

Discovery of two new persistent Be/X-ray pulsar systems

Pablo Reig^{1,2} and Paul Roche^{3,4}

¹*Foundation for Research and Technology–Hellas, 711 10 Heraklion, Crete, Greece*

²*Physics Department, University of Crete, 710 03 Heraklion, Crete, Greece*

³*Astronomy Centre, CPES, University of Sussex, BN1 9QJ*

⁴*Department of Physics and Astronomy, University of Leicester, Leicester*

Accepted 1999 January 13. Received 1998 December 17; in original form 1998 September 18

ABSTRACT

We present *RXTE* observations of two recently identified massive X-ray binaries. RX J0440.9+4431/BSD 24–491 and RX J1037.5–564/LS 1698 are confirmed as accreting Be/X-ray systems following the discovery of X-ray pulsations, with barycentric pulse periods of 202.5 ± 0.5 s and 860 ± 2 s respectively. The X-ray spectral analysis shows that the energy spectra of the pulsars can be represented by a power law, modified at low energy by an absorption component and at high energy by a cut-off. Very weak Fe lines may be present. Both sources appear to display a low cut-off energy when compared with typical X-ray pulsars, low X-ray variability (factor of ≤ 10), and no dependence of the X-ray spectrum on energy. Given the similarity of these X-ray properties to those of the other persistent Be X-ray binary pulsars, 4U0352+309/X Per and RX J0146.9+6121/LS I +61 235, we suggest that RX J0440.9+4431/BSD 24–491 and RX J1037.5–564/LS 1698 are also members of this subclass.

Key words: stars: emission-line, Be – pulsars: general – X-rays: stars.

1 INTRODUCTION

Motch et al. (1997) (hereafter M97) reported the discovery of several new high-mass X-ray binaries. These systems were found during the *ROSAT* Galactic plane survey by cross-correlating the position of low-latitude X-ray sources ($|b| < 20^\circ$) with SIMBAD OB star catalogues. The search was restricted to stars earlier than B6 and X-ray luminosities $\geq 10^{31}$ erg s^{−1}. When the X-ray data were combined with optical observations, five sources remained candidates for new accreting binary systems. These sources are BSD 24–491 (RX J0440.9+4431), LS 992 (RX J0812.4–3114), LS 1698 (RX J1037.5–5647, also probably 4U1036–56 according to M97), LS 5039 (RX J1826.2–1450) and LS I +61 235 (RX J0146.9+6121). In this paper we present *RXTE* observations of BSD 24–491 and LS 1698. Hereafter, we will refer to sources by the names of the optical companion.

Be/X-ray binaries (BeXRBs) and supergiant systems represent the general class of high-mass X-ray binaries. These are systems consisting of an early-type star, the exact size forming part of the classification of the system. In addition to the normal stellar component, a compact object is also present in the system, and accretion on to it is the principal source of X-ray emission in the system. Follow-up optical spectroscopic observations carried out by M97 showed H α in emission in both BSD 24–491 and LS 1698, hence classing them as Be stars. The spectral type for both sources is B0V–IIIe (M97).

A Be star is an early-type luminosity class III–V star, which at some time has shown emission in the Balmer series lines. This

emission, as well as the characteristic infrared excess, is attributed to the presence of circumstellar material, most likely forming a disc around the equator of the Be star.

BeXRBs were first identified by the presence of X-ray flares, and so were named X-ray transients. Type I flares were observed to occur regularly, with a fixed period, and it was hypothesized that the systems consist of a neutron star in an eccentric orbit around the Be star. This model predicts that an X-ray flare will be observed at the time of the periastron passage of the neutron star, and this explains the periodicity observed in the timing of the flares. The size of the flare will be dictated by the amount of material available for accretion and by the magnetic field of the neutron star. The flare occurs at periastron when the neutron star impinges on the region of denser circumstellar material surrounding the Be star. BeXRBs also show giant X-ray outbursts (Type II events) in which the X-ray luminosity increases by a factor of 100–1000 above the quiescent level. The X-ray luminosity during the outburst may reach 10^{38} erg s^{−1}, close to the Eddington luminosity. These outbursts do not correlate with the orbital phase, but occur in an unpredictable way and are thought to be related to mass ejections from the circumstellar envelope of the Be star.

It has been proposed that a subclass of BeXRBs exists which is characterized by persistent, weak X-ray emission, and which does not display type I or II outburst behaviour. This subclass is currently represented by X Persei and LS I +61 235 (Haberl et al. 1998a). These systems have relatively low X-ray luminosities ($\sim 10^{34}$ erg s^{−1}) and long spin periods (837 s X Persei and 1412 s

Table 1. Journal of the X-ray observations.

Name of Source	Date	Start time	Stop time	Luminosity ^{a,b} (erg s ⁻¹)	Spin Period (s)	HR ^c
BSD 24–491	30/01/98	06:24:25	11:19:14	3.0×10^{34}	202.5 ± 0.5	-0.56
	01/02/98	05:26:38	11:07:14			
LS 1698	04/02/98	16:25:14	19:49:14	4.5×10^{35}	860 ± 2	-0.40
	05/02/98	08:40:50	09:20:14			
	05/02/98	10:03:38	16:35:14			

^a In the energy range 3–30 keV.^b The assumed distances are (from M97) BSD 24–491: 3.2 kpc, LS 1698: 5.0 kpc.^c HR = [(10 – 30) – (3 – 10)]/(3 – 30).

LS I +61 235). To date, these two represent the only examples of persistent BeXRBs amongst the ~ 40 known BeXRB systems. For a recent summary of the observed properties of BeXRBs, see Negueruela (1998).

2 X-RAY OBSERVATIONS

The sources were observed with the Proportional Counter Array (PCA) on board the *Rossi X-ray Timing Explorer* (RXTE) in 1998 February. Table 1 shows the journal of the X-ray observations. The total on-source time was 25 ks for each target. The PCA covers the lower part of the energy range, 2–60 keV, and consists of five identical co-aligned gas-filled proportional units (PCU), providing a total collecting area of $\sim 6500 \text{ cm}^2$, an energy resolution of < 18 per cent at 6 keV and a maximum time resolution of 1 μs . For a more comprehensive description of the RXTE PCA see Jahoda et al. (1996).

Good time intervals were defined by removing data taken at low Earth elevation angle ($< 8^\circ$) and during times of high particle background. An offset of only $0^\circ.02$ between the source position and the pointing of the satellite was allowed, to ensure that any possible short stretch of slew data at the beginning and/or end of the observation was removed. This screening criterion allowed us to divide the observations up into continuous sections of clean data, on which the X-ray analyses were carried out. The main objective of these observations was to search for pulsations in the X-ray flux in an attempt to confirm the accreting nature of the sources.

3 TIMING ANALYSIS

In this section we present the results of the X-ray timing analysis. For each source, light curves, power density spectra (PDS), pulse profiles and hardness ratios are given and the best value of the spin period determined.

3.1 BSD24–491

Fig. 1 shows an enlarged section of the light curve at three different energy ranges: 3–6, 6–10 and 10–20 keV. Pulsations are clearly seen at the three energy ranges considered and they show up in the power density spectrum (PDS) as a peak at $\approx 0.005 \text{ Hz}$, which corresponds to a spin period of $\sim 200 \text{ s}$. The X-ray intensity of the source, after background subtraction, was $10.7 \pm 0.1 \text{ PCA count s}^{-1}$ in the energy range 3–30 keV. Other than pulsations, no type of variability was seen during the $\sim 6 \text{ h}$ interval of our observation. The extrapolated luminosity between 0.1–2.4 keV is $1.4 \times 10^{33} \text{ erg s}^{-1}$, compared with the maximum value of $6.0 \times 10^{33} \text{ erg s}^{-1}$ given by M97 during a *ROSAT* pointed observation, indicating some long-term variability.

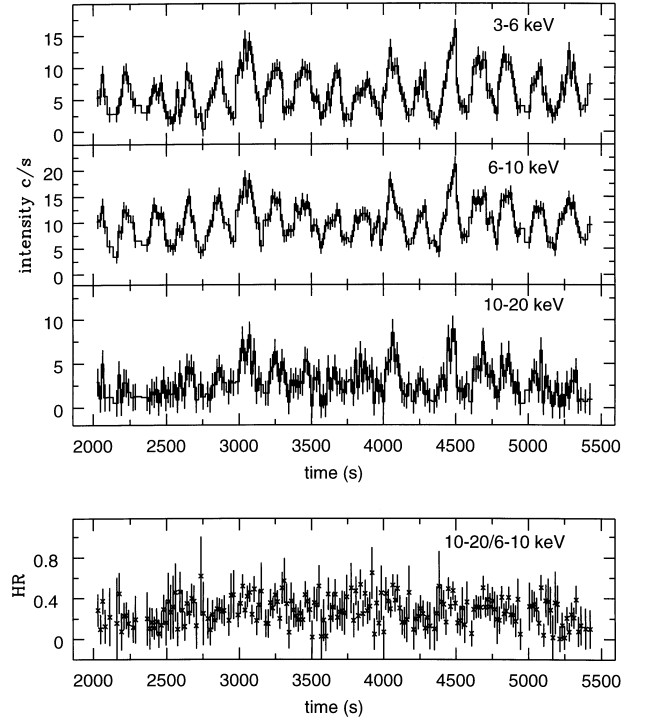


Figure 1. X-ray pulsations in BSD24–491 at three different energies, with each bin representing 16 s. The starting time is JD 245 0843.398. Also shown is the variation of the HR at 10–20/6–10 keV with time.

In fact M97 reported a variation in the count rate of a factor of 2.5 over their observations.

In order to determine the pulsation period, a period search by epoch folding was performed near to the period expected from the fast Fourier transform (FFT) power spectrum. A solar barycentric pulse period of 202 s was obtained from the resulting pulse-folding periodogram. The pulse profile obtained from this period was used as a template. Then both the observations and the template were divided into four roughly equal time intervals. The difference between the actual pulse period at the epoch of observation and the period used to fold the data was determined by cross-correlating the original light curve and the template. The $P_{\text{actual}} - P_{\text{template}}$ shifts were fitted to a linear function to obtain an improved period. A new template was derived for this period and the process repeated. The derived pulse period was $202.5 \pm 0.5 \text{ s}$. The error represents the scatter of the points about the best-fitting straight line. The accuracy in the determination of the spin period is limited by the length of the time series with respect to the length of the period.

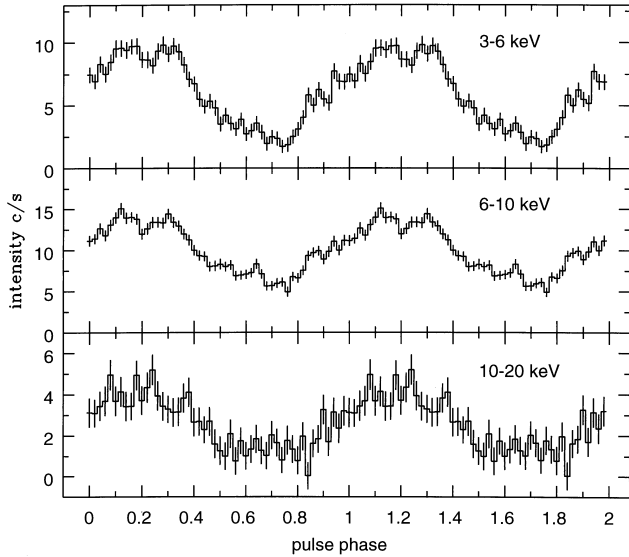


Figure 2. Pulse profiles of BSD 24–491 at three different energy bands.

Once the pulse period is known, the pulse profile can be derived by folding the light curve modulo the best-fitting value of the pulse period. Such a pulse profile is shown in Fig. 2 at the same three energy ranges into which the light curve was separated. No dependence on energy is seen. The pulse shape is nearly sinusoidal, as might be expected from the absence of second or higher harmonics in the PDS. The amplitude of the modulation is ~ 75 per cent in the 3–30 keV energy range.

3.2 LS 1698

M97 reported a maximum X-ray luminosity $L_x(0.1 - 2.4 \text{ keV}) \approx 1.1 \times 10^{34} \text{ erg s}^{-1}$ for LS 1698. The average 3–30 keV *RXTE* PCA count rate, after background subtraction, was $45.8 \pm 0.1 \text{ count s}^{-1}$, without significant changes in intensity. The PDS averaged over two intervals of 3600 s revealed the presence of one peak at $\nu \sim 0.0011 \text{ Hz}$, corresponding to a coherent modulation with a period of $\sim 900 \text{ s}$.

In order to determine the pulse period we rebinned the light curve into 32-s bins spanning a total on-source time of $\sim 23\,500 \text{ s}$ (including gaps caused by Earth occultations or passage through the South Atlantic Anomaly). Times were corrected to the Solar System barycentre, and periodicities searched for in these light curves using the epoch-folding technique. Data were folded over a range of trial periods and the χ^2 of the folded light curve calculated. The period adopted is the one that shows a maximum in the χ^2 versus period diagram. The period providing the highest χ^2 was found to be $860 \pm 2 \text{ s}$. Although the observations do not cover a long enough baseline to further constrain this period, e.g. by applying the cross-correlation method explained above, pulsations are distinctly seen in the X-ray light curve (Fig. 3). Fig. 4 displays the 3–6, 6–10 and 10–20 keV folded lightcurves of LS 1698. These pulse profiles are highly structured with a broad peak covering phases 0.1–0.7. The pulse fraction, $\text{PF} = (I_{\text{max}} - I_{\text{min}})/(I_{\text{max}} + I_{\text{min}})$ is $\sim 53 \pm 2$ per cent and remains the same for the three energy ranges considered. I_{max} and I_{min} are the intensity at pulse peak and pulse dip, respectively.

M97 noted that the source 4U1036–56/3A1036–565 may be the same as RX J1037.5–564/LS 1698, based on the positional coincidence of the *ROSAT* error circle with those of *Uhuru* and *Ariel V*.

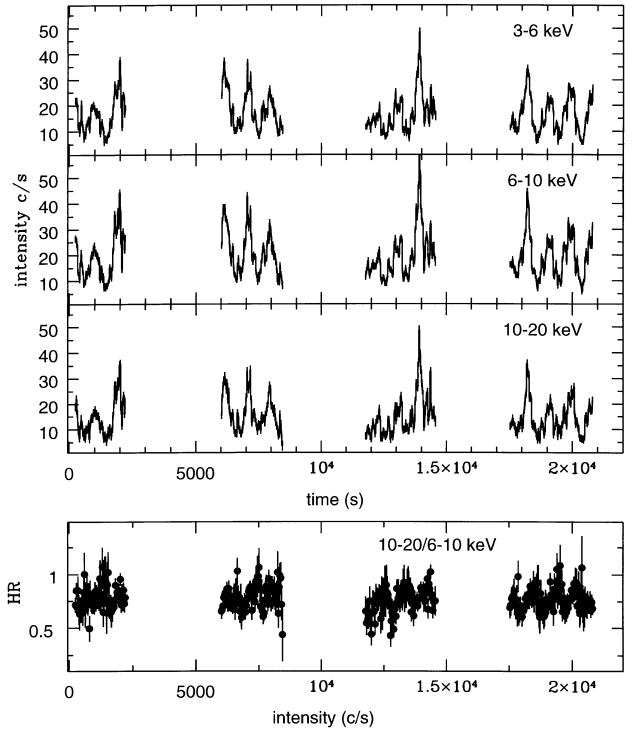


Figure 3. X-ray light curve of LS 1698 showing pulsations at different energy bands. Each bin represents 32 s. Time 0 is JD 245 0849.420. Also shown is the hardness ratio at 10–20/6–10 keV as a function of time. Note that the HR follows the pulses.

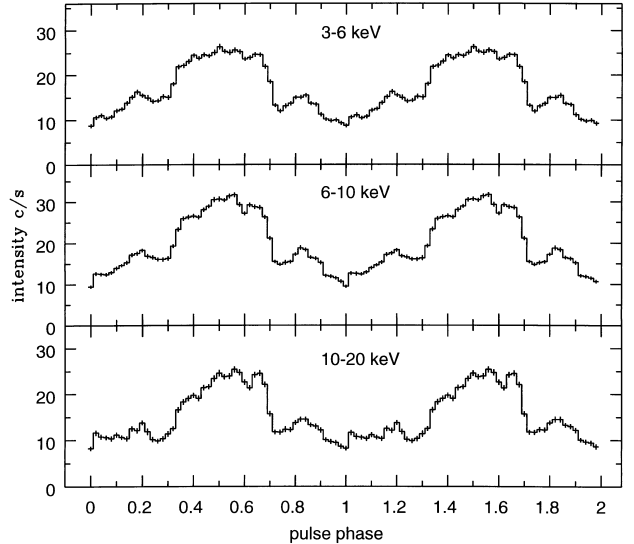


Figure 4. Pulse profiles of LS 1698 at 3–6, 6–10 and 10–20 keV.

However, despite observations with several satellites (*Uhuru*, *Ariel V*, *OSO 7*, *EXOSAT*, *ROSAT*), no pulsations have previously been detected from 4U 1036–56 (although this may simply be attributable to the lower sensitivity of previous observations rather than a real indication that no pulsations are present). The reported detection of a flare in the *Ariel V* observations (Markert et al. 1979) only shows a slight increase ($\times 2.4$) over the *Uhuru* flux in the same energy region (2–10 keV), and the *ROSAT* observations were about an order of magnitude lower than this. The *Uhuru* and *Ariel* luminosities are consistent with those we obtain from our *RXTE*

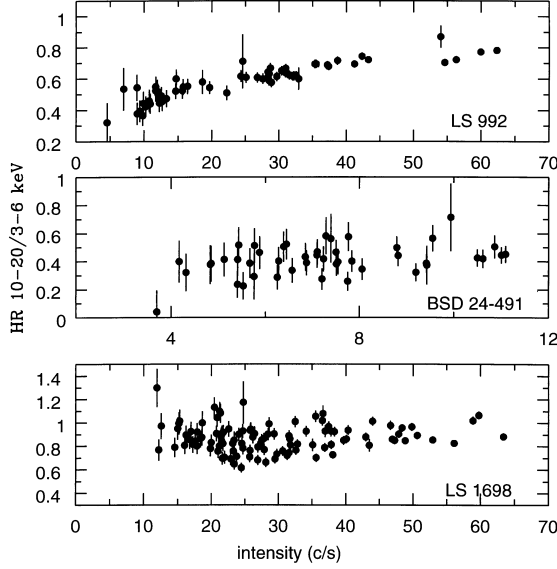


Figure 5. Hardness ratio at 10–20/3–6 keV as a function of intensity of the persistent BeXRBs BSD 24–491 and LS 1698. Shown also for comparison is the HR variation of a transient BeXRB (from Reig & Roche 1999).

observations, $\sim 3 \times 10^{35} \text{ erg s}^{-1}$ compared to our value of $\sim 2 \times 10^{35} \text{ erg s}^{-1}$ (2–10 keV and assuming a distance of $\sim 5 \text{ kpc}$). It would thus appear that 4U1036-56 displays a low level of X-ray variability, which might support the identification with LS 1698, but we cannot confirm this.

3.3 Hardness ratios

LS 1698 is the hardest of the two sources, as indicated by a hardness ratio (HR) of ~ 0.40 , defined as $(10 - 30) - (3 - 10)/(3 - 30)$, compared to ~ 0.56 displayed by BSD 24–491 (see Table 1). This fact also becomes apparent in Fig. 5, which shows the hardness ratios in the photon-energy bands 10–20 and 3–6 keV as a function of the summed count rate of the two bands. It is worth pointing out a few interesting results. First, the HR of BSD 24–491 and LS 1698 remains basically constant at ~ 0.4 and ~ 0.9 respectively. This contrasts with the behaviour of the ‘typical’ BeXRB pulsar system RX J0812–3114/LS992 shown for comparison, where a clear dependence on intensity is seen (Reig & Roche 1999). Secondly, as stated above, the X-ray emission from LS 1698 is much harder than that of BSD 24–491.

4 SPECTRAL ANALYSIS

Although each source adds its peculiarities, the X-ray photon energy spectra of accreting X-ray pulsars share the following general characteristics:

- (i) broad-band emission, not dominated by sharp spectral features;
- (ii) a continuum described in terms of a power law with low-energy absorption and a cut-off above 10–20 keV;
- (iii) X-ray flux mainly emitted in the energy range 2–20 keV with a rapid fall-off above 20 keV;
- (iv) an iron line at $\sim 6.4 \text{ keV}$ resulting from fluorescent reprocessing by cold circumstellar material is present in a number of systems.

Table 2. Spectral fit results. Uncertainties are given at 90 per cent confidence for one parameter of interest. Spectra were fitted in the energy range 3–30 keV for LS 1698 and 3–20 keV for BSD 24–491.

	BSD 24–491	LS 1698
Power law		
α	2.33 ± 0.07	
N_{H} ($10^{22} \text{ atom cm}^{-2}$)	6.2 ± 0.7	
$\chi^2_{\text{r}}(\text{dof})$	1.14(43)	
Power law and blackbody		
α		1.84 ± 0.06
kT (keV)		2.9 ± 0.2
R (km)		0.10 ± 0.01
N_{H} ($10^{22} \text{ atom cm}^{-2}$)		8.2 ± 0.5
$\chi^2_{\text{r}}(\text{dof})$		1.66(54)
Two blackbody		
kT_1 (keV)	1.30 ± 0.06	1.55 ± 0.04
R_1 (km)	0.22 ± 0.01	0.49 ± 0.02
kT_2 (keV)	3.8 ± 0.6	4.48 ± 0.12
R_2 (km)	0.03 ± 0.01	0.085 ± 0.004
N_{H} ($10^{22} \text{ atom cm}^{-2}$)	–	2.1 ± 0.3
$\chi^2_{\text{r}}(\text{dof})$	0.78(43)	1.34(55)
Cut-off power law*		
α	1.5 ± 0.4	$1.20 \pm 0.08[1.02 \pm 0.07]$
E_{cut}	$\sim 1.9[4.5]$	$6.2 \pm 0.4[4.7 \pm 0.4]$
N_{H} ($10^{22} \text{ atom cm}^{-2}$)	$4.1 \pm 1.0[1.9]$	$5.5 \pm 0.5[4.5 \pm 0.4]$
$\chi^2_{\text{r}}(\text{dof})$	0.94(41)[0.56(40)]	1.23(55)[0.98(53)]

* The values in [] represent the best-fitting parameters when an iron line is included. For BSD 24–491, $E_{\text{cut}} = 6.2 \pm 0.2 \text{ keV}$ with fixed $\sigma = 0.1 \text{ keV}$, whereas for LS 1698 $E_{\text{cut}} = 6.5 \pm 0.2 \text{ keV}$ and $\sigma \approx 0.2 \text{ keV}$.

In order to investigate the X-ray energy emission of our sources, fits using a variety of models were performed. Table 2 gives the results of the spectral analysis. We have included only the values of the models which gave acceptable fits, i.e. reduced $\chi^2 \leq 2$.

4.1 BSD 24–491

The analysis of the X-ray spectrum of BSD 24–491 is complicated by the low count rate. To improve the signal-to-noise ratio we used only data from the top layer anodes of the four PCUs that were on during the entire observation. Also, models were fitted to the energy range 3–20 keV instead of the 3–30 keV used for LS 1698. In spite of this, the errors are too large to distinguish meaningfully between the different spectral models listed in Table 2. An F -test shows that the inclusion of a blackbody component to the power-law model is not justified by the reduction of the χ^2 . For the purpose of the subsequent discussion, and in order to compare spectral parameters with the other sources, we will consider only the results from the power law plus cut-off model. An emission feature at around 6.2 keV shows up in the residuals (Fig. 6) but the fit does not allow us to constrain its parameters precisely. We set an upper limit for the equivalent width of the iron line of $\sim 100 \text{ eV}$. The line centre remained at the same value of $6.2 \pm 0.2 \text{ keV}$ despite fixing the linewidth to $\sigma \sim 0.1, 0.2$ and 0.3 keV , indicating that the linewidth is narrower than the spectral resolution of the PCA (18 per cent at 6 keV). BSD 24–491 also shows a very low cut-off energy of $\sim 1.9 \text{ keV}$. This value is outside the detector response range and is thus not well constrained. However, if the iron line is included in the fit the

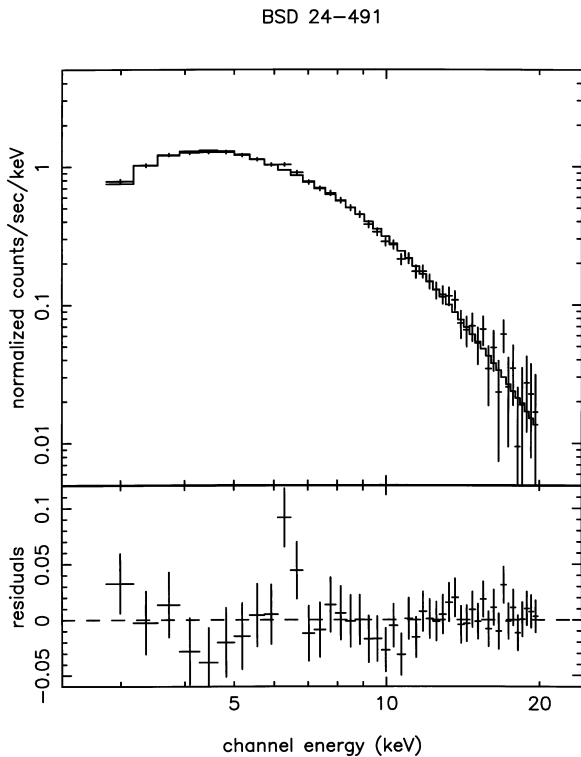


Figure 6. PCA spectrum of BSD 24–491. The continuum was fit to a power law plus a high-energy cut-off. If no gaussian component is added to the fit, an emission feature at ≈ 6.2 keV shows up in the residuals.

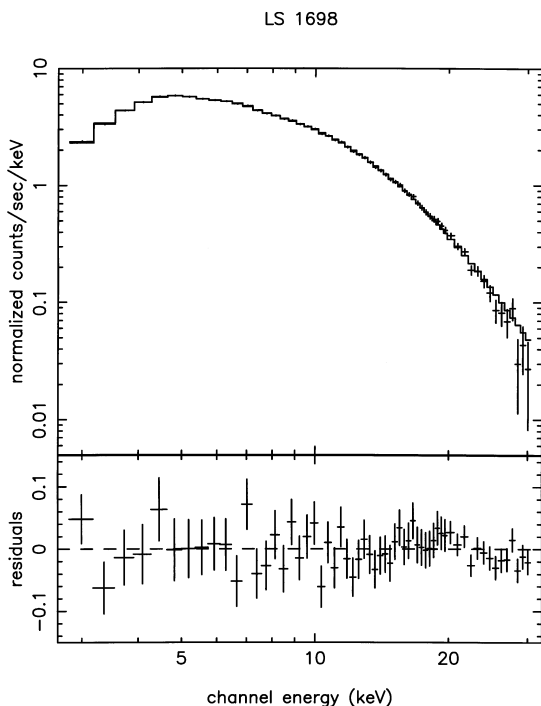


Figure 7. PCA spectrum of LS 1698 and residuals. The best-fitting power law with high-energy cut-off is plotted as a straight line.

cut-off energy increases to ~ 4.5 keV. In the energy range 3–30 keV, $L_X \sim 3.0 \times 10^{34}$ erg s $^{-1}$, assuming a distance of 3.2 kpc.

4.2 LS 1698

The best fit to the X-ray spectrum of LS 1698 is obtained using the power law plus high-energy cut-off model ($\chi_r^2 = 1.23$ for 55 d.o.f.; Fig. 7). The inclusion of a gaussian component, representing an iron line, improved the fitting by reducing χ_r^2 to 1.00 for 52 dof. However, an F -test shows that the probability of this happening by chance is higher than 10 per cent. The best-fitting line centre energy and width are 6.5 ± 0.2 keV and $\sigma \sim 0.2$ respectively. If the gaussian component is taken into account, the cut-off energy is 4.7 keV, much lower than the values of 10–20 keV typically found in X-ray pulsars. This may represent a signature of persistent BeXRB systems (see Discussion). An upper limit for the equivalent width of the iron line is estimated to be ~ 65 eV. The photon index lies in the interval $\alpha = 1.0$ –1.2 depending on whether the iron line is included in the fit or not. LS 1698 has $E(B - V) \approx 0.75$ (M97), implying $N_H \sim 0.5 \times 10^{22}$ cm $^{-2}$ (Ryter, Ceasarsky & Audouze 1975). However, the absorption implied from the spectral fitting is much higher, $\sim 5 \times 10^{22}$ cm $^{-2}$. Thus, some amount of matter must be located close to the system, which would justify the presence of the iron line. The X-ray luminosity is $\sim 4.5 \times 10^{35}$ erg s $^{-1}$ in the energy range 3–30 keV and assuming a distance of 5 kpc.

5 DISCUSSION

Pulsations have previously been found in both high- and low-mass X-ray binaries. However, of the 38 X-ray pulsars currently known, only five have been identified as low-mass XRBs, whereas 33 have an OB-type star as the optical counterpart. For the confirmed BeXRB systems, around 70 per cent are found to be pulsators, rising to 75 per cent if suspected BeXRBs are included.

The periods of X-ray pulsars are distributed over a factor of $\sim 10^5$, from 2.5 ms (SAX J1808–369, the bursting millisecond X-ray pulsar) to 1412 s (LS I +61 235, a persistent BeXRB), with no evidence for clustering at any particular period. The range for BeXRBs is almost as extensive, the shortest being 69 ms (A 0535–668).

We have carried out X-ray timing and spectral analysis of two of the four newly discovered high mass X-ray binaries found by M97. We have detected pulsations in both BSD 24–491 (period 202.5 s) and LS 1698 (~ 860 s). In addition to slow pulsars, LS 1698 and BSD 24–491 seem to share further similarities in their X-ray variability characteristics. They have both been detected every time that they have been observed [during the *ROSAT* All-Sky Survey and subsequent follow-up pointed observations using *ROSAT* (M97) and here with *RXTE*] and they do not appear to show short-term variability (of time-scales of hours or days).

5.1 Is there a class of persistent Be/X-ray binaries?

Until recently, X Per/4U0352+309 was unique among massive X-ray binary systems in that it was the only persistent BeXRB. The optical component is a B0Ve star at a distance of ~ 700 pc (Lyubimkov et al. 1997). Persistent high-mass X-ray binaries do exist but they harbour an evolved, i.e. supergiant, companion. In these systems the X-rays are attributed to constant accretion from the strong stellar wind of the primary.

Table 3. Comparison of the X-ray properties of persistent and transient BeXRBs.

X-ray name	Optical type	Spectral period (s)	Spin index	Spectral (keV)	$E_{\text{cut}} \times 10^{36}$	$L_{\text{X,max}}^b$	variability ^c	X-ray (eV)	EW (Fe)
4U0352+309	X Per	B0Ve	837	0.8	2.2		0.03	5	≤ 100
RX J0146.9+6121	LS I +61 235	B1Ve	1404	1.2	4.0		0.5	20	≤ 90
RX J1037.5–5647	LS 1698	B0V–IIIe	860	1.0	4.7		0.5	20	≤ 65
RX J0440.9+4431	BSD 24–491	B0V–IIIe	202	1.3	4.5		0.03	6	≤ 100
EXO 2030+375		Be	41.7	1.3–1.8 ^a	5–19 ^a	100		1000	200
4U0115+63	V635 Cas	O9e	3.6	0.4	7.5	30		200	110

^a Dependent on luminosity; higher values correspond to higher luminosity.

^b Energy range 1–20 keV except that of LS I +61 235 which is 0.5–10 keV.

^c $L_{\text{X,max}}/L_{\text{X,min}}$.

In the case of X Per, the weak but persistent emission is most likely a result of the fact that the neutron star is *always* a long way from the Be star and never enters the denser inner regions of the circumstellar disc. An orbital period of 580 d has been proposed (Hutchings et al. 1974), but not subsequently confirmed by later studies. However, there appear to be characteristic time-scales of photometric variability ranging from hundreds to thousands of days (Roche et al. 1997), but nothing that appears to be orbital in nature. In most respects, X Per behaves like a classical Be star, presumably because the separation of the components means that the B0V star and its disc are unaffected by the distant neutron star. The neutron star can be affected by episodes of mass ejection from the circumstellar disc (e.g. Roche et al. 1993, 1997), but is usually only accreting from the Be star wind.

Recently, Haberl et al. (1998a) and Haberl, Angelini & Motch (1998b) have suggested that LS I +61 235/RX J0146.9+6121 may be another persistent BeXRB. This source is the pulsar with the longest spin period (~ 1400 s). With two such systems one can look for more similarities in an attempt to establish the existence of a distinct subclass of BeXRBs. Comparing the X-ray observational characteristics of X Per and LS I +61 235, we find that they both share the following properties:

- (i) long pulse periods, 837 s for X Per and 1404 s for LS I +61 235;
- (ii) persistent, low-luminosity ($\leq 10^{34-35}$ erg s⁻¹) X-ray emission;
- (iii) low cut-off energy derived from the spectral fitting, compared with the typical value of 10–20 keV found in transient X-ray pulsars – 2 keV for X Per (Schlegel et al. 1993) and 4 keV for LS I +61 235 (Haberl, Angelini & Motch 1998);
- (iv) absent or very weak iron line at 6.4 keV, indicative of only small amounts of material in the vicinity of the neutron star;
- (v) low X-ray variability: flat light curves with rare and unpredictable increases in flux by a factor of ≤ 10 ;
- (vi) no dependence of the X-ray spectrum on intensity.

If we use these characteristics as defining a subclass of BeXRBs, we find that the newly discovered systems LS 1698 and BSD 24–491 are also potential members. Both have been detected every time they have been observed, indicating persistent X-ray emission, and their X-ray flux is relatively low compared with that of other accreting pulsars when they are active. Furthermore, both have long spin periods (~ 860 s for LS 1698, ~ 202.5 s for BSD 24–491) and low cut-off energies of 6.2 (4.7) and 1.9 (4.5) keV respectively – the values in brackets are obtained when an iron line is included in the fit, but this is not statistically required, again as in

the cases of X Per and LS I +61 235. We have also shown in Section 3.3 that the HRs did not change significantly throughout the observations, indicating that the X-ray spectrum is insensitive to changes in the count rate. This absence of spectral changes with intensity was also seen in LS I +61 235 by Haberl et al. (1998b). In contrast, transient BeXRBs show, in general, a positive correlation between HR and intensity, as seen in LS 992 (Reig & Roche 1999) or EXO 2030+375 (Reig & Coe 1998). It is worth noting that displaying just one of these characteristics is not enough to qualify a system as a member of the group, but the combination is suggestive of a real association. For example, the X-ray spectrum of LS 992 also presents a low cut-off energy (4.7 keV), but it does not share any of the other X-ray properties (Reig & Roche 1999). The X-ray properties of persistent and transient BeXRBs are compared in Table 3.

It therefore seems that we now have a growing subclass of BeXRBs, characterized by persistent, low-luminosity X-ray emission and slowly rotating pulsars. A possible model for these systems is that of a neutron star orbiting a Be star in a relatively wide orbit, accreting material from only the low-density outer regions of the circumstellar envelope. Sporadic ejection of the disc itself, however, will result in the ejected material and the neutron star interacting, producing a flare in the X-ray light curve. The increase in flux during these flares is typically less than a factor of ~ 10 (Roche et al. 1993), although further work needs to be done on characterizing the range of X-ray variabilities observed in the whole range of BeXRBs. Note that the expelled material can reach the neutron star at any orbital phase (not necessarily at periastron) and that flares need not be periodic. Thus, the combination of little material being accreted plus slow rotation plus possibly a relatively weak magnetic field makes these systems weak but persistent pulsing sources.

Owing to the low accretion rate outside these rare events (e.g. X Per has undergone only 2 observed periods of flaring activity in almost 30 yr, both associated with disc loss events, Roche et al. 1997; LS I +61 235 only two flares in 13 yr, Haberl et al. 1998b), the neutron star may not be spinning at the equilibrium period, and will thus not follow the relationship predicted from the Corbet diagram of P_{spin} versus P_{orbit} (Corbet 1986; Waters & van Kerkwijk 1989). However, a long orbital period is expected, to account for the presumed distance of the neutron star from the envelope.

Of these persistent systems, only X Per has been the subject of detailed, long-term study. In this case, whilst many of the physical characteristics of the system have been elucidated [e.g. disc parameters by Telting et al. (1998), photometric and polarimetric behaviour of the disc by Roche et al. (1997), etc.], there are still

doubts about basic parameters such as the orbital period. None of the proposed members of this subclass has an orbital period determination, and so their position on the Corbet diagram cannot be ascertained. Future work should therefore focus on a search for orbital variations in these two objects.

6 CONCLUSIONS

We have discovered two new Be/X-ray pulsars which appear to display X-ray characteristics in common with the proposed subclass of persistent BeXRBs currently consisting of X Per and LS I +61 235. If the association of LS 1698 and BD 24–491 with these other objects is correct, the sample of persistent BeXRBs has doubled, and further observations of all these sources is encouraged to study the properties of this subclass. Currently, only X Per has been studied extensively for any duration, but the existence of similar systems provides us with probes of the behaviour of neutron stars in low-density accretion regimes. A possible model for these systems is that of a neutron star orbiting a Be star in a relatively wide orbit, accreting material from only the low-density outer regions of the circumstellar envelope. Small increases in X-ray luminosity (e.g. of the order of 10 times the quiescent flux) may result from mass ejection episodes where the neutron star is temporarily in a region of increased matter density.

ACKNOWLEDGMENTS

P. Reig acknowledges support via the European Union Training and Mobility of Researchers Network Grant ERBFMRX/CP98/0195.

We thank I. Negueruela, D. Beckham, B. Scouza and V. Adams for useful discussions. We are grateful to the anonymous referee for helpful comments.

REFERENCES

- Corbet R. H. D., 1986, *MNRAS*, 220, 1047
 Haberl F., Angelini L., Motch C., White N. E., 1998a, *A&A*, 330, 189
 Haberl F., Angelini L., Motch C., 1998b, *A&A*, 335, 587
 Hutchings J. B., Cowley A. P., Crampton D., Redman R. O., 1974, *ApJ*, 191, L101
 Jahoda K., Swank J. H., Giles A. B., Stark M. J., Strohmayer T., Zhang W., Morgan E. H., 1996, in Siegmund O. H. W., Gumm M. A., eds, *Proc. SPIE 2808, EUV, X-ray and Gamma-ray Instrumentation for Space Astronomy VII*. SPIE, Bellingham, p. 59
 Lyubimkov L. S., Rostopchin S. I., Roche P., Tarasov A. E., 1997, *MNRAS*, 286, 549
 Markert T. H. et al., 1979, *ApJS*, 39, 573
 Motch C., Haberl F., Dennerl K., Pakull M., Janot-Pacheco E., 1997, *A&A*, 323, 853 (M97)
 Negueruela I., 1998, *A&A*, 338, 505
 Reig P., Coe M. J., 1998, *MNRAS*, 294, 118
 Reig P., Roche P., 1999, *MNRAS*, in press
 Roche P. et al., 1993, *A&A*, 270, 122
 Roche P. et al., 1997, *A&A*, 322, 139
 Ryter C., Ceasarsky C. J., Audouze J., 1975, *ApJ*, 198, 103
 Schlegel E. M. et al., 1993, *ApJ*, 407, 744
 Telting J. H. et al., 1998, *MNRAS*, 296, 785
 Waters L. B. F. M., van Kerkwijk M. H., 1989, *A&A*, 223, 196

This paper has been typeset from a $\text{T}_{\text{E}}\text{X}/\text{L}^{\text{A}}\text{T}_{\text{E}}\text{X}$ file prepared by the author.