Observations of the ultra-compact binary RX J1914+24

Gavin Ramsay¹, Pasi Hakala², Kinwah Wu¹, Mark Cropper¹, K. O. Mason¹
F. A. Córdova³, W. Priedhorsky⁴

¹Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey, RH5 6NT, UK
²Observatory, University of Helsinki, PO Box 14, FIN-00014 University of Helsinki, Finland
³University of California, Riverside, CA 92521, USA
⁴Los Alamos National Laboratory, MS D436, Los Alamos, NM 87545, USA

15 September 2018

ABSTRACT

We present XMM-Newton observations of the 569 sec period system RX J1914+24 (V407 Vul). This period is believed to represent the binary orbital period making it an ultra-compact binary system. By comparing the phase of the rise to maximum X-ray flux at various epochs (this includes observations made using ROSAT, ASCA and Chandra) we find that the system is spinning up at a rate of 3.17 ± 0.07 × 10⁻¹² s/s. We find that the spectra soften as the X-ray flux declines towards the off-phase of the 569 sec period. Further, the spectra are best fitted by an absorbed blackbody component together with a broad emission feature around 0.59keV. This emission feature is most prominent at the peak of the on-phase. We speculate on its origin.

Key words: Stars: individual: – RX J1914+24 – Stars: binaries – Stars: cataclysmic variables – X-rays: stars

1 INTRODUCTION

RX J1914+24 (also known as V407 Vul) is one of 3 sources discovered in recent years which show intensity variations on periods of less than ~10 mins. As no other periods have been detected in these systems, and for other reasons, these periods have been associated with the binary orbital period. As such, these systems would have the shortest binary period of any known system. In addition, they would be amongst the strongest sources of constant gravitational radiation in the sky and easily detectable using the future LISA space mission. Their nature, however, remains controversial.

Of the 3 systems, ES Cet (Warner & Woudt 2002), with a period of 620 sec, has been shown to have an accretion disc. Both RX J1914+24 (Cropper et al 1998, Ramsay et al 2000, 2002) with a period of 569 sec, and RX J0806+15 (Ramsay, Hakala & Cropper 2002, Israel et al 2002) with a period of 321 sec, do not show evidence for an accretion disc and share many similar properties. Their X-ray light curves are almost identical, being ‘off’ for around half their cycle, showing a sharp rise to maximum flux and a more gradual decay. In contrast, their optical light curves are sinusoidal in shape, and in anti-phase with the X-ray phase (Ramsay et al 2000, Israel et al 2003). The period of both systems are reported to be evolving in the same direction (ie spinning up) as predicted if their binary orbit is evolving through gravitational radiation (Hakala et al 2003, Strohmayer 2003, Hakala, Ramsay & Byckling 2004 for RX J0806+15 and Strohmayer 2002, 2004a for RX J1914+24).

They do, however, differ in some respects. RX J0806+24 shows weak optical emission lines, with Hydrogen blending with Helium lines (Israel et al 2002, Norton, Haswell & Wynn 2004). On the other hand RX J1914+24 shows a generally featureless optical spectrum but with weak absorption lines which appear similar to that of a K star (Steeghs et al 2004). At present it is unclear as to how to interpret this spectrum, although a triple system is a possibility.

RX J1914+24 has been observed in X-rays using ROSAT, ASCA (Cropper et al 1998, Ramsay et al 2000, 2002) and Chandra (Strohmayer 2004a). With its larger effective area, XMM-Newton provides the possibility of obtaining phase resolved spectroscopy through the 569 sec cycle. Here, we present observations of RX J1914+24 made using XMM-Newton.

2 OBSERVATIONS AND DATA REDUCTION

XMM-Newton was launched in Dec 1999 by the European Space Agency. The EPIC instruments contain imaging detectors covering the energy range 0.15–10keV with moder-
Table 1. The observation log of XMM-Newton observations of RX J1914+24. The start time is in UTC.

| XMM Orbit | Start Date   | Duration (ksec) | Mean EPIC pn (Ct/s) |
|-----------|--------------|-----------------|---------------------|
| 0718      | 2003-11-09:22:36:10 | 9.5  | 0.80  |
| 0721      | 2003-11-15:22:08:26  | 8.5  | 0.73  |

The EPIC pn detector was configured in small window mode and thin filter, the EPIC MOS1 detector in timing mode and thin filter, and the EPIC MOS2 detector in small window mode and medium filter. The Optical Monitor used two UV filters (UVW2 and UVM2). Because of the high extinction to RX J1914+24 (Cropper et al 1998), RX J1914+24 was not detected, as expected, in either filter.

The X-ray data were processed using the XMM-Newton Science Analysis Software (SAS) v6.0. The data were barycentrically corrected and in units of TT. For the EPIC detectors (Strüder et al 2001, Turner et al 2001), data were extracted using an aperture of 40′′ centered on the source position: this ∼87 percent of the encircled energy. Background data were extracted from a source free region. The background data were scaled and subtracted from the source data. We show the mean background subtracted EPIC pn count rate for the two observations in Table 1. We extracted the RGS spectra in the standard way using rgsproc. Although they were of low signal-to-noise no bright distinct lines were detected.

3 LIGHT CURVES

We show the folded and binned light curve in 3 energy bands in Figure 1. As found by previous X-ray studies, the system is ‘off’ for ∼0.4 cycles. We extracted images of the field of RX J1914+24 during the faint phase using the EPIC pn data and do not detect RX J1914+24. After the off-phase, there is a sharp increase in flux in the 0.15–0.5keV (soft) and 0.5–1.0keV (medium) bands. The softness curve (soft/medium), (Figure 1), shows that the spectrum of RX J1914+24 softens towards the descent from the peak intensity of the bright phase. This implies that the X-ray emission region has a temperature structure. We also show the 1–2keV (hard) folded light curve in Figure 1: the count rate is much reduced compared to the soft or medium bands. It shows a pronounced drop in intensity at the point where the softness curve starts to soften.

Ramsay et al (2000) showed using ASCA data that RX J1914+24 has no significant flux above 2keV. With the higher effective area of XMM-Newton compared to ASCA we can test this assertion more rigorously. We extracted images of the immediate field around RX J1914+24 using data from the EPIC pn detector taken at both epochs. There is no significant detection above 2.0keV in either epoch. To determine an upper limit to the hard X-ray emission we added a Bremsstrahlung component to the model described in §5.

For a temperature of $kT = 10$keV we find an upper limit to the 2–10keV unabsorbed flux of $1.3 \times 10^{-13}$ ergs s$^{-1}$ cm$^{-2}$, which reduces to $9.6 \times 10^{-15}$ ergs s$^{-1}$ cm$^{-2}$ for $kT = 1$keV.

We searched for periods above 20 min using all the ROSAT, ASCA, Chandra and XMM-Newton data, and just the XMM-Newton separately. We found no evidence for a significant period(s) in either combination of data. (Care has to be taken since the ROSAT data are in units of UTC; ASCA is on a system very close to UTC, while Chandra and XMM-Newton data are on TT).

4 PHASING OF THE DATA

Strohmayer (2002) performed a coherent timing analysis of ROSAT and ASCA data and found that the 569 sec period in RX J1914+24 was spinning up at a rate of $8.3 \pm 1.8 \times 10^{-10}$ Hz/s (=2.6×10$^{-12}$ s/s). This was later refined with the addition of Chandra data to $7.0 \pm 0.8 \times 10^{-10}$ Hz/s (=2.3×10$^{-12}$ s/s, Strohmayer 2004a). This result was consistent with the expected spin up rate if the systems was being driven entirely by gravitational radiation and the secondary star has a low mass.

The spin-up in both RX J0806+15 and RX J1914+24 has been met with some degree of scepticism (eg Woudt
& Warner 2003). To show the effect of the spin-up in RX J1914+24 we show in Figure 2 the ROSAT, ASCA, Chandra (which were extracted from the Chandra archive and reduced in the same manner as Strohmayer 2004a) and XMM-Newton data folded on the constant period term (1/νo) of Strohmayer (2004a). The phase of the rise to maximum flux has continued to arrive progressively earlier since the epoch of the Chandra data: it is clear that RX J1914+24 is spinning up. It is highly unlikely that the true period is a side-band power peak Strohmayer (2004a).

For the phased light curves shown in Figure 2 we estimated the start of the bright phase by noting the phase at which the count rate rose by a significant level compared to the previous phase bin. We show how the start of the bright phase varies over time in Figure 3 together with an estimate of the uncertainty in the phase. We fitted these points with a constant P term: the best fit is shown as a solid line in Figure 2. We note that the shift in phase for a constant P term is not linear over time (see Cropper et al 2004). We find a spin-up rate of 3.17±0.10 × 10−12 s/s (=1.0×10−17 Hz/s). Because the errors on the phase of the rise to the bright phase are not strictly 1σ errors, we determined the error using a bootstrap method. This gave a larger error than the formal error to the fit (0.07×10−12 s/s). The spin-up rate which we determine is slightly greater than the spin-up rate derived by Strohmayer (2004a).

We also show the long term X-ray intensity of RX J1914+24 in the lower panel of Figure 3. These values were obtained by converting the peak X-ray count rate in each epoch to the equivalent ROSAT HRI count rate (since most observations were determined using this instrument). We used the spectral parameters shown Table 2 and the PIMMS tool (Mukai 1993) to convert the count rate in other detectors to that expected for the ROSAT HRI. We note that the largest residual to the fit occurred after the peak X-ray flux had decreased from a short epoch of enhanced X-ray emission. However, the deviation is small, (1.9σ), so therefore probably not significant.

Ramsay et al (2000) showed that the peak of the X-ray and optical band emission were offset in phase. Since their ASCA and I band data were taken within 3 months of each other, this phase offset is still valid despite the spin-up of the system.

5 SPECTRA

To fully utilise the data from the two observations (cf Table 1), we combined the EPIC pn event files from the two epochs (we also did this for EPIC MOS2). We used single and double events for the pn spectrum, and single to quadruple events for the MOS spectrum, and those events with FLAG=0. We created response and auxiliary files using the SAS tasks arfgen and rmfgen. The spectra are shown in Figure 4. Ramsay et al (2000) fitted X-ray spectra taken using ROSAT and ASCA using an absorbed blackbody model. We used XSPEC (Arnaud 1996) to fit the spectra, binned them so there was a minimum of 50 counts per min and we applied a low energy cut-off of 0.25keV. The XMM-Newton spectra are not well fitted using such a model. Various other models were fitted including: an absorbed two temperature blackbody model; a thermal plasma model with varying element

Table 2. The best fit spectral parameters to the integrated EPIC pn spectrum. Fluxo refers to the observed flux in the 0.1–10keV energy band and Fluxu refers to the unabsorbed, bolometric flux.

| Parameter       | Value          |
|-----------------|----------------|
| N_H             | 4.2±0.1 × 10^{21} cm^{-2} |
| kT_bb           | 58.6±0.9 eV    |
| line center     | 0.58±0.004keV  |
| EW              | 257±0.9 eV     |
| Flux_o          | 1.35±0.04 × 10^{-12} ergs s^{-1} cm^{-2} |
| Flux_u          | 3.18±0.16 × 10^{-10} ergs s^{-1} cm^{-2} |

abundances; the previous model together with a blackbody; and an emission model together with a line in absorption around 0.55keV. The only model which even approached a reasonable fit (χ^2=1.63, 79 dof in EPIC pn) was an absorbed blackbody plus broad Gaussian line in emission at 0.59 keV: this was an unexpected result (the fit to the EPIC MOS2 spectra was poorer giving χ^2=2.20, 29 dof – the response of the MOS cameras has changed over time, especially at energies <0.5keV). The spectral parameters for the integrated EPIC pn spectrum together with the flux is shown in Table 2. Spectra were also extracted from both RGS instruments: no distinct strong individual lines were detected with any confidence.
Figure 3. Top panel: The phase of the sharp rise to maximum X-ray flux determined for all the epochs shown in Figure 2 determined using a constant period, $P_0$. The solid line shows the best fit to the data giving a spin-up rate of $3.17 \times 10^{-12}$ s/s. Lower Panel: The X-ray intensity of the peak of the bright phase expressed in equivalent ROSAT HRI Ct/s. The start date is JD=2449259. We show the error on the phase of the sharp rise, while the error on the X-ray intensity is smaller than the plotted symbol.

Figure 4. The integrated EPIC pn spectrum together with the best fit absorbed blackbody plus Gaussian line. We ignored events with energies below 0.3keV and above 1keV and binned the spectrum so that there was a minimum of 50 counts per min.

There are still significant residuals in the fit to the integrated spectrum using the absorbed blackbody plus line model. This is not unexpected since the softness ratio variation (Figure 1) suggests that the shape of the spectrum changes over the bright X-ray phase. We therefore extracted four spectra covering the bright phase from the EPIC pn data. Again our model was an absorbed blackbody plus Gaussian line in emission near 0.59keV. The spectral parameters for each spectrum were tied together apart from the normalisations which were allowed to vary. A simultaneous fit to the four spectra gave $\chi^2=1.45$ (170 dof): the fit was not improved by letting the blackbody temperature vary. We find that the normalisation of both the blackbody and line components roughly follow the shape of the X-ray light curve, although the normalisation of the blackbody falls more rapidly compared to that of the Gaussian after intensity maximum resulting in a rise in the equivalent width. Although the Gaussian line may not be physically realistic, it does, however, provide a suitable way of characterising the spectra. To show the effect of the Gaussian line, we show in Figure 6 the fits to phase resolved spectra including the line and then when we switch the line normalisation to zero: the line has a very significant effect on the fits.

In light of these results, we revisited the ROSAT PSPC integrated spectrum and used the above model to fit that spectrum (extracted from the public archive in 'Rev2' calibrated form). We tied the normalisation of the blackbody and Gaussian components so that they were the same ratio as found in the integrated XMM-Newton fits. We find that this model gives a better fit ($\chi^2=1.18$ 6dof) compared to an absorbed blackbody ($\chi^2=1.58$ 6dof). We note that the resulting fit give a lower absorption column ($N_H = 1.7 \times 10^{21}$ cm$^{-2}$) and higher blackbody temperature ($kT_{bb}=78$eV) compared to the fits of Cropper et al (1998). Ramsay & Cropper (2004) have noted that ROSAT observations of
The non-accreting model is the Unipolar-Inductor (UI) model proposed by Wu et al. (2002). In this model, a non-magnetic white dwarf traverses the magnetic field of the primary white dwarf, which causes large currents to be driven. Resistive dissipation occurs at the foot-points of the primary white dwarf and X-rays are released. This model also predicts that the system is an electron-cyclotron maser source in the UI phase (Willes, Wu & Kuncic 2004).

It is important to note that these systems have been observed for less than 10 years and therefore the period decrease may simply be due to a slow variation rather than a long term trend.

In spite of the complicated interaction between the stellar spin rates and the binary orbital period, the change in the binary orbital period is determined only by the energy and angular momentum losses and redistribution in the system.

We illustrate this using the UI model given in Wu et al (2002). For a binary with a secondary star in synchronous rotation with the orbit, it can be shown that the change in the orbital angular velocity \( \omega_o \) is given by

\[
g(\omega_o) \left( \frac{\dot{\omega}_o}{\omega_o} \right) + \frac{2}{5} M_1 R_1^2 \omega_1 \dot{\omega}_1 = E_{gr} + E_{diss},
\]

where \( E_{gr} \) is the energy loss due to gravitational radiation, \( E_{diss} \) is the energy loss due to dissipation, and \( \omega_1 \) is the angular velocity of the primary (see Wu et al. (2002) for the explicit expression of \( g(\omega_o) \)).

In the UI model, the energy dissipation is caused by the resistive heating at the foot-points of the magnetic field lines on the magnetic white dwarf. In terms of the asynchronicity parameter of the spin of the primary, \( \alpha \equiv \omega_1 / \omega_o \), the energy dissipation

\[
E_{diss} = - \frac{2}{5} \left[ (1 - \alpha) M_1 R_1^2 \omega_1 \dot{\omega}_1 \right].
\]

It can be shown that

\[
\left( \frac{\dot{\omega}_o}{\omega_o} \right) = \frac{1}{g(\omega_o)} \left[ \hat{E}_{gr} + \frac{2}{5} \alpha M_1 R_1^2 \omega_1^2 \left( \frac{\dot{\omega}_1}{\omega_1} \right) \right].
\]

As \( \left( \omega_1 / \omega_o \right) = \left( \omega_o / \omega_1 \right) + (\dot{\alpha} / \alpha) \), the rate of change in the orbital angular velocity may be expressed as

\[
\left( \frac{\omega_0}{\omega_1} \right) = \frac{\hat{E}_{gr}}{g(\omega_o)} \left[ 1 + \frac{2}{5} \alpha M_1 R_1^2 \omega_1^2 \left( \frac{\dot{\omega}_1}{\omega_1} \right) \right] \left[ 1 - \frac{2}{5} \alpha M_1 R_1^2 \omega_1^2 \right]^{-1}.
\]

This implies that the secular evolution of the orbital angular velocity is also determined by the coupling between the
spin of the primary and the orbital rotation in spite of the ultimate driver being the energy and angular momentum losses due to gravitational radiation. More detailed work is needed to determine the range of $\alpha$ which could give rise to the observed spin-up rate.

6.2 X-ray luminosity

The lower panel of Figure 3 shows that the observed count rate of RX J1914+24 varies by an order of magnitude. At the XMM-Newton epoch, the unabsorbed, bolometric flux determined using the model fits is shown in Table 2. Due to projection effects we correct the observed count rate by the ratio of the peak to mean count rate (a factor of 3.4) which gives a luminosity of \( \sim 1 \times 10^{35} \text{ erg s}^{-1} \) (for 1 kpc, Steeghs et al 2004). For the same distance this is \( \sim 2 \text{ orders of magnitude lower than the X-ray luminosity estimate in} \) Cropper et al (1998): this due to the higher absorption originally derived using the ROSAT PSPC spectrum. Figure 3 implies that it has reached \( \sim 4 \times 10^{35} \text{ ergs s}^{-1} \) in the past.

If the X-ray flux is driven by accretion and all of the accretion flow was liberated as X-rays, then the required mass transfer rate would exceed \( 7 \times 10^{17} \text{ g s}^{-1} \) (or \( 1.2 \times 10^{-8} M_\odot/\text{yr} \)). This would place it at the upper end of the range of mass transfer rates in known magnetic cataclysmic variables (Patterson 1994). However, the UI model proposed by Wu et al (2002) is well within the constraints of the observed X-ray luminosity, despite its dependence on the orbital period of the system. Although the maximum power for a system with an orbital period of 569 sec, \( M_2 = 0.1 M_\odot \), and a spin-orbit asynchronicity of 0.1 percent is less than \( \sim 10^{34} \text{ ergs s}^{-1} \) (Wu et al 2002), an increase in the asynchronicity to 1.0 percent would easily give rise to the observed luminosity.

Unless the dipole axis was closely aligned with the spin axis of the white dwarf, then this asynchronicity may be expected to have an observational signature. For an asynchronicity of 1 percent, then that would give rise to a ‘beat’ period of \( \sim 16 \text{ hrs} \). The XMM-Newton X-ray observations are separated by 6 days and have relatively short durations so are not particularly suitable to search for such a period. A dedicated ‘whole-Earth’ type of observing campaign is the best method to detect the signature of the asynchronous motion.

We note that an increase of the asynchronicity parameter would not significantly reduce the total lifetime of the binary, as the primary driver of the orbital evolution is gravitational radiation, in spite of short term effects caused by spin-orbit coupling between the stars and the orbital rotation. An increase or decrease in $\alpha$ would alter the duration of the duty cycle of the unipolar-induction process, and hence the brightness and discovery probability of the system.

6.3 The X-ray spectrum of RX J1914+24

The X-ray spectra of RX J1914+24 in §5 showed a soft blackbody component plus a broad feature resembling an emission line with a central energy close to \( \sim 0.59 \text{ keV} \). We fitted the spectra with a range of possible models, including a two-temperature blackbody model and found that this did not give good fits. More detailed work is needed to determine if irradiated white dwarf atmosphere models can provide better fits (see Williams, King & Brooker 1987). Observations of the disc accreting double degenerate binaries, the AM CVn systems, show that their optical spectra can show metal abundances very different from Solar (eg Marsh, Horne & Rosen 1991). The relative abundances are affected as a result of the CNO process and mixing in the common envelope phase of the binary. X-ray observations of AM CVn stars also show this non-solar abundance, eg Strohmayer (2004c), Ramsay et al, in prep. Fits made using an emission model of different metal abundances for each element gave better fits than a two-temperature blackbody model, but poorer than a blackbody plus Gaussian line.

Using the blackbody plus Gaussian line, we find that the broad line is brightest at X-ray maximum, implying that it arises from a region close to the hot spot where most X-rays are emitted. The high resolution RGS spectra, however, do not show any significant evidence for distinct individual lines. This is in contrast to Chandra observations of the 10.3 min binary ES Cet (Strohmayer 2004b) which shows tentative evidence for narrow emission lines at 0.47 and 0.89 keV. It is also in contrast to XMM-Newton observations of the double degenerate AM CVn system GP Com (Strohmayer 2004c) which show narrow emission lines of NVII, NVI, Ne X and Ne IX. The line centre of 0.59 keV is close to the O VII photoionised line at 0.57 keV which has been detected in some intermediate polars (Mukai et al 2003). The lines in these systems, however, have much narrower width.

It is possible that the broad feature could be line emission from material with large velocity dispersion. In the UI model the large e.m.f. inside the magnetic flux tubes joining the two stars could accelerate charged particles, thus causing difficulty in the confinement of line emitting ionised atomic species right above the X-ray emitting hot spot. However, ionised particles could be present in a region close to the hot spot, yet outside the magnetic flux tubes that join the two stars (see the schematic illustration in Figure 7). Nevertheless, we argue that the feature is unlikely to be due to a low-order harmonic hump of cyclotron emission, as it would require a magnetic field strength \( \sim 10^{11} \text{ G} \) in the emission region. Such a field is much stronger than the strongest magnetic fields measured in magnetic white dwarfs (\( \sim 10^{8-9} \text{ G} \), eg Barstow et al 1995).
6.4 The nature of RX J1914+24

The true nature of RX J1914+24 is still unclear. Whilst the UI model of Wu et al (2002) perhaps comes closest to predicting the observed characteristics, it too has question marks. For instance, Barros et al (2004) explored the set of binary parameters (masses, binary inclination and the spin-magnetic axis offset) which could give rise to the observed X-ray light curves of both RX J1914+24 and RX J0806+15 and concluded that only a very small set of parameter space could work. This implies that either the UI model is unlikely to be applicable to these systems or that the magnetic white dwarf has a field structure more complex than a simple dipole.

The XMM-Newton data presented here raise a number of issues, all of which need further work to address them in detail:

(i) RX J1914+24 has a highly unusual X-ray spectrum, with a peculiar feature near 0.6keV. Grating spectra with higher signal to noise are required and more theoretical work is needed to determine if the UI model can produce such an X-ray spectrum.

(ii) We need to determine how system parameters, such as the asynchronicity parameter $\alpha$, can produce the observed spin-up rate and X-ray luminosity.

(iii) Unless the spin and magnetic axes are very closely aligned, the asynchronicity should give rise to a beat period. More work is needed observationally to search for such a period, and theoretically to predict the amplitude of such a beat period.

(iv) Steeghs et al (2004) show an optical spectrum which has features similar to that of a K star. To resolve the nature of these features phase resolved spectroscopy is urgently required. If RX J1914+24 is a triple system, then this will obviously have implications for the systems' evolutionary history.

7 ACKNOWLEDGMENTS

We thank Andrew Willes for useful discussions and the anonymous referee for useful suggestions which clarified aspects of the text. This is work based on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and the USA (NASA). These observations were part of the XMM-Newton OM guaranteed time programme.

REFERENCES

Arnaud K. A., 1996, Astronomical Data Analysis Software and Systems V, eds. Jacoby G. and Barnes J., p17, ASP Conf. Series volume 101
Barros, S. C. C., Marsh, T. M., Groot, P., Nelemans, G., Ramsay, G., Roelofs, G., Steeghs, D., Wilms, J., submitted, MNRAS
Barstow, M. A., Jordan, S., O'Donoghue, D., Burleigh, M. R., Napiwotzki, R., Harrop-Allin, M. K. 1995, MNRAS, 277, 971
Cropper, M., Harrop-Allin, M. K., Mason, K. O., Mittaz, J. P. D., Potter, S. B., Ramsay, G., 1998, MNRAS, 293, L57
Cropper, M., Haberl, F., Zane, S., Zavlin, V. E., 2004, MNRAS, 351, 1099
den Herder, J. W., et al, 2001, A&A, 365, L7

© 0000 RAS, MNRAS 000, 000-000