RR Pictoris: an old nova showing superhumps and QPOs

L. Schmidtobreick\(^1\)\(*\), C. Papadaki\(^2,1\)\(†\), C. Tappert\(^3\)\(‡\), and A. Ederoclite\(^1\)\(§\)

\(^1\)European Southern Observatory, Casilla 19001, Santiago 19, Chile
\(^2\)Vrije Universiteit Brussel, PLeinlaan 2, 1050 Brussels, Belgium
\(^3\)Departamento de Astronomía y Astrofísica, Pontificia Universidad Católica, Casilla 306, Santiago 22, Chile

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ABSTRACT
We present time–resolved V–photometry of the old nova RR Pic. Apart from the hump–like variability, the light curves show the strong flickering and random variation typical for RR Pic. We do not find any convincing evidence for the previously reported eclipse. The extrapolated eclipse phase coincides with a broad minimum, but comparing the overall shape of the light curve suggests that the eclipse should actually be located around phase 0.2. The orbital period which we derive from these data agrees well with the old one, any uncertainty is too small to account for the possible phase shift. Apart from the 3.48 h period, which is usually interpreted as the orbital one, we find an additional period at \(P = 3.78\) h, which we interpret as the superhump period of the system; the corresponding precession period at 1.79 d is also present in the data. We also find indications for the presence of a 13 min quasi–periodic oscillation.

Key words: Physical data and processes: accretion, accretion discs – stars: novae, cataclysmic variables – individual: RR Pic.

1 INTRODUCTION
Classical novae are a subclass of cataclysmic variables (CVs), close interacting binary stars with a white dwarf primary receiving matter from a Roche–lobe–filling late–type star. They are distinguished by the observation of a thermonuclear runaway outburst, the nova explosion. As such, RR Pic was discovered by Spencer Jones (1931) at maximum light in 1925 and, although it was a slow nova, it is supposed to be in its quiescence state by now. The orbital period of 0.145025 days (Vogt 1975) places it just above the period gap and into the regime of the SW Sex type stars. Indeed, RR Pic has been found to show several observational features typical for SW Sex stars (Schmidtobreick et al. 2003) and can thus be regarded as a nova–like CV with very high mass transfer rate.

Vogt found the lightcurve dominated by a very broad hump, often interrupted by superimposed minima. He explained this behaviour by an extended hot spot region with an inhomogeneous structure. Haefner & Metz (1982) however, explained their own time–resolved photometric and polarimetric observations together with radial velocity variations of the He II (4686 A) emission line (Wyckoff & Wehinger 1977) by suggesting the presence of an additional source of radiation in the disc opposite of the hot spot. The presence of such an emission source was confirmed via Doppler tomography by Schmidtobreick et al. (2003) and Ribeiro & Diaz (2006). From high speed photometry, Warner (1986) concluded that during the 1970s (about 50 yr after outburst) structural changes have taken place in the system, resulting in a more isotropic distribution of the emitted radiation. In addition, he has found evidence for a shallow, irregular eclipse, showing RR Pic to be a high inclination system. Note that no signature of an eclipse had been found in the previous lightcurves. In addition to the orbital period, Kubiak (1984) found a periodic modulation in the optical with a 15 min period. He interpreted this as the rotation of the white dwarf and concluded that RR Pic is an intermediate polar. Haefner & Schoembs (1983) however, repeated the high time–resolved photometry on a longer time–scale and could not find any sign of this short period. Since no 15 min period variation is found in X–ray measurements (Becker & Marshall 1981) either, they concluded that Kubiak’s variation was more likely a transient event in the disc rather than a rotating white dwarf. Also Warner’s high–speed photometry does not reveal any period other than the orbital one.

Schmidtobreick et al. (2005) compared radial velocity curves of different epochs and noticed a shift of about 0.1 phases of the radial velocity curves of data taken two years apart. They argue that this might be due to unstable emission sources in the accretion disc or might indicate a change in the orbital period. To test these alternatives, we per-
Table 1. Summary of the observational details: Date & UT at the start of the first exposure, the number of exposures, the individual exposure time, the covered orbital cycles and the acquisition ID are given.

| Date     | UT    | #exp | $t_{\text{exp}}$ [s] | cycles | ID   |
|----------|-------|------|----------------------|--------|------|
| 2005-02-08 | 00:45:44 | 483  | 20                  | 2.03   | 1    |
| 2005-02-09 | 01:17:57 | 533  | 20                  | 1.76   | 1    |
| 2005-02-10 | 01:17:23 | 495  | 20                  | 1.63   | 1    |
| 2005-02-11 | 01:13:37 | 530  | 20                  | 1.74   | 1    |
| 2005-02-12 | 01:09:17 | 540  | 20                  | 1.77   | 1    |
| 2005-02-13 | 01:07:03 | 499  | 20                  | 1.79   | 1    |
| 2005-02-14 | 01:06:42 | 534  | 20                  | 1.76   | 1    |
| 2005-03-18 | 01:36:23 | 240  | 20                  | 0.80   | 1    |
| 2005-03-20 | 01:35:17 | 320  | 20                  | 1.08   | 1    |
| 2005-03-25 | 02:31:58 | 80   | 20                  | 0.26   | 2    |
| 2005-03-26 | 00:24:42 | 320  | 20                  | 1.06   | 2    |
| 2005-03-26 | 23:58:29  | 329  | 20                  | 1.15   | 2    |
| 2005-03-31 | 00:38:39  | 241  | 20                  | 0.92   | 2    |
| 2005-03-31 | 03:52:05  | 56   | 20                  | 0.18   | 1    |
| 2005-04-09 | 23:29:27  | 318  | 20                  | 1.06   | 2    |

We performed new time–resolved photometry of RR Pic with the aim to determine the orbital period and look for a possible change that could account for the observed phase shift. These data and the results are presented in this paper.

2 DATA

The time resolved photometry was done using a V–filter in front of a 512x512 CCD mounted on the 1.0 m SMARTS telescope at CTIO, Chile. The data were taken in 2005 between Feb 07 and April 10 and cover about 18 orbital cycles with a time resolution of 40 s. The details of the observations are given in Table 1. The reduction was done with IRAF and included the usual steps of bias subtraction and division by skyflats.

Aperture photometry for all stars on the CCD field was computed using the stand–alone version of DAOPHOT and DAOMASTER. Differential light curves were established with respect to an average light curve of those comparison stars, which were present on all frames and checked to be non–variable. While the original idea was to use the same comparison stars for all epochs, we had to settle for two sets of comparison stars, as some of the later data were taken with a different acquisition. The first set included five, the second set six comparison stars; the two sets are distinguished by the acquisition IDs 1 and 2 in Table 1 corresponding finding charts are given in the appendix. The difference in the target’s magnitudes between the two sets were established from three common stars as 0.31. The magnitudes of the second set were shifted accordingly.

3 RESULTS

3.1 The orbital period

The obtained light curves are plotted in Figure 1. They show a clear variation. The data were analysed with the Scargle and analysis-of-variance (AOV) algorithms implemented in MIDAS, as well as with PERIOD 04. All three methods agree on the same period $P_{\text{orb}} = 0.14503(7)$ which corresponds to a strong and unambiguous peak in the periodograms at $f_0 = 6.895$ cycles/day (Fig. 2). We subdivided the observations in different sets but always obtained the same result, which thus indicates the robustness of this peak. We included photometric data taken in 2004 to increase the accuracy of the orbital period and derived $0.1450255(1)$ d. This value agrees very well with the former reported one of $P = 0.1450254(7)$ d.

We averaged our data with respect to the orbital period $P = 0.14502545$ d. The orbital phase was computed for each data point using the ephemeris for the eclipse of Schmidtobreick et al. (2005). The data points have been averaged into bins of 0.01 phases. On average, 55 individual data points went into each point of the average light curve. The result is plotted in Fig. 3. For clarity, two orbital cycles are plotted (phase 0–2). For the first cycle, the sigma of each average point is indicated with an error bar. Apart from the broad hump, the light curve shows two clear features, a narrow peak on top of the hump at a phase of 0.42 and a sharp minimum at a phase of 0.18. As expected for an average light curve, the flickering, which is present in the individual light curves is completely gone.

With PERIOD 04, we checked for the harmonics of the orbital period and found peaks close to the theoretical values and down to the 6th harmonic at 0.0207 d which has a power around 2 and is thus at the edge of detection. We used the theoretical harmonics to fit the shape of the light curve. We then built an average fit in the same way as the average light curve. The result is plotted in Fig. 3. For clarity, two orbital cycles are plotted (phase 0–2). For the first cycle, the residuals with the average light curve plotted below. Note that this best harmonic fit also contains the above mentioned features: the narrow peak and the sharp minimum. The residuals of fit and average light curve show high frequency periodic variations with an amplitude around 0.01 mag and harmonic to the orbital one (as they would otherwise not appear in a phase diagram). This indicates, that harmonics of an order higher than 6 are present in the data even though they do not appear in the power spectrum.

We point out that neither the individual light curves of RR Pic nor the average one show the eclipse that has been observed before. At phase 0, which is the phase of the eclipse by Warner (1986), we find a broad minimum.

3.2 The search for superhumps

For the further analysis, we subtracted from each data point the corresponding value of the average light curve. The resulting residual light curves are plotted in Fig. 4.
Figure 1. The light curves of RR Pic. The phase refers to the orbital period of $P = 0.14502545(7)$ d, $\phi = 0$ corresponds to the eclipse-ephemeris as defined by Schmidtobreick et al. (2005).
As expected they are dominated by the strong flickering. However, there seems to be an additional brightness variation present on longer time-scales. We checked the periodograms for any periodic signal and indeed found a peak at \( f_{\text{sh}} = 6.34 \text{ cycles/day} \), which corresponds to a period of \( P_{\text{sh}} = 3.78 \text{ h} \) (see Fig. 4). The interpretation of this periodic signal is supported by the presence of various typical frequencies in the numerology of superhumps as described e.g. by Patterson et al. (2005). We find peaks at 0.56, 13.21, and 20.14 cycles/day, which correspond to \( \Omega = 1/P_{\text{orb}} - 1/P_{\text{sh}}, 2f_0 - \Omega \) and \( 3f_0 - \Omega \). The beat period \( 1/\Omega = 1.79 \text{ d} \) is thus interpreted as the probable precession period of the accretion disc.

A detailed investigation on the robustness of this peak is not as successful as for the orbital period. While the peak is present in all combinations of data taken in February, it does not appear in the data taken in March or April. This might in part be explained by the way the observations were performed. The February observing run was dedicated to RR Pic, which was thus observed for at least two orbits every night. In March and April, the observations were done in service mode, and in general, only slightly more than one orbit was observed per night.

We averaged the residual light curve for the different data sets using the period of the superhump. In Fig. 5, these average residual light curves are plotted. They clearly show that the superhump is present during all our observing runs. The absence of a clear corresponding peak in the Scargle-diagram is thus only due to the observing strategy and does not indicate the absence of the superhump in the latter data.

Fig. 6 also gives the impression that the superhump is highly structured. Short-periodic variations are present especially during the early phases (0–0.7), while the later part of the lightcurve looks rather stable. The amplitude of the high-frequency variations is around 0.01 mag, thus it is similar in frequency and amplitude to the variations seen in the residuals of Fig. 3.

### 3.3 Quasi-periodic oscillations (QPOs) and flickering

High-frequency variations present in Fig. 1 and Fig. 4 suggest the possible presence of QPOs. The time-scale of these variations is in the order of 15 min, and they seem to repeat themselves albeit with inconsistency in amplitude and frequency. We therefore searched the periodograms for signals that might indicate the existence of possible QPOs in RR Pic. Although, we did not detect any coherent signal, all nights do show several peaks in the power spectrum in the range between 90 and 130 1/d. As Fourier analysis can omit signals, such as QPOs, that are unstable in amplitude and frequency (see Papadaki et al. (2006) for such examples), we applied the following procedure in order to enhance a possible QPO signal. The power spectra of all nights were averaged and plotted in log-log scale (see Fig. 5). In this plot, the harmonics of the orbital period can be followed down to the 11th harmonic at 82.81 1/d, whose power exceeds the continuum by a factor of 1.9. Around \( \log F = 2.041 \text{ 1/d} \) a broad peak becomes visible, pointing to the counterpart of a QPO as suspected from the inspection of our light curves. The individual average power spectra of February and March–April 2005 (middle and lower plot of Fig. 6 respectively) show that the 13 min QPO is always there but more prominent in the March–April data. The power of this feature exceeds the continuum by a factor of 4. It is the counterpart of a 13 min oscillation which agrees with the typical value for the oscillations present in the light curves and even more visible in the residual light curves (see Fig. 1 and 5). Note that the peak is present in the February data as well as the March–April data but is more dominant in the latter.

The flickering in CVs, described through a shot noise–like process, results in the so-called “red noise” seen in the power spectra of CVs as the exponential decrease of power with frequency. It thus follows linearity in a log-log scale diagram. If all shots have the same duration, the periodogram of the resulting light curve equals the periodogram of a single shot and thus just describes its shape. The power law
Figure 4. The residual light curves of RR Pic, with the average light curve subtracted.
index $\gamma$, given by the slope of the linear decrease in the log–log scale, has a value of 2 in the classical "shot noise", where the shots have an infinite rise–time and then decay. If, however, as expected from mechanisms generating the flickering, the shots’ durations are different and follow some kind of distribution, then $\gamma$ gets smaller (Bruch 1992). In this way, $\gamma$ can be used for the characterisation of flickering activity but so far has been unsuccessful to advance on understanding the physical origin of flickering activity. For more detailed information on the mechanisms and the resulting power law, see Papadaki et al. (2006) and references therein.

Clearly, Fig. 7 shows that RR Pic is also characterised by "red noise". We fitted the linear part for frequencies above 100 c/d by a least–square linear fit and determined $\gamma = 1.40(2)$ for the average log–log power spectrum. Given the noisiness of the power spectrum, the precise choice of the fitting interval becomes more difficult. Applying small changes of this interval causes changes in the value of $\gamma$ up to 0.13 and therefore 0.1 should be considered as the real uncertainty of $\gamma$. Within this error, the flickering pattern remains stable within the span of our observations.

We checked the photometric data taken in 2004 (Schmidtobreick et al. 2005) for the presence of the QPOs and the flickering pattern. Only two orbits go into this analysis and the average power spectrum is rather noisy. We find no indication for the presence of a QPO. The slope of the linear decrease in the log–log power spectrum has been determined as $\gamma = 1.6$.

4 DISCUSSION

4.1 The orbital period and the radial velocity phase shift

With the data spanning two years, we derive an orbital period of $P = 0.1450255(1)$ d which agrees well with the formerly reported ones within our uncertainty. We can thus only give an upper limit to any possible change of the orbital period as $10^{-7}$ d or about 0.1s.

The formerly reported phase shift of 0.1 phases that was observed in the radial velocities of data taken two years apart (Schmidtobreick et al. 2003), can thus not be explained by a change of the orbital period. To obtain a shift of 0.1 phases after such about 5000 cycles, the period must have changed by at least $0.1 \times 0.14502545d/5000 = 3 \times 10^{-6}$ d, which is in contradiction to the new measurements. This shift is thus best explained by a varying emission structure in the accretion disc of RR Pic which can influence the shape and phasing of the radial velocity curve. Such variations have been observed by Schmidtobreick et al. (2006) using Doppler tomography techniques on several emission lines in the spectra of RR Pic. Also, the structural change suggested by Warner (1986) supports the idea that the accretion disc of RR Pic is not stable but undergoes changes of various extent.
4.2 Superhumps and QPOs

The interpretation of the newly found variation with a period of $P_{sh} = 3.78$ h as a superhump seems obvious due to the presence of the typical frequencies as described in section 3.2. However, it has to be noted that the resulting value for $P_{sh} - P_{orb} = 18$ min is rather large for a nova-like star and implies a rather large mass ratio. Still, such large mass ratios are not unlikely for high-mass transfer CVs. Patterson (2001) relates the mass ratio $q$ to the orbital and superhump period via an empirical formula $\epsilon = 0.216 \cdot q$ with $\epsilon = \frac{P_{sh} - P_{orb}}{P_{sh}}$. In the case of RR Pic, we find $\epsilon = 0.0860$ and thus derive a mass ratio of $q = 0.39$. This value would actually be above the critical mass ratio for which superhumps are observed and is unlikely to be correct. In fact, Patterson et al. (2005) revised the formula especially for large mass ratios where the original one would predict too large values of $q$. Using this new formula $\epsilon = 0.18q + 0.29q^2$, we derive a mass ratio $q = 0.31$ for RR Pic, which is more reasonable. This value is slightly higher than the value found by Ribeiro & Diaz (2006) who used a mass diagram calculated from their radial velocity measurements to derive $0.1 < q < 0.2$. However, they do acknowledge the fact that the radial velocities might be strongly influenced by emission sources in the accretion disc. Since we know that these are not stable, the radial velocity curve might not actually trace the velocity of the white dwarf. Increasing the velocity of the white dwarf would yield a higher mass ratio $q$. On the other hand, the formula used above describes an empirical average and does not necessarily give the mass ratio for individual systems, so caution is advised also with this method. To unambiguously determine the masses involved in the RR Pic system, observations of the secondary star and its radial velocities are needed.

Looking at Figure 6, there seems to be some short-term variation pattern stable with the superhump period. Thus the question arises whether the QPOs are connected to the superhump phenomenon. However, zooming into the lightcurve folded on the orbital period one notices a similar short-term variation (not shown). So both, the orbital variation as well as the superhump have sub-structures. Note that the frequency of the found QPOs is not a harmonic of the superhump’s main frequency, it rather lies right in between the 17th and 18th harmonic.

Kubiak (1984) had found some similar oscillations, which however were not confirmed afterwards. He reported a most likely period of 15 min, although 13 or 17 min were also possible with his data. Comparing this information with Fig. 4 we see a small peak at 15 min, nothing at 17 min and the maximum is clearly at 13 min. From this, we conclude that we actually confirm Kubiak’s findings although we would place the most likely period at 13 min rather than at 15 min. The fact that these QPOs were not present in our data from 2004 is consistent with the fact that Kubiak’s variations were not confirmed in later observations. RR Pic seems indeed to change its behaviour every now and then and not all observational phenomena are present at all times.

4.3 Is RR Pic eclipsing?

RR Pic has been reported by various authors to show eclipse-like features (Warner 1986, Haefner & Betzenbichler 1991), while others have not noted this (Vogt 1973, Kubiak 1984). Vogt confirmed that he never saw any evidence for the presence of an eclipse in his data (private communication). In fact, Warner (1986) compared the lightcurves taken during the 60s and beginning of the 70s with those taken later in the 70s and 80s and suggested a change in the structure of the accretion disc to explain the different appearance of the lightcurves. While the early lightcurves were dominated by two humps of about 0.3 mag brightness and several small minima, the later lightcurves were rather flat (no variation larger than 0.1 mag) and showed the already mentioned eclipse-like feature.

If we put our observations in this context, it seems as if RR Pic is back to or at least closer to its state in the early 70s. We observe a hump-like feature of about 0.3 mag brightness, we see the two minima reported by Vogt, a broad one followed by a smaller one, but we find no evidence for an eclipse.

Comparing the overall shape of the average light curve with previous observations (found e.g. at 'The Center for Backyard Astrophysics') suggests that if the eclipse was present, it should actually correspond to the small minimum that we observe at phase 0.2 and not to phase 0 which would be the original eclipse phase reported by Warner. Another interesting point is the fact that the minimum of the superhump falls on the phase of the eclipse. Since no ephemeris were known for the superhump, we arbitrarily set the 0-phase of the superhump lightcurve to Warner’s eclipse phase. This means that at least on this eclipse observed by Warner, the superhump feature was also in minimum. Maybe, the eclipse feature is in fact a resonance phenomenon of the minima of the orbital lightcurve and the superhump lightcurve. Such resonance phenomena have been observed before. E.g. in the dwarf nova OU Vir, a clearly eclipsing system, shows superhumps during outburst, in which case the deepness of the eclipse varies between 0.4 and 1 mag and is modulated with the precession cycle, i.e. the beat of orbital and superhump period. Assuming that RR Pic has a lower inclination and in general more shallow eclipse, it’s detection or non-detection could well be modulated with the 1.79 d precession period. (Patterson et al. 2003). Warner stated that the eclipse was shallow and not present in all cycles, so this might support the idea of a resonance amplification. If the superhump minimum coincides with the second minimum in the lightcurve, it might enhance this one to be taken for an eclipse as in the 'The Center for Backyard Astrophysics' data.

On the other hand, we know from Doppler tomography Schmidtobreick et al. (2003), Schmidtobreick et al. (2003) and Ribeiro & Diaz (2006) that structural changes do take place in the accretion disc of RR Pic. As such, also the visibility of an eclipse might be influenced by these changes. It would be interesting to combine photometric variability observations with Doppler tomography of the same night to actually compare the appearance of the accretion disc in the

1 http://cbastro.org/cataclysmics/atlas/rrpic.html
Doppler map with the shape of the lightcurve, and i.e. the presence of an eclipse.

5 CONCLUSIONS

We have presented optical lightcurves of RR Pic and shown that they are dominated by a strong orbital variation. The orbital period derived from this data is consistent with the previous reported ones. I.e. a change of this period can not be responsible for the previously observed shift in the phases of radial velocity curves. Instead, this shift is rather due to structural changes that are known to occur in the accretion disc of RR Pic.

In addition to the orbital variation, a superhump is found that was used to derive the mass ratio $q = 0.31$. This value does not agree with a previously reported lower one, further observations are needed for clarification.

QPOs of 13 min are present in all our data taken between February and April 2005. Older data from 2004, do not show this oscillation. While our analysis thus confirms the variations reported earlier, it also shows that these QPOs are a transient phenomenon. Their presence might be connected with the accretion disc's structure if they occur due to an illumination of blobs in the inner accretion disc from a spinning white dwarf.

From our data we can not confirm the presence of an eclipse. Instead, we note that at least in one historical case the eclipse occurs when the minima of orbital light curve and superhump lightcurve fall together. This might indicate that the observed eclipse is a resonance phenomenon between the two lightcurves and its existence or not-existence is modulated with the precession period. We would like to clarify that we do not rule out the presence of a shallow eclipse but insist that either its visibility is enhanced by the resonance or a favourable structure of the accretion disc is needed for an eclipse to be observed.

In general we conclude that RR Pic is a highly variable system. The previously reported changes that happen in the accretion disc are probably responsible for the various features in the lightcurve that are not present at all times. To really understand what is going on in this system, parallel time-resolved spectroscopy and photometry would be needed over several cycles.

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Figure 1. The finding chart of RR Pic (indicated by the square in both images) with the two selected sets of comparison stars (indicated by circles). The left image corresponds to ID1, the right one to ID2 (see table I and text).