Discovery of X-ray pulsations in the Be/X-ray binary LS 992/RX J0812.4–3114

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ABSTRACT

We report on the discovery of X-ray pulsations from the Be/X-ray system LS 992/RX J0812.4–3114 during an RXTE observation. From a timing analysis of the source we obtained a barycentric pulse period of 31.8851±0.0004 s. The pulse profile is highly structured and departs from a pure sinusoidal shape. It shows a sharp dip that may indicate absorption by the accretion flow. The energy spectrum from 3-30 keV can be fitted by a power-law model with an exponential cut-off in accordance with other X-ray pulsars. The X-ray luminosity is estimated to be $\sim 1.1 \times 10^{36}$ erg s$^{-1}$ in the energy range 3-30 keV, assuming a distance of $\sim 9$ kpc.

Key words: stars: emission-line, Be - stars: X-rays: stars - stars: pulsars - stars: individual - LS992

1 INTRODUCTION

The X-ray source RX J0812.4–3114 was discovered by Motch et al. (1997) 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 maximum X-ray luminosity in the energy range 0.1-2.4 keV was reported to be $1.3 \times 10^{35}$ erg s$^{-1}$, with some evidence for short-term (hours) variability. Follow-up optical observations confirmed the identification of source with the star LS 992. The optical spectra revealed a B0-III-V companion, showing H$\alpha$ in emission (M97). Optical photometry of LS 992 by Reed (1990) gives V=12.4, B–V=0.41 and U–B=–0.69. This gives a reddening free Q parameter of –0.99, implying a spectral class of B0 or earlier (Halbedel 1993). These data are all consistent with the source being a new Be/X-ray binary.

Be/X-ray binaries (BeXRBs) consist of a neutron star orbiting a Be companion. Accretion onto the compact star is the principal source of X-ray emission in the system. 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. The X-ray emission is characterised by the presence of flares interspersed with inactivity periods, in which this high energy emission lies below the threshold of the detectors. When the flares are modulated with the orbital period, the increase in flux is typically a factor $\leq 10$. Sometimes a giant and unpredictable X-ray outburst takes place with an increase in flux of 100-1000 above quiescent level. Thus BeXRBs are also termed massive X-ray transients (see Negueruela 1998 for a recent review of BeXRBs).

1.1 X-ray observations

LS 992/RX J0812.4–3114 was observed with the Proportional Counter Array (PCA) onboard the Rossi X-ray Timing Explorer (RXTE) on 1998 February 1 and 3. The total on-source time was 25 ks. The PCA covers the lower part of the energy range, 2-60 keV, and consists of five identical coaligned gas-filled proportional units (PCU), providing a total collecting area of $\sim 6500$ cm$^2$, an energy resolution of $< 18$ % at 6 keV and a maximum time resolution of 1µs. 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 0.02$^\circ$ 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. These screening criteria allowed us to divide the observations
2 TIMING ANALYSIS

The X-ray lightcurves at 3-10 and 10-20 keV of LS 992/RX J0812.4-3114 are shown in Fig. 1, together with the time variability of the hardness ratio 10-20/3-10 keV. The mean PCA count rate in the energy range 3-30 keV is, after background subtraction, $\sim 37$ s$^{-1}$. A FFT was applied to each of two series of 8192 data points accumulated with a time resolution of 0.366 s, and the result averaged to produce the power density spectrum (PDS) of Fig. 2. A modulation at 0.031 Hz and several of its harmonics are clearly seen. In order to measure the pulsation period, an epoch folding search was performed near to the period expected from the FFT power spectrum. A solar barycentric pulse period of 31.9 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 5 roughly equal time intervals of 676 s each ($\sim 21$ cycles). 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 31.8851 ± 0.0004 s. The error represents the scatter of the points about the best-fit straight line.

LS 992/RX J0812.4–3114 shows significant variability on timescales of a few hours, with variations in the amplitude of almost an order of magnitude (see Fig. 3) which cannot be attributed to the pulsations. Motch et al. (1997) reported a decline in X-ray flux for this source of a factor $\sim 100$ between the ROSAT survey observations and the follow-up pointed observations over a year later. This amplitude of variation is typical of BeXRBs.

Fig. 2 also shows the hardness ratio in the photon-energy bands 10-20 and 3-6 keV as a function of the summed count rate of the two bands. A positive correlation is observed, the spectrum becoming harder with increasing intensity, the hardness ratio increasing from 0.3 at $\sim 5$ s$^{-1}$ to 0.8 at $\sim 60$ s$^{-1}$, behaviour typical of X-ray pulsar systems in general.

The pulse profiles folded with the best-fit period are shown in Fig. 4 for the 3-6 keV, 6-10 keV and 10-20 keV energy bands. The three pulse profiles clearly do not resemble sinusoidal curves, as expected from the presence of the harmonics in the PDS. They consist of a broad and irregular peak divided into two halves by a sharp absorption feature. The strength of this dip decreases with increasing energy. The peak appears to be flatter at low energies.

The pulse fraction, which we have defined here as $PF = (I_{\text{max}} - I_{\text{min}})/(I_{\text{max}} + I_{\text{min}})$, decreases as we progress into higher energies: $\sim 70\%$, $51\%$ and $47\%$ for the low, middle and high energy intervals. $I_{\text{max}}$ and $I_{\text{min}}$ are the counts per second at pulse peak and pulse dip.

3 SPECTRAL ANALYSIS

In order to investigate the X-ray energy emission of LS 992/RX J0812.4–3114, fits using a variety of models were performed. Table 1 gives the results of the spectral analysis when the entire observation is considered. The power-law plus high-energy cut-off model gave the lowest reduced $\chi^2$ ($\chi^2 = 1.00$ for 56 dof) for a cut-off energy of 4.9±0.4 keV. The best-fit value of the photon index $\alpha$ is 1.0±0.1 and low-energy absorption, $N_H$, equivalent to $\sim 0.5\pm 0.3 \times 10^{22}$ cm$^{-2}$ is required (see Fig. 5). This value is consistent (Ryter, Ceasarsky & Audouze 1975) with a colour excess of...
Figure 3. Upper panels: Lightcurve of LS 992/RX J0812.4–3114 covering the entire observation. Significant variability is seen on timescales of hours. Time 0 is JD 2,450,845.546 and the bin size is 300 s. The scale of the Y-axis in the upper panel has been kept the same as the lower panel to allow direct comparison. Lower panel Hardness ratio as a function of intensity.

Figure 4. Pulse profiles of LS 992/RX J0812.4–3114 at 3-6, 6-10 and 10-20 keV. Note the sharp absorption feature at relative pulse phase \( \sim 0.95 \).

Figure 5. PCA spectrum of LS 992/RX J0812.4–3114. The straight line represents the best-model fit, a power-law plus exponential cut-off. The residuals are shown in the lower panel.

\[ E(B-V)=0.70 \] (Motch et al. 1997) and indicates that the absorption is entirely due to the interstellar medium and that very little circumstellar matter exists. This fact would then explain the lack of an iron line.

Since the HR varied significantly throughout the observation, indicating some spectral changes with X-ray intensity, we divided the observation up into two different intervals and a spectrum for each interval was obtained. The difference in the mean 3-30 keV luminosity between the intervals is a factor \( \sim 3.5 \). Whilst the value of \( \alpha \) remained constant at 1.0, the cut-off and absorption showed a slightly higher value at higher count rate, varying from \( 4.5 \pm 0.4 \) keV and \( 0.2 \times 10^{22} \) cm\(^{-2}\) at \( L_x \sim 4.7 \times 10^{35} \) erg s\(^{-1}\), to \( 5.5 \pm 0.5 \) keV and \( 0.8 \times 10^{22} \) cm\(^{-2}\) at \( L_x \sim 1.6 \times 10^{36} \) erg s\(^{-1}\). The higher \( N_H \) at higher luminosities supports the idea that the flare is due to enhanced accretion from the stellar wind/disc of the Be star.

The observed cut-off energy is lower than the typical value found in other X-ray pulsars. However, Reynolds, Parmar & White (1993) showed a correlation between the cut-off energy and the X-ray luminosity in the BeXRB EXO 2030+375, with \( E_{\text{cut}} \sim 4.7 \) keV for a \( L_x \sim 1.2 \times 10^{36} \) erg s\(^{-1}\). Therefore the value of 4.9 keV may be a consequence of the low luminosity observed in LS 992/RX J0812.4–3114. The X-ray luminosity is \( \sim 1.1 \times 10^{36} \) erg s\(^{-1}\) in the energy range 3-30 keV assuming a distance of \( \sim 9 \) kpc. The two blackbody component model may be disregarded as unrealistic, since it gives a hydrogen column density of 0.0 cm\(^{-2}\), whereas the power-law plus blackbody component model gives a radius for the emitting area much lower than the minimum accepted radius of the polar caps of \( \sim 1 \) km.
Table 1. Spectral fits results. Uncertainties are 90% confidence. The spectrum was fitted in the energy range 2.7-30 keV.

| parameters                        | value          |
|-----------------------------------|----------------|
| Power-law & blackbody             |                |
| $N_H$ ($10^{22}$ atoms cm$^{-2}$) | 3.4±0.5        |
| $\alpha$                          | 1.96±0.08      |
| $kT$ (keV)                        | 2.7±0.2        |
| $R$ (km)                          | 0.21±0.02      |
| $\chi^2$ (dof)                    | 1.59(56)       |
| Two blackbody                     |                |
| $kT_1$ (keV)                      | 1.27±0.03      |
| $R_1$ (km)                        | 1.08±0.03      |
| $kT_2$ (keV)                      | 3.57±0.09      |
| $R_2$ (km)                        | 0.20±0.01      |
| $N_H$ ($10^{22}$ atoms cm$^{-2}$) |                |
| $\chi^2$ (dof)                    | 1.53(57)       |
| Cut-off power-law                 |                |
| $N_H$ ($10^{22}$ atoms cm$^{-2}$) | 0.5±0.3        |
| $\alpha$                          | 1.0±0.1        |
| $E_{cut}$ (keV)                   | 4.9±0.4        |
| $E_{fold}$ (keV)                  | 11.6±1.3       |
| $\chi^2$ (dof)                    | 1.00(56)       |

Table 2. Spectral parameters as a function of the pulse phase. Uncertainties are 90% confidence. The photon index was fixed to $\alpha = 1.04$

| phase | Flux$^a$ (3-20 keV) | $N_H^b$ | $E_{cut}$ (keV) | $E_{fold}$ (keV) | $\chi^2$ (dof) |
|-------|---------------------|---------|----------------|-----------------|----------------|
| 0.1   | 1.8                 | 0.7±0.3 | 5.4±0.4        | 14.9±0.8        | 1.16(44)       |
| 0.3   | 1.2                 | 0.8±0.4 | 5.6±0.5        | 11.2±0.6        | 1.19(44)       |
| 0.5   | 1.4                 | 1.2±0.3 | 6.0±0.4        | 13.0±1.0        | 1.08(44)       |
| 0.7   | 1.0                 | 0.5±0.4 | 5.6±0.5        | 13.3±1.0        | 0.97(44)       |
| 0.9   | 1.3                 | 0.6±0.3 | 5.2±0.4        | 15.0±1.0        | 1.02(44)       |

$^a$ in units of $10^{-10}$ erg cm$^{-2}$ s$^{-1}$

$^b$ in units of $10^{22}$ cm$^{-2}$

4 PULSE PHASE-RESOLVED SPECTROSCOPY

In order to investigate the pulse phase dependence, 5 phase-resolved energy spectra were produced, and each fitted with the power-law plus cut-off energy model used in Sect. 3. To improve the signal to noise ratio we used data only from the top layer anode from the detectors. We also restricted the energy interval to 2.7-20 keV.

Initially, in order to secure enough counts we considered the entire observation. However, it was not possible to simultaneously constrain the power-law index $\alpha$, the cut-off energy $E_{cut}$ and the absorption column $N_H$. This inconsistency in the data may be attributed to the variation of the X-ray intensity observed throughout the observation. That is, the spectral parameters during the “flare” event (middle panel of Fig 3) show different values to those obtained during the “quiescent” state (upper panel of Fig 3), except the photon index which remained fairly constant. Consequently, the results presented in Table 2 and Fig 6 correspond to the second interval only (“flare” event).

In spite of the complex pulse profile, no correlation could be found between the X-ray flux in the energy range 3-20 keV and the absorption column and cut-off energy. Nevertheless, these two parameters do vary with pulse phase, as can be seen in Fig 6.

5 DISCUSSION

Pulsations have previously been found in both high and low mass X-ray binaries. However, of the $\sim$65 X-ray pulsars currently known, only 5 have been identified as LMXRBs, whereas $\sim$60 have an OB-type star as the optical counterpart. For the confirmed BeXRB systems, around 70% are found to be pulsators, rising to 75-80% if suspected BeXRBs are included. The periods of X-ray pulsars are distributed over a factor $\sim 10^5$, 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 fastest being 69 ms (A 0535–668).

LS 992/RX J0812.4–3114 appears to be a typical transient BeXRB. This source was active during the ROSAT survey observations reported by Motch et al. (1997), but those authors failed to detect the source during a pointed ROSAT PSPC observation in 1992 November 20, indicating that the X-ray emission decreased by about a factor of $\sim 100$. During the RXTE observation, however, we obtained an extrapolated X-ray luminosity in the energy range covered by ROSAT (0.1-2.4 keV) of $9.1 \times 10^{34}$ erg s$^{-1}$, similar to the maximum reported by Motch et al. (1997), $1.3 \times 10^{35}$ erg s$^{-1}$. In the energy range 3-30 keV LS 992/RXJ0812.4–3114...
displayed an X-ray luminosity of $1.1 \times 10^{36}$ erg s$^{-1}$ for an assumed distance of $\sim 9$ kpc.

In addition to this long-term variability, LS 992/RX J0812.4–3114 also shows changes in the X-ray intensity on short time scales. Fig. 3 displays the lightcurve of the entire observation, where X-ray intensity variations of one order of magnitude are seen on a time scale of a few hours. LS 992/RX J0812.4–3114 was found to be one of the brightest and hardest new BeXRB candidates in the ROSAT all-sky survey (0.1-2.4 keV) (Motch et al. 1997).

The sharp minimum that appears in the pulse profiles may be interpreted as absorption by the accretion flow. Cemeljić & Bulik (1998) have shown that X-rays produced near the surface of the neutron star may be eclipsed at a certain phase due to the passage of the accretion flow through the line of sight as the compact star rotates. The greater penetration of harder X-rays would explain the decrease in the strength of the peak with energy.

At first glance, the low absorption column $N_H = 0.5 \times 10^{22}$ cm$^{-2}$ and the classification of the system as a relatively bright V=12.4 Be star may seem not to agree with a distance of 9 kpc. However, we note that the location of LS 992/RX J0812.4–3114 (l=249.6, b=1.55) within Puppis shows a remarkable lack of interstellar reddening (Lucke 1978). Wilson & FitzGerald (1972) studied the distribution of OB stars and color excesses in the region of Puppis (l=245) and find very low excesses even out to 5 or 6 kpc. The observed $E(B-V)=0.70$ and $m_v=12.4$ suggests an absolute magnitude $M_v\sim -4.6$ for a distance of 9 kpc, consistent with an O9.5V star (e.g. Deutschman, Davis & Schild 1976, Wegner 1994). Therefore, a distance of 9 kpc is not unreasonable for the assumed Be star identification.

6 CONCLUSION

We have carried out X-ray timing and spectral analyses of the newly discovered high mass X-ray binary LS 992/RX J0812.4–3114. The timing analysis has resulted in the detection of pulsations with a barycentric spin period of 31.8851 $\pm$ 0.0004 s. Like many other X-ray pulsars the energy spectrum is well represented by a power-law component, modified at energies above a high energy cut-off $E_{\text{cut}}$ by an exponential function with folding energy $E_{\text{fold}}$ and at low energies by photoelectric absorption due to intervening cold matter of density $N_H \sim 0.5 \times 10^{22}$ cm$^{-2}$. No iron line at $\sim 6.4$ keV is required. Thus LS 992/RX J0812.4–3114 appears to be a typical transient BeXRB, with an expected orbital period in the region of tens of days according to the Corbet diagram (Corbet 1986).

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REFERENCES

Cemeljić M., Bulik T., 1998, Acta Astronomica, 48, 65.
Corbet R.H.D., 1986, MNRAS, 220, 1047.

Deutschman W.A., Davis R.J. & Schild R.E., 1976, ApJS, 30, 97.
Halbedel E.M., 1993, PASP, 105, 465.
Jahoda K., Swank J.H., Stark M.J., Strohmayer T., Zhang W., Morgan E.H., 1996 EUV, X-ray and Gamma-ray Instrumentation for Space Astronomy VII, O.H.W. Siegmund & M.A. Gummin eds., SPIE 2808, 59, 1996.

Lucke, P.B., 1978, A&A, 64, 367.

Motch C., Haberl F., Dennerl K., Pakull M., Janot-Pacheco E., 1997, A&A, 323, 853.

Negueruela I., 1998, A&A in press.

Reed B.C., 1990, AJ, 100, 737.

Reynolds A.P., Parmar A.N., White N.E., 1993, ApJ, 414, 302.

Ryter C., Ceasarsky C.J., Audouze J., 1975, ApJ, 198, 103.

Wegner W., 1994, MNRAS, 270, 229.

Wilson W.J.F., FitzGerald M.P., 1972, Roy. Astron. Soc. Canada 66, 254.

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