Spin up in RX J0806+15: the shortest period binary

Pasi Hakala,1* Gavin Ramsay,2 Kin Wah Wu,2 Linnea Hjalmarsdotter,1 Silva Järvinen,3,4 Arto Järvinen3,4 and Mark Cropper2

1Observatory, University of Helsinki, PO Box 14, FIN-00014 University of Helsinki, Finland
2Mullard Space Science Laboratory, University College London, Holmbury St Mary, Dorking, Surrey RH5 6NT
3Nordic Optical Telescope, Apartado 474, E-38700 Santa Cruz de La Palma, Canarias, Spain
4Astronomy Division, PO Box 3000, 90014 University of Oulu, Finland

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ABSTRACT
RX J0806+15 has recently been identified as the binary system with the shortest known orbital period. We present a series of observations of RX J0806+15, including new optical observations taken one month apart. Using these observations and archival data, we find that the period of this system is decreasing over time. Our measurements imply that $f = 6.11 \times 10^{-16}$ Hz s$^{-1}$, which is in agreement with a rate expected from the gravitational radiation for two white dwarfs orbiting at a given period. However, a smaller value of $f = 3.14 \times 10^{-16}$ Hz s$^{-1}$ cannot be ruled out. Our result supports the idea that the 321.5-s period is the orbital period, that the system is the shortest period binary known so far and that it is one of the strongest sources of constant gravitational radiation in the sky. Furthermore, the decrease of the period strongly favours the unipolar inductor (or electric star) model rather than the accretion models.

Key words: binaries: general – stars: individual: RX J0806+15 – stars: neutron – novae, cataclysmic variables.

1 INTRODUCTION

For accreting stellar binary systems in which the secondary star (mass donating) is on the main sequence, the minimum orbital period is $\sim$80 min (Paczynski & Siekiewicz 1981). For secondary stars not on the main sequence (such as helium stars), systems can also have orbital periods of less than 80 min (Savonije, de Kool & van den Heuvel 1986, and references therein). The other option for short-period systems is that the secondary star must be degenerate, forming a double degenerate binary with a compact primary. A number of these systems have been known for some time, although it is only relatively recently that their nature has been revealed (cf. Warner 1995). The orbital periods of these systems lie in the range of tens of minutes.

Recently, a group of three binaries have been discovered in which the orbital period is thought to be less than $\sim$10 min: ES Cet (KUV01584−0939), with an orbital period of 10.3 min (Warner & Woudt 2002); V407 Vul (RX J1914+24), with an orbital period of 9.5 min (Cropper et al. 1998); and RX J0806+15, with an orbital period of 5.4 min (Israel et al. 2002; Ramsay, Hakala & Cropper 2002a). If these periods have been correctly identified as the binary orbital period, then these have the shortest known binary periods. As such, they should be strong sources of gravitational waves.

In the case of ES Cet, strong He lines are seen in optical spectra (Wegner, McMahon & Boley 1987) which have recently been found to be double-peaked (Woudt, private communication), suggesting the presence of a disc. In the case of V407 Vul, no emission lines are seen (Ramsay et al. 2002b), whereas RX J0806+15 shows only weak He lines (Israel et al. 2002). Very recently, Israel et al. (2003) demonstrated that the optical and X-ray emission of RX J0806+15 are in antiphase, as in the case of V407 Vul (Ramsay et al. 2000).

Currently, there are several models to explain the observations of V407 Vul and RX J0806+15. A neutron star primary and an intermediate polar model cannot be excluded, although they are considered unlikely. The most likely models all have a white dwarf primary and secondary. Two models (a polar and a direct accretor model) are driven by mass transfer, whereas one (a unipolar inductor or electric star model) is driven by an electrical current. Of these models, the unipolar inductor model fits the observational properties better than the accretion models, although these cannot be ruled out [Marsh & Steeghs 2002; Norton, Haswell & Wynn 2002; Ramsay, Hakala & Cropper 2002a; Wu et al. 2002; Cropper et al. 2003 (review)].

The best method to differentiate between these models is to measure the period change of these systems. For systems driven by mass transfer, the period should increase over time (e.g. Savonije et al. 1986; Nelemans et al. 2001). In the case of the unipolar inductor model, the system should be driven entirely by gravitational radiation and the period should decrease (Wu et al. 2002).

Strohmayer (2002) showed using ROSAT observations that for V407 Vul, the period is decreasing at a rate consistent with that predicted from the emission of gravitational radiation. In this paper, we present observations of the 5-min system RX J0806+15 and...
determine the change in the period. We then discuss the implications of this result.

2 OBSERVATIONS

In order to measure possible period changes in RXJ0806+15, we have obtained data from the Nordic Optical Telescope (NOT) La Palma from 2003 January 5–8 and from 2003 February 5–7. These observations consist of high-speed CCD photometry with an approximate time resolution of 15 s (10 s integration time). The observations were carried out using the Andalucia Faint Object Spectrograph and Camera (ALFOSC) in imaging mode without any filter. We binned the CCD chip by a factor of two in both directions and selected only a small 100 × 100 subwindow for fast readout. A total of 4687 images were obtained. These were bias-corrected and flat-fielded in the usual manner. Conditions in 2003 January were photometric and the seeing was typically better than 1 arcsec. In February, however, seeing was poorer (about 1.5 arcsec).

Additionally, some archival European Southern Observatory Very Large Telescope (ESO VLT) data from 2001 November 12 was analysed to provide further constraints for a period from our earlier (2002 January) NOT run. There were a total of 214 data points that were combined with our 1314 data points from two nights in 2002 (2002 January) NOT run. There were a total of 214 data points that were combined with our 1314 data points from two nights in 2002 January. These data were also reduced using standard procedures. All of the data were heliocentric corrected.

There are also some archival Chandra observations available. However, given the length of the observation (20 ks), we have not included it here.

3 PERIOD ANALYSIS

We have three different data sets that can be used to search for the change in the orbital period (Table 1). Chronologically, these are: (i) the ROSAT observations from 1994–95; (ii) the combined VLT data from 2001 November and NOT data from 2002 January; and finally (iii) the NOT data from 2003 January–February. We will now proceed to estimate the best period for each of these data sets and then use the results to derive the change in the orbital period.

The earliest of our three data sets is the 1994–1995 ROSAT data. Burwitz & Reinsch (2001) found two possible values for the best period in their ROSAT data, namely 321.5393 or 321.5465 s (±0.0004 s). Their preference was the first of these. For consistency, we have re-analysed the ROSAT data and confirm their results.

For our optical data sets, we have used the Lomb–Scargle power spectrum (Scargle 1982) to search for the periods. However, in order to obtain reliable error estimates (crucial for the measurement of \( P \)), we have performed Monte Carlo simulations of our time series. This enables us to take into account the true effects of aliasing in a rigorous manner. Our Monte Carlo approach consists of the following steps. (i) Find the best period using the Lomb–Scargle algorithm. (ii) Fix the period and fit the light-curve shape with a second-order Fourier fit. (iii) Use the (Gaussian) errors from the Fourier fit to produce 10 000 synthetic data sets using the same time-points as in the original data set, and add noise comparable to the noise in real data. (iv) Finally, analyse the 10 000 data sets around the best period. To do this in a reasonable amount of CPU time, we have used the minimum string-length method (Dwortskey 1983) which can be easily restricted to the immediate neighbourhood of the best period.

Our second data set, which consists of VLT data from 2001 November and NOT data from 2002 January, is problematic in terms of aliasing. Both of these runs are too short to ‘phase’ them together in a unique manner; as a result, severe aliasing arises. However, we can use some a priori information from our later 2003 January–February NOT run to remove the aliasing (i.e. pick the correct spike from a handful of possible spikes suggested by the Lomb–Scargle analysis and the subsequent Monte Carlo simulation).

The \( P \) from the 2003 January data combined with the ROSAT runs is about 1.2 ms yr\(^{−1}\). Further, our best period from the NOT 2003 run is 321.529 57 ± 0.000 45 s (see below). Assuming these values, we can estimate that the period in 2002 January should be approximately 321.532 s. The possible spikes present in the periodogram are 321.515, 321.534 and 321.552 s. Only one of these (321.534 s) has a period close to the ROSAT and the NOT 2003 periods. If we now assume this is the ‘correct’ power peak, we can use our Monte Carlo study to get 321.533 52 ± 0.000 34 s for our second run.

The third run consists of data from three consecutive nights in 2003 January (5–8) and from two nights in 2003 February (5–6). This run does not suffer from serious aliasing; using the Monte Carlo technique outline above, we find 321.529 57 ± 0.000 45 s as the best period. We have plotted the periodogram of the NOT 2003 run in Fig. 1. The inset shows the part near the best period.

4 THE PERIOD CHANGE

To measure the possible change in the orbital period, we have fitted our periods from different epochs (defined as the mean of the time-points from each of the epochs) with a linear fit (Fig. 2). Depending on the choice of which ROSAT period we use, we obtain two sets of frequency; \( f \) and \( f = −P / P^2 \).

If we adopt 321.5393 s as the true ROSAT period (as preferred by Burwitz & Reinsch 2001), we get \( f = 3.14 \times 10^{-16} \) Hz s\(^{−1}\). On the other hand, the longer ROSAT period of 321.5465 s yields \( f = 6.11 \times 10^{-16} \) Hz s\(^{−1}\). In both cases, the error is 2.0 \( \times 10^{-17} \) Hz s\(^{−1}\). Judging from our fit, the latter period is better.

### Table 1. The times of observation and best periods for our three different data sets.

| Observation                  | Dates (h:m:s) | Best period (s) | Error (s)  |
|------------------------------|--------------|----------------|------------|
| ROSAT (1994 and 1995)        | 49648.9-49658.2 | 321.5393 or 321.5465 | 0.00040     |
|                              | 49822.9-49827.0 |                |            |
| VLT (2001 November) and NOT (2002 January) | 52226.258-373 | 321.53352 | 0.00034     |
|                              | 52289.533-653 |                |            |
|                              | 52290.354-740 |                |            |
| NOT (2003 January–February) | 52645.443-674 | 321.52957 | 0.00045     |
|                              | 52646.453-639 |                |            |
|                              | 52647.435-773 |                |            |
|                              | 52676.420-438 |                |            |
|                              | 52677.493-576 |                |            |
Figure 1. The Lomb-Scargle power spectrum of the 2003 January–February data and (inset) the same plot zoomed in near the best period.

Figure 2. The fits to the change in period, assuming two different values for the ROSAT period.

Figure 3. The 2002 January (top) and 2003 January–February white light light curves folded on the orbital period.

of the fits is very good, but given the number of measurements to be fitted (three), we cannot make a definitive conclusion between the two solutions.

We have also folded both the NOT 2002 and 2003 data over the orbital period and plotted that in Fig. 3. In order to do this, we need to adopt a value for \( \dot{f} \) that gives us the correct phasing. This can be used as a feasibility test for our model where the period is decreasing. We find two epochs when the flux should be at minimum – one just before the 2002 NOT data set and another before the NOT 2003 data set. These are 245 2288.999 256 and 245 2645.436 696. Now, to produce correct phasing, an integer number of (changing) periods must have passed in between these two epochs. As we expect the period change to be linear, at least in short time-scale, we can estimate an average number of periods that have passed (95 780) using the average of the best periods from the 2002 and 2003 data sets as the mean period. We can then check if we can produce the correct phasing using our best periods for the two epochs, together with the two possible values of \( \dot{f} \) and their errors. As a result, we conclude that the data can be phased together using either of the two \( \dot{f} \) values. The larger value of \( \dot{f} \) produces a better fit, but we cannot exclude the smaller value of \( \dot{f} \).

The resulting phase-folded light curves are plotted in Fig. 3. The modulation and its asymmetry are roughly the same in both data sets. However, it appears that the 2003 data shows a broader, flatter flux maximum than the earlier data set. The two data sets are identical in terms of instrumentation used.

5 DISCUSSION

The current competing models for the system can be classified into two types: accreting and non-accreting models (cf. Section 1). The accreting and the non-accreting models can be distinguished by determining the period change in the system.

As \( \dot{f} = - \dot{P} / P \), we can calculate \( \dot{f} \) from the orbital parameters of the system. For an accreting system, the period change is given by

\[
\frac{\dot{P}}{P} = -3 \frac{J_o}{J_o} - 3 \frac{M_2}{M_1} (1 - q)
\]

(Appendix A), where \( J_o \) is the orbital angular momentum, \( M_2 \) is the mass of the secondary star and \( q \) is the ratio of the mass of the secondary star to the primary star. For systems with matter transfer from the secondary to the primary, \( M_2 \) is negative, whereas \((1 - q)\) is positive. In general, \( \dot{P} / P \) may take a positive or negative value, depending on \( J_o \) and the driving mechanism of the mass transfer. However, if the secondary is a degenerate star, \( \dot{P} / P \) is positive (i.e. \( \dot{f} \) is negative) when the angular momentum loss from the system is caused by gravitational radiation (see Ritter 1986).

For non-accreting system with no coupling between the stellar spins and the orbit,

\[
\frac{\dot{P}}{P} = -96 \left( \frac{GM}{c^2 a} \right)^3 \left( \frac{c}{a} \right) \left[ \frac{q}{(1 + q)^2} \right]
\]

where \( G \) is the gravitational constant, \( c \) is the speed of light, \( M \) is the total mass of the two stars and \( a \) is the orbital separation. If the spin-orbit coupling occurs and the angular momenta of the orbit and stellar spins maintain roughly constant ratios, then

\[
\frac{\dot{P}}{P} = -96 \left( \frac{GM}{c^2 a} \right)^3 \left( \frac{c}{a} \right) \left[ \frac{q}{(1 + q)^2} \right] \times \left\{ 1 - \frac{6}{5} \left[ \alpha_1 \left( \frac{1 + q}{q} \right) \left( \frac{R_1}{a} \right)^2 + \alpha_2 (1 + q) \left( \frac{R_2}{a} \right)^2 \right] \right\}^{-1}
\]

(Appendix A), where \( R_1 \) and \( R_2 \) are the radii of the primary and secondary respectively, and \( \alpha_1 \) and \( \alpha_2 \) are the coupling parameters of the spins of the two stars with the orbit. For parameters typical
of double-degenerated systems, $\dot{P}/P$ is negative and hence $\dot{j}/j$ is positive (with and without spin-orbit coupling), which is in contrast to the prediction by the accreting models.

If the 321.5-s period is the orbital period of the system, the observed period change is not consistent with the prediction of the accreting models, but is consistent with non-accreting models. If we interpret that the observed period is the spin period of the white dwarf in an intermediate polar, both spin up and down is possible. However, we consider that the spin interpretation is unlikely (Cropper et al. 2003).

In contrast, the detected decrease in the orbital period strongly favours the non-accreting models, in particular the unipolar-inductor model (Wu et al. 2002), in which the two stars in the systems are white dwarfs. In this model, angular momentum loss from the system and system evolution are caused by gravitational radiation, and the spin-orbit coupling process (if present) occurs via unipolar induction.

In the absence of accretion, the secondary must reside well within its Roche lobe. From the Roche-lobe relation of Eggleton (1983) and the Nauenberg (1972) mass–radius relation for white dwarfs, we find that for $M_1 = 1.0 \ M_\odot$ and an orbital period of 321.5 s, the white dwarf secondary has mass $M_2 > 0.14 \ M_\odot$ in order that it stays within its Roche lobe.

Now, suppose that the observed period is the orbital period and that the change is a result of orbital evolution. We show in Fig. 4 the predicted change in frequency for a range of component masses, for the case with no spin-orbit coupling. Using the longer ROSAT period, we find that for $M_1 = 1.0 \ M_\odot$, a secondary mass of 0.3 $M_\odot$ is required. For a less massive primary, a more massive secondary is required. Taking the shorter ROSAT period, an $M_1 = 1.0 \ M_\odot$ primary requires a secondary of mass $> 0.15 \ M_\odot$. The studies of double white dwarf systems (e.g. Marsh 2000; Napiwotzki et al. 2002) have shown that all such systems tend to have a mass ratios of the order of 1.0. Furthermore, the individual white dwarf masses in these systems are below 0.5 $M_\odot$. Such masses are compatible with the measured period change. In all of the above mentioned cases, the deduced masses for the secondary are consistent with the requirement that the star is detached from its critical Roche surface.

If the masses of the system could be determined independently, the degree to which the period decrease differs from that expected from gravitational radiation losses alone would provide information about the degree of asynchronism in the spin of the primary. This asynchronism is the origin of the power generation in the unipolar inductor model, so continuing timing observations are essential to determine whether this is consistent with the observed luminosity and reasonable component masses.

To conclude, we note that for perfectly acceptable masses of the components, $\dot{j}$ is compatible with gravitational radiation. This is consistent with the results for V407 Vul (Strohmayer 2002). The implication is that there is no mass transfer in either of these systems, favouring the unipolar inductor (electric star) model.

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APPENDIX A: ORBITAL EVOLUTION

Consider a binary with masses $M_1$ and $M_2$ and radii $R_1$ and $R_2$. Let the binary orbital period be $P$ and the orbital separation be $a$. Then $\omega (=2\pi/P)$ is the orbital angular velocity and $M$ is the total

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure4.png}
\caption{$\dot{j}$ as a function of the component masses (assuming no spin-orbit coupling). The two labelled contours show the measured $\dot{j}$ for the two different ROSAT periods; the contours next to them give the 3σ limits.}
\end{figure}
mass. The angular momenta of the orbitals of star 1 and star 2 are, respectively,

\[ J_0 = \frac{M_1 M_2}{M} a^2 \dot{\omega}, \]
\[ J_1 = \frac{2}{5} M_1 R_1^2 \omega_1, \]
\[ J_2 = \frac{2}{5} M_2 R_2^2 \omega_2, \]

where \( \omega_1 \) and \( \omega_2 \) are the spin angular velocity of the two stars. Define two spin parameters \( \alpha_1 \equiv \omega_1 / \omega \) and \( \alpha_2 \equiv \omega_2 / \omega \). The total angular momentum of the binary system can then be expressed as

\[ J = J_0 + J_1 + J_2 = \lambda_0 \omega^{-1/3} + \lambda_\omega \omega, \]

where the two coefficients \( \lambda_0 \) and \( \lambda_\omega \) are

\[ \lambda_0 = \frac{G^{2/3} M_1 M_2}{(M_1 + M_2)^{1/3}}, \]
\[ \lambda_\omega = \frac{2}{5} (\alpha_1 M_1 R_1^2 + \alpha_2 M_2 R_2^2). \]

If there is no mass exchange, \( d\lambda_\omega / dt = 0 \). Moreover, if the spin-orbit coupling maintains roughly constant angular momentum ratios between the orbit and the stars, we may set \( d\lambda_\omega / dt = 0 \) and obtain the following for \( J \) in terms of \( \dot{\omega} \):

\[ J = -\frac{1}{3} \left( \frac{\alpha_0}{\omega} \right) \left[ 1 - 3 \left( \frac{\lambda_\omega}{\lambda_0} \right) \omega^{2/3} \right] \frac{\dot{\omega}}{\omega}. \]

For systems with angular momentum loss owing to gravitational radiation,

\[ J = -\frac{32}{5} \frac{G}{c^5} \left( \frac{M_1^2 M_2^2}{M^2} \right) a^4 \omega^5 \]

(see e.g. Landau & Lifshitz 1958), where \( c \) is the speed of light. It follows that

\[ \frac{\dot{P}}{P} = -\frac{\dot{\omega}}{\omega} = -\frac{96}{5} \left( \frac{GM}{c^2 a} \right)^3 \left( \frac{c}{a} \right) \left[ \frac{q}{(1 + q)^2} \right] \times \left\{ 1 - \frac{6}{5} \left[ \alpha_1 \left( \frac{1 + q}{q} \right) \left( \frac{R_1}{a} \right)^2 \right] + \alpha_2 (1 + q) \left( \frac{R_2}{a} \right)^2 \right\}^{-1}. \]

The last term in the above is the spin-orbit coupling correction. For systems with the spins of the stars decoupled from the orbit, \( \alpha_1 = \alpha_2 = 0 \), and

\[ \frac{\dot{P}}{P} = -\frac{96}{5} \left( \frac{GM}{c^2 a} \right)^3 \left( \frac{c}{a} \right) \left[ \frac{q}{(1 + q)^2} \right]. \]

From the above, we can also see that \( \dot{P} / P \) is always negative when the \{ \ldots \} term is positive. This can be satisfied easily for positive \( \alpha_1 \) and \( \alpha_2 \). This implies that the orbit period of a binary system decreases because the gravitational radiation that it emits carries away the orbital angular momentum, and, if in the presence of spin-orbit coupling, orbital angular momentum is also extracted to synchronize the spins of the stars. We note that for systems with zero mass loss but non-zero mass exchange between the two stars,

\[ \frac{\dot{J}_0}{J_0} = \frac{M_1}{M_1} + \frac{M_2}{M_2} + \frac{1}{2} \frac{\dot{a}}{a} + \frac{M_2}{M_2} (1 - q) \]

\[ = \frac{M_2}{M_2} (1 - q) - \frac{1}{3} \frac{\dot{\omega}}{\omega}. \]

It follows that

\[ \frac{1}{3} \frac{\dot{P}}{P} = \frac{\dot{J}_0}{J_0} - \frac{J_0}{J_0} (1 - q). \]

(Here, \( \dot{J}_0 \) consists of contributions of orbital angular momentum loss by gravitational radiation and by spin-orbital coupling.)