

# RAT J1953+1859: a dwarf nova discovered through high amplitude QPOs in quiescence

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## ABSTRACT

We report the discovery of an accreting binary, RAT J1953+1859, made during the RApid Temporal Survey (RATS) on the Isaac Newton Telescope. It showed high amplitude (0.3 mag) quasi-periodic oscillations on a timescale of  $\sim 20$  mins. Further observations made using the Nordic Optical Telescope showed it to be  $\sim 4$  mag brighter than in the discovery images. These photometric observations, together with radial velocity data taken using the William Herschel Telescope, point to an orbital period of  $\sim 90$  mins. These data suggest that RAT J1953+1859 is a dwarf novae of the SU UMa type. What makes RAT J1953+1859 unusual is that it is the first such system to be discovered as a result of high amplitude QPOs during quiescence. This suggests that high-cadence wide-field surveys could be another means to discover cataclysmic variables as a result of their short period variability.

**Key words:** Stars: binary - close; novae - cataclysmic variables; individual: - RAT J1953+1859; X-rays: binaries

## 1 INTRODUCTION

The RApid Temporal Survey (RATS) is a deep, wide-field, fast-cadence photometric survey which allows the discovery of objects which vary in their intensity on timescales ranging from a few minutes to several hours (Ramsay & Hakala 2005). Whilst our primary aim is to discover AM CVn binaries (the hydrogen deficient cataclysmic variables, CVs, with orbital periods less than  $\sim 70$  min) we expect to discover objects ranging from contact binaries, pulsating stars, flare stars and accreting binaries in general. In our pilot survey, we discovered more than 40 new variable objects including one system which we identified as a short period pulsating sdB star (Ramsay et al 2006).

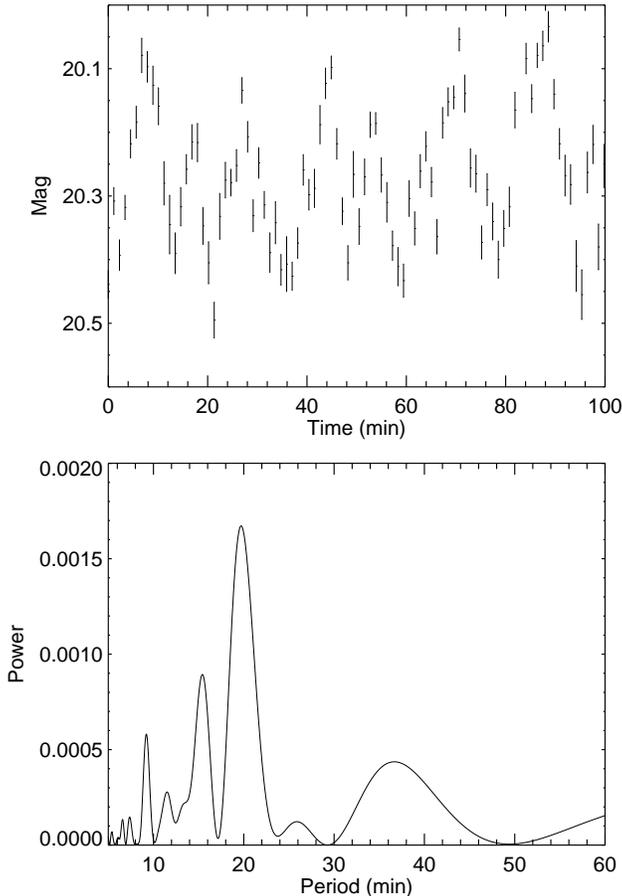
Since our pilot survey, we have obtained further wide-field camera data using the 2.5m Isaac Newton Telescope (INT) on La Palma. Currently, we have discovered many 1000's of new variable stars. Most of them have periods longer than a few hours, but a number were found to show

periods shorter than 30 mins (and hence candidate AM CVn binaries). For these systems we have obtained followup spectroscopy. Here we report on observations on one such source, RAT J1953+1859, which is an accreting binary system.

## 2 WIDE FIELD CAMERA DISCOVERY DATA

Data were taken using the Wide Field Camera on the 2.5m INT on 30 May 2005. There are 4 CCDs with approximate total field of view of  $33' \times 33'$  (with a  $11' \times 11'$  gap missing on one of the corners). The field was centered on the globular cluster M71 which has a tidal radius of  $9.0'$  (Harris 1996). A series of 30 sec white light exposures were taken for 100 min – this includes the  $\sim 30$  sec readout time of the camera. Data were flat fielded and bias subtracted in the usual manner.

Variable sources were identified using the difference image analysis package *Dandia* (see Bramich et al 2005 for a description). Full details of how we identified variable



**Figure 1.** Upper panel: The light curve of RAT J1953+1859 taken using the Wide Field Camera on the INT in June 2005. The data were taken in white light and each exposure was 30 sec. Lower panel: The power spectrum of the light curve shown in the upper panel.

sources will be given elsewhere. Suffice to say, we identified a strongly variable object which was modulated on a period of  $\sim 20$  min with an amplitude of 0.3 mag. The light curve and the corresponding power spectrum are shown in Figure 1. While the dominant period is at 19.7 min there are also prominent peaks at  $\sim 15.5$  and  $\sim 9.2$  min. We pre-whitened the light curve on a period of 19.7 min period, and found that the peaks at 15.5 and 9.2 min were still present. We therefore do not believe these peaks are related to the window function. We phased the data on all three periods and find that they are not strictly periodic, rather they are quasi-periodic oscillations (QPOs).

To determine the sky co-ordinates of this variable source, we identified objects in the field which were in the 2MASS catalogue. We then used `astrom` (Wallace & Gray 2002) to obtain the astrometric solution for the field. The position of the variable source is  $\alpha=19^h 53^m 27.2^s$ ,  $\delta=+18^\circ 59' 13.5''$  (2000) and the residuals on the positions are  $0.4''$ . This places it  $13.3'$  distant (equating to  $1.5 \times$  the cluster tidal radius) from the globular cluster M71. We therefore consider it unlikely that the variable source is associated with the cluster. We show the finding chart in Figure 2.

We took *BVI* images prior to the sequence of white

light exposures. Although we did not obtain images of photometric standard fields we were able to place our filter data on the standard system by matching up objects which were in the catalogue of Geffert & Maintz (2000) who obtained photometry of stars in the field of M71. Our variable source was  $V \sim 20.4$  and  $(B - V) \sim 0.2$  at the time of our observations (we note that our *BV* data was not simultaneous). Compared with other stars in the same field, our variable source is clearly blue.

### 3 FOLLOWUP PHOTOMETRY

We obtained further photometry of RAT J1953+1859 using the 2.5m Nordic Optical Telescope (NOT) sited on La Palma on 28th Sept 2008 using ALFOSC. It was immediately clear that RAT J1953+1859 was much brighter than in the discovery data (the right hand panel of Figure 2). We did not obtain any filtered data of the field, but comparison with our INT white light images suggest that RAT J1953+1859 was  $V \sim 16.5$ , or  $\sim 4$  mag brighter than our INT discovery data.

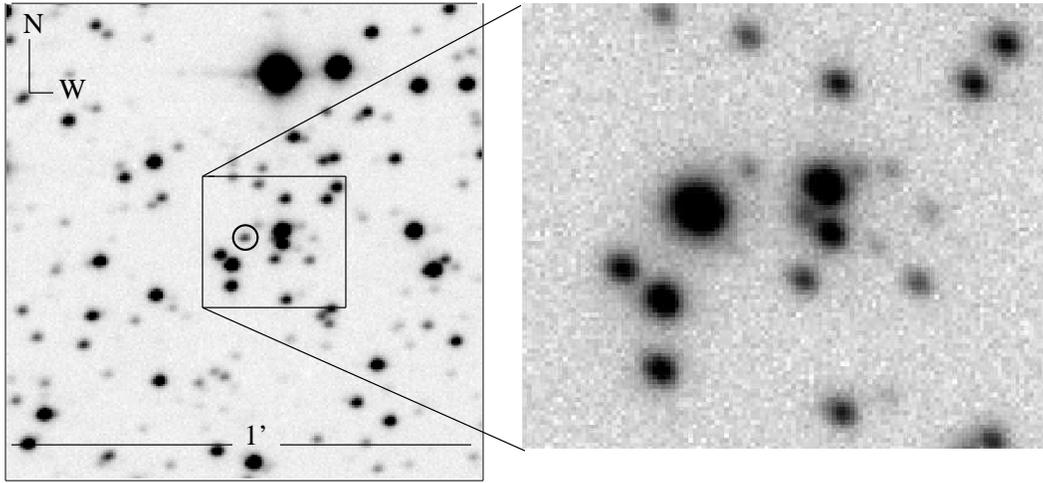
We proceeded to obtain a sequence of 15 sec exposures in white light which lasted for 140 min. The chip was windowed to reduce readout time to 5 sec. We show the full light curve in the top left hand panel of Figure 3. There is some evidence that the light curve repeats itself after  $\sim 90$  mins with an amplitude of  $\sim 0.4$  mag, although we note that the observation length was 140 mins. The second highest peak in the power spectrum is at  $\sim 46$  mins (lower left hand panel of Figure 3). We removed the  $\sim 90$  min trend and the resulting ‘residual’ light curve is shown in the top right hand panel of Figure 3. It is clear even by ‘eye’ that low amplitude ( $\sim 0.02$  mag) quasi-periodic behaviour is seen in the first half of the light curve. The power spectrum of this residual light curve is shown in the lower right hand panel of Figure 3 and shows peaks near 5.7, 10.2 and 12.7 mins. None of these peaks coincides with the peaks seen in the power spectra of the data taken using the INT.

### 4 OPTICAL SPECTROSCOPY

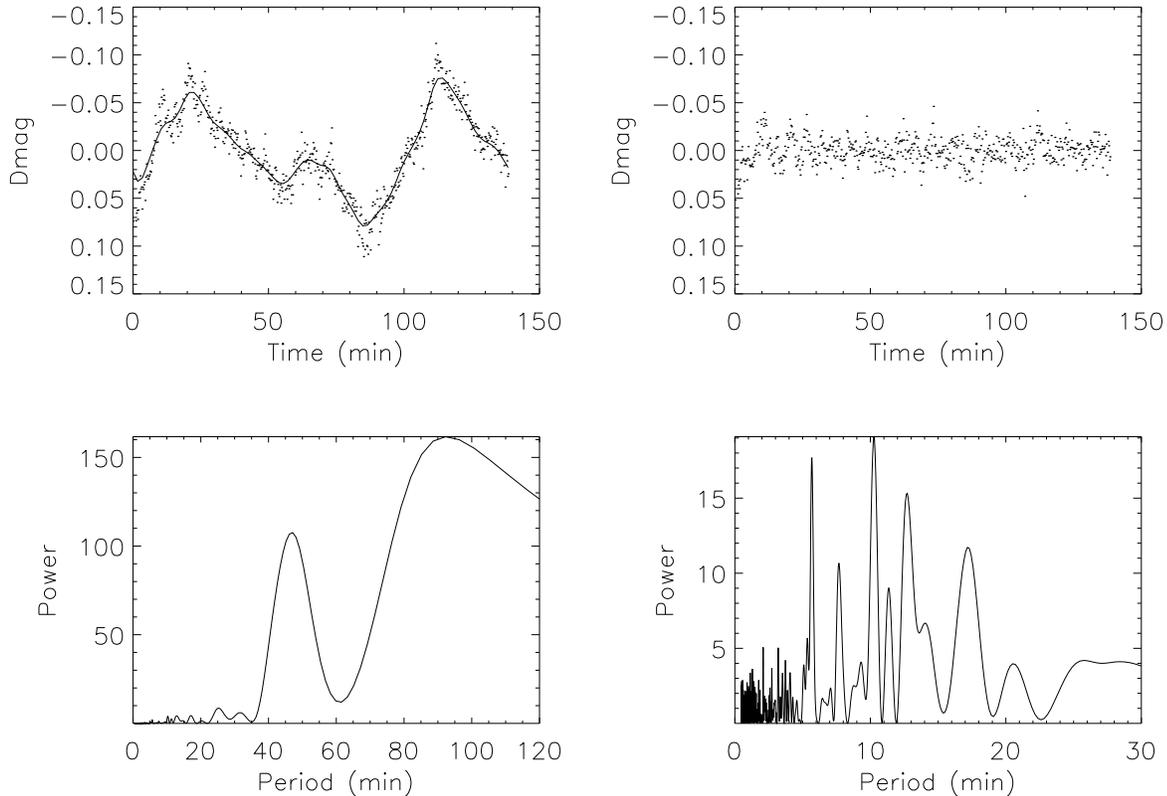
#### 4.1 Main spectral features

We obtained spectra of RAT J1953+1859 using the 4.2m William Herschel Telescope (WHT) and the Intermediate dispersion Spectrograph and Imaging System (ISIS) on La Palma at three separate epochs (Table 1). All the data were bias subtracted and the spectra were created using optimal extraction. Since we only took one arc lamp observation at the start and end of each sequence we cross-correlated the sky spectra and applied this small correction (less than 1 pixel) to the spectra.

Our first set of spectra, which had exposures ranging from 120 sec to 420 sec and were taken when the source was in quiescence, shows emission lines of  $H\alpha$ ,  $H\beta$  and  $H\gamma$  decreasing in prominence (Figure 4). The Balmer lines are also split (most clearly in  $H\alpha$ ) and broad (a FWHM of  $\sim 40\text{\AA}$ , corresponding to velocities of 1800 km/s) indicating the presence of an accretion disk. We also note the presence of a He I emission line at 5876 and 6678  $\text{\AA}$  but the absence of the He II 4686  $\text{\AA}$  line. Strong Balmer emission is typical of



**Figure 2.** Left hand panel: The white light finding chart for RAT J1953+1859 made using the Wide Field Camera on the INT in June 2005. The circle shows the position of RAT J1953+1859. Right hand panel: The image taken the NOT on Sept 28th 2008 – RAT J1953+1859 was  $\sim 4$  mag brighter than in the INT image.

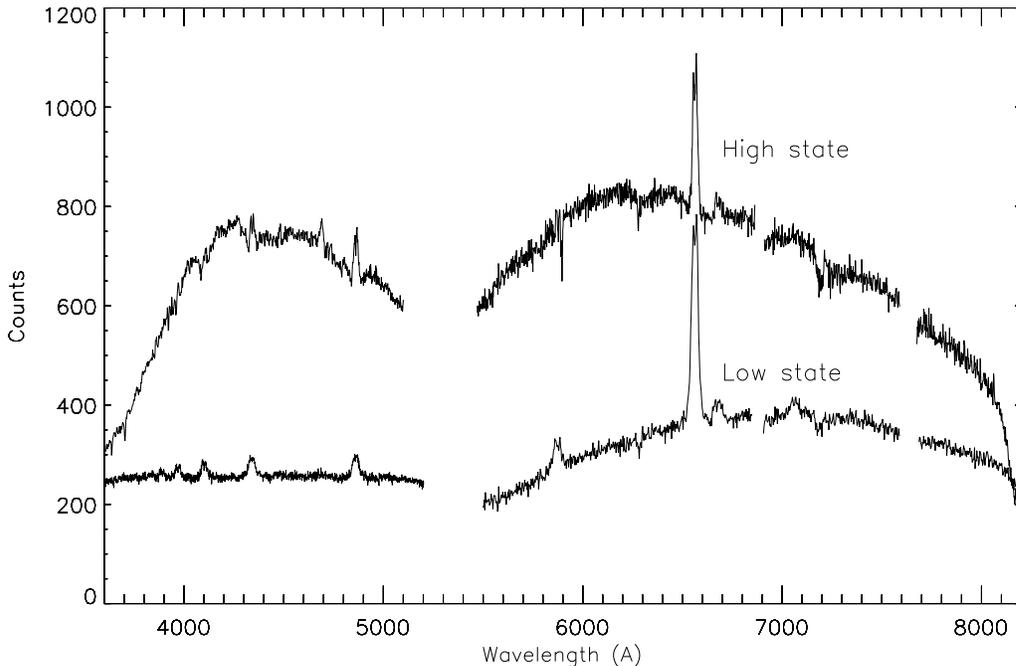


**Figure 3.** Photometric observations made using the Nordic Optical Telescope on 28th Sept 2008. In the top left panel we show our full light curve and its power spectrum in the lower left. In the top right hand panel we show the light curve with the general trend removed. Clear QPO like features are seen in the light curve with periods between 5 and 13 min (lower right hand panel).

dwarf novae in quiescence, although the He II 4686 Å line is present in some dwarf novae (eg YZ Cnc, Shafer & Hershman 1988), but not in others (eg SS Cyg Martinez-Pais et al 1994).

The second epoch observations were taken on the same night as we obtained observations using the NOT when RAT

J1953+1859 was in outburst. The exposure time was 90 sec with a further 12 sec for readout. By the epoch of the third observation, the source had returned to quiescence and the exposure time was 240 sec with a further 25 sec for readout. We show the mean of the spectra taken in the blue and red arms in Figure 4. The spectra again show H $\alpha$  strongly



**Figure 4.** The blue and red spectra of RAT J1953+1859 taken using ISIS on the WHT on Sep 29 2008 and Oct 6 2008 when the source was in an outburst and quiescence respectively. We have not flux corrected the spectra so the instrumental response is partly reflected in the data.

**Table 1.** The log of our optical spectral observations of RAT J1953+1859 made using the WHT and ISIS. We show the date of the observations, the number of spectra in each arm, the gratings used (red and blue respectively), the slit width, the spectral resolution in the red and blue arms and the accretion state of the source (QU - quiescence, OB - outburst).

Date	No. Spec	Gratings	Slit ''	Res	Accn State
2008 Aug 03	6	R158R R158B	0.6	5Å, 5Å	QU
2008 Sep 29	24	R316R R300B	1.5	8Å, 5Å	OB
2008 Oct 06	53	R158R R300B	0.8	8Å, 3Å	QU

in emission with the subsequent Balmer lines decreasing in strength with some evidence for the emission lines lying in a broader absorption core. At H $\delta$  there is no sign of emission. In contrast to the quiescent state spectrum, He II (4686 Å) is seen as a weak emission line. These spectral features are typical of a dwarf nova in outburst (see Martinez-Pais et al 1996 for spectral observations of SS Cyg taken over an outburst).

#### 4.2 A search for periods

We show the spectra centered on H $\alpha$  in Figure 5. Although there are clear variations in the spectral profile over time, there are no obvious repeating features. We then performed a search for periods by determining the radial velocity of the H $\alpha$  emission features by fitting one or more Gaussian components – some spectra can be well fitted using a single Gaussian, but in others three components were required. We tried a number of approaches, including fixing the line

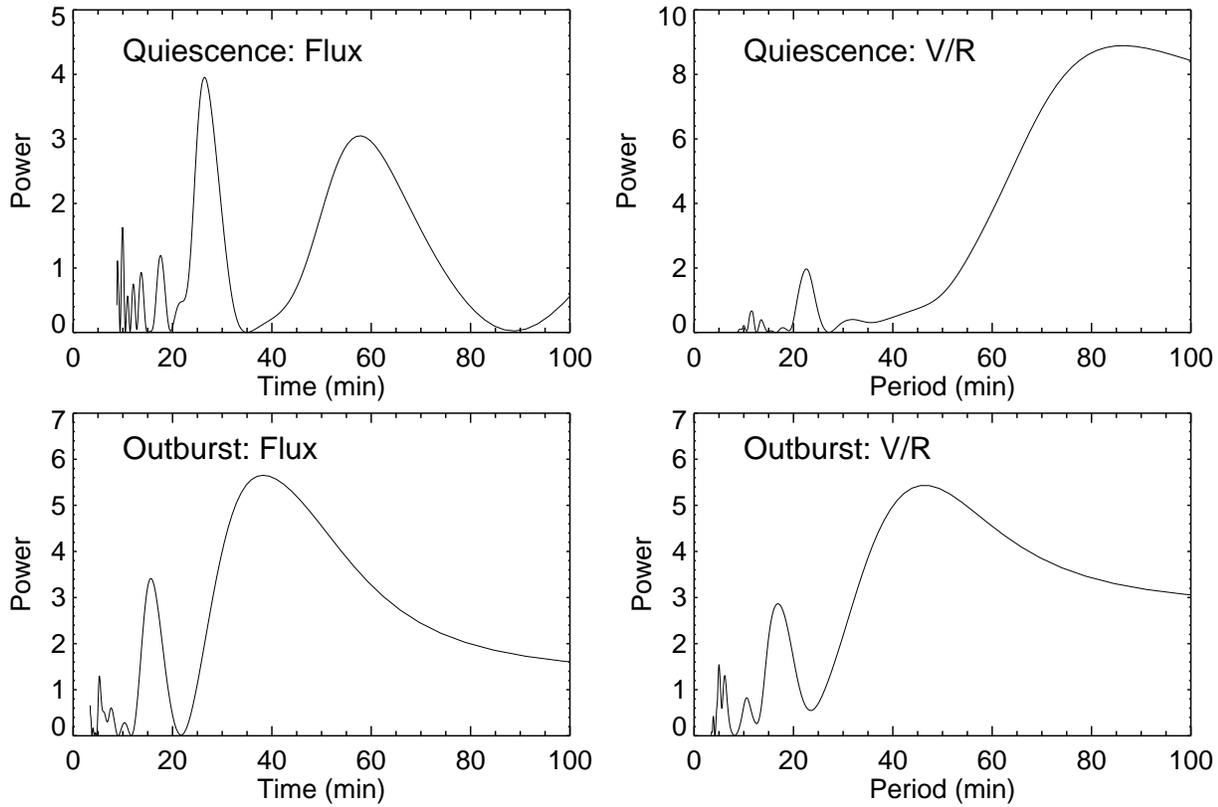
width of the higher velocity components. However, we were not able to find convincing evidence for any periods in the data.

Our second approach has the minimum of assumptions and splits the emission line into ‘violet’ and ‘red’ components (the ‘V/R’ ratio) at an arbitrary, but fixed, wavelength. We then performed a Lomb-Scargle power spectrum on the total flux and the resulting V/R time series. The longer time series made on Oct 6th 2008 when the source was in quiescence, gives a peak in the flux power spectra near  $\sim 1$  hr and 27 min, and peaks near 80–90 min and 22 min in the V/R ratio power spectra (Figure 6). The shorter time series made when the source was in outburst shows a peak near 40 mins and 16 mins in both the flux and V/R time series data.

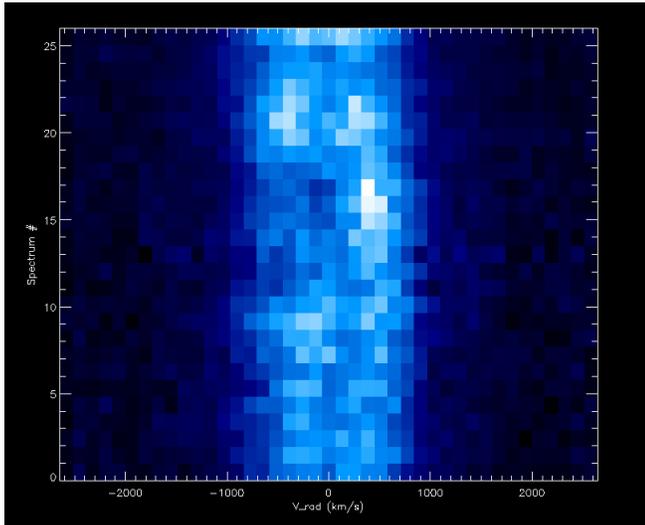
## 5 ROSAT OBSERVATIONS

A pointed observation of the field of RAT J1953+1859 was made on 10th Apr 1994 using the ROSAT High Resolution Imager (pass band 0.2–2.4keV) which lasted for 31.7 ksec. Extracting an image using this data shows a clear X-ray source close to the position of RAT J1953+1859. Although not obvious from this image, there are two sources noted in the ROSAT HRI pointed catalogue which are 4.1'' and 6.2'' distant from the optical position of the variable object and have quoted count rates of 0.0034(6) and 0.0057(8) counts/sec. In the subsequent analysis we assume that the wavelet analysis which was used in making the HRI catalogue has mistakenly distinguished two sources when there is only one in reality. We therefore believe that we have identified the X-ray counterpart of RAT J1953+1859 and has a count rate of 0.0091 ct/s in the HRI.

We took the event data and corrected the arrival times



**Figure 6.** The top panel shows the power spectra of the flux (left hand panel) and the V/R ratio (right hand panel) of the  $H\alpha$  line in quiescence. In the lower panel we show the same plots made using data taken in outburst (in Oct 2008).



**Figure 5.** The stacked spectra showing the  $H\alpha$  emission line taken on Oct 6 2008 when the source was in a quiescent state. Each spectrum has been normalised so the continuum is unity and time increases vertically.

of every event to the solar system barycenter. We searched for a periodic modulation in the X-ray light curve using a Discrete Fourier Transform. There is no evidence for any modulation period in the data. Because of its low count rate it is difficult to put an upper limit on the amplitude of any inherent period. However, we consider it to be quite possible

that a period of 20 mins with an amplitude of, say, 10 percent could easily go undetected.

We used the on-line tool PIMMS (Mukai 1993) to convert the *ROSAT* HRI count-rate to flux assuming a Galactic column density of  $1 \times 10^{20} \text{ cm}^{-2}$  and an internal absorption of  $5 \times 10^{20} \text{ cm}^{-2}$  (appropriate for an accreting binary source). Assuming a thermal bremsstrahlung emission spectrum of temperature of 20 keV a count rate of 0.0091 ct/s gives an observed flux (0.2–2.4keV) of  $3.6 \times 10^{-13} \text{ ergs s}^{-1} \text{ cm}^{-2}$ . This gives an observed X-ray luminosity of  $4.3 \times 10^{29} d_{100}^2 \text{ erg/s}$  (0.2–2.4keV) and an unabsorbed bolometric luminosity of  $2 \times 10^{30} d_{100}^2 \text{ erg/s}$ .

We can estimate the distance to RAT J1953+1859 using the absolute magnitude in outburst versus orbital period relationship for hydrogen (non-magnetic) accreting CVs (see Warner 1987 and Patterson 2009). Although there is some uncertainty in the peak brightness of RAT J1953+1859 in outburst, we assume  $V_{max} = 16.5$  (cf §3). To account for the apparent orientation of the disc we assume a binary inclination  $i = 45^\circ$ , which gives an inclination corrected peak brightness of  $V = 16.1$  (cf Patterson 2009, eqn 2). For an orbital period of 90 min, the  $M_V, max, P_{orb}$  relationship implies  $M_V = 5.3$  and therefore a distance of  $\sim 1.5 \text{ kpc}$ . Such a distance would indicate an X-ray unabsorbed bolometric luminosity of  $4.5 \times 10^{32} \text{ erg/s}$ . This implies that RAT J1953+1859 is one of the more luminous dwarf novae observed using *ROSAT* (van Teeseling, Beuermann & Verbunt 1996).

van Teeseling & Verbunt (1994) plot the X-ray Optical/UV flux ratios for a number of CVs of different types. For sources not observed using *IUE* they use the rela-

tionship  $\log F_{(UV+Opt)} = -0.4m_V - 4.32$  as an approximate guide. For RAT J1953+1859 in a low state, this gives  $F_{UV+Opt} = 3.3 \times 10^{-13}$  ergs s<sup>-1</sup> cm<sup>-2</sup>. For an unabsorbed X-ray flux over the energy range 0.1–2.0keV of  $5.0 \times 10^{-13}$  ergs s<sup>-1</sup> cm<sup>-2</sup> this gives an  $F_X/F_{UV} \sim 5$ . Although there is considerable uncertainty in this calculation, this ratio suggests an orbital period of approximately 1 hour (cf Figure 7 of van Teeseling & Verbunt 1994).

## 6 DISCUSSION AND CONCLUSION

RAT J1953+1859 shows clear evidence for low and high accretion states and has a clear X-ray counterpart. Further, it shows no emission from He II (4686Å) during quiescence, while the Balmer emission lines appear rather broad (1800 km/s). During outburst, there is some evidence that the light curve repeats on a period of  $\sim 90$  mins. This is consistent with the 80–90 min period seen in the V/R ratio derived from spectra taken during quiescence. All of these characteristics point to RAT J1953+1859 being a CV and a dwarf nova in particular.

Most dwarf novae with periods shorter than the period gap (2 hrs) are SU UMa systems – these dwarf novae experience super-outbursts which are brighter and last much longer than normal outbursts. If we assume for argument that the 90 min period is real, then this period would be the signature of the super-hump modulation, which is typically a few percent longer than the orbital period. The 80–90 min modulation seen in the V/R ratio power spectra during quiescence is therefore likely due to the binary orbital period.

What makes RAT J1953+1859 unusual is that it was discovered by means of high amplitude QPOs seen during quiescence. QPOs have been seen in many CVs, ranging from  $\sim 100$  sec to  $\sim 2000$  sec (see Warner 2004 for a recent review of the whole range of quasi-periodic behaviour seen in CVs). However, QPOs are mostly seen during a dwarf nova outburst, or in the rise up to, or decline from an outburst. We know of only two instances where quasi periodic behaviour has been seen in dwarf novae in quiescence and both had periods which were shorter than that observed in RAT J1953+1859. V893 Sco showed oscillations on a period of 5.7 mins (and an amplitude of  $\sim 0.2$  mag) during one night of observation (Bruch, Steiner & Gneiding 2000) and WX Hyi which showed QPOs with a period near 3 min (and amplitude of  $\sim 0.1$  mag) at several quiescent epochs (Pretorius, Warner & Woudt 2006).

Gänsicke (2005) gave a summary of the different means for discovering CVs. While around half were discovered as a result of their optical variability, all these systems were found as a result of the source undergoing an outburst. RAT J1953+1859 is the first CV to be identified as a result of high amplitude QPOs seen during quiescence. We agree with Pretorius et al (2006) who note that the apparent lack of QPO's found in dwarf nova in quiescence could be simply that people have not looked for them.

The RATS project has several million light curves in its archive. We have so far concentrated on identifying sources which show periodic behaviour in their light curves. A next step is to apply a number of different variability measures. Since CVs show prominent flickering behaviour (eg Bruch 1992) we expect to discover many more CVs through this

means in our survey. We therefore have good reason to expect that high time resolution photometric surveys such as RATS are likely to become an increasingly important tool for identifying accreting binaries in general and cataclysmic variables in particular. More complete samples of such systems may be selected by this methods using, for instance, the LSST and VST.

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## REFERENCES

- Bramich, D. M., et al, 2005, MNRAS, 359, 1096
- Bruch, A., 1992, A&A, 266, 237
- Bruch, A., Steiner, J. E., Gneiding, C. D., 2000, PASP, 112, 237
- Gänsicke, B. T., 2005, ASP Conf Series, 330, 3
- Geffert, M., Maintz, G., 2000, A&AS, 144, 227
- Harris, W.E. 1996, AJ, 112, 1487
- Martinez-Pais, I. G., Giovannelli, F., Rossi, C., Gaudenzi, S., 1994, A&A, 291, 455
- Martinez-Pais, I. G., Giovannelli, F., Rossi, C., Gaudenzi, S., 1996, A&A, 308, 833
- Mukai, K. 1993, Legacy 3, 21
- Patterson, J., submitted MNRAS, arXiv:0903.1006v1
- Pretorius, M. L., Warner, B., Woudt, P. A., 2006, 368, 361
- Ramsay, G., Hakala, P., 2005, MNRAS, 360, 314
- Ramsay, G., Napiwotzki, R., Hakala, P., Lehto, H., 2006, MNRAS, 371, 957
- Shafter, A. W., Hessman, F. V., 1988, AJ, 95, 178
- van Teeseling, A., Verbunt, F., 1994, A&A, 292, 519
- van Teeseling, A., Beuermann, K., Verbunt, F., 1996, A&A, 315, 467
- Wallace, P. T., Gray, N., 2002, Starlink User Note, 5
- Warner, B., 1987, MNRAS, 227, 23
- Warner, B., 2004, PASP, 116, 115