes in the morphology of the circum-stellar envelope are indicated. The V-band light curve shows extended faint states and spectroscopic observations revealed a phase transition of the Be star to a normal B star in the last extended low state 1989 to 1993 (Roche et al. 1993, 1997) which indicates the disappearance of the equatorial low-velocity and high-density outflow around the Be star. The X-ray outburst of X Persei in 1975 happened during an optical extended low-state, suggesting that the dissipating circum-stellar matter crossed the neutron star and leading to enhanced accretion. In contrast no similar X-ray outburst was observed during the last extended optical low-state. One possibility may be that the orbital plane is inclined against the equatorial plane of the Be star with the neutron star well outside the equatorial dense outflow during the last phase transition. However UV observations of Be stars indicate a low-density wind at higher latitudes and the derived low mass loss rates of the order of 10^{-9} to 10^{-8} $M_\odot$ y^{-1} and high outflow velocities up to 2000 km s^{-1} can not account for the observed X-ray luminosity of 10^{34} erg s^{-1} (see e.g. Waters et al. 1988). If the neutron star moves in the equatorial plane a radially outward moving dense wind region can only miss the neutron star if it is highly non-axisymmetric. Long term variations in the ratio of the intensity of the violet and red peak of the Balmer emission lines is commonly observed from Be stars, consistent with such an asymmetry in the matter distribution around the star (e.g. γ Cas, Telting & Kaper 1994). In particular the optical counterpart of RX J0146.9+6121 shows that either the violet or the red part of the line can be in absorption (Motch et al. 1997, Reig et al. 1997) indicating that the dense wind outflow responsible for Balmer emission is sometimes located only on one side of the star. The relatively constant X-ray luminosity then suggests that even in the case of a “complete loss” of the dense equatorial stellar envelope as indicated by Balmer lines in absorption, a basic high-density low-velocity outflow is permanently present to power the X-ray source. This picture also suggests that the frequency of X-ray outbursts in wide Be/X-ray binaries is lower than that of Be – B star phase transitions. To prove this, further monitoring of RX J0146.9+6121, X Persei and other low-luminosity

Be/X-ray binaries like those discovered by ROSAT (Motch et al. 1997) is required.

Acknowledgements. The ROSAT project is supported by the German Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF/DARA) and the Max-Planck-Gesellschaft. CM acknowledges support from a CNRS-MPG cooperation contract. NEW thanks the US ASCA Guest Observer facility staff for their assistance in enabling the observation of two pulsars.

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