

Periodic variations in the colours of the classical T Tauri star RW Aur A

P. P. Petrov^{1,*}, J. Pelt^{1,2}, and I. Tuominen¹

¹ Astronomy Division, PO Box 3000, 90014 University of Oulu, Finland

² Tartu Observatory, 61602 Tõravere, Estonia

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Abstract. The classical T Tauri star RW Aur A is an irregular variable with a large amplitude in all photometric bands. In an extended series of photometric data we found small-amplitude periodic variations in the blue colours of the star, with a period of $2^{\text{d}}64$. The period was relatively stable over several years. The amplitude of the periodic signal is $0^{\text{m}}21$ in $U-V$, $0^{\text{m}}07$ in $B-V$, and about $0^{\text{m}}02$ in $V-R$ and $V-I$. No periodicity was found in the V magnitude. The relevance of this photometric period to the recently discovered periodicity in spectral features of the star is discussed, and the hypothesis of a hot spot is critically considered.

Key words. stars: individual: RW Aur – stars: pre-main sequence – stars: variables – methods: statistical

1. Introduction

RW Aur is a classical T Tauri star (CTTS) with an unusually strong and variable emission line spectrum and large amplitude irregular variations in the brightness as well as in the veiling of the photospheric spectrum. The star is a resolved triple system (Ghez et al. 1993) with RW Aur A dominating the brightness in the optical spectrum. In a recent detailed investigation of RW Aur A (Petrov et al. 2001, hereafter referred to as Paper I) periodic variations in many spectral features were found, with a period within $2^{\text{d}}6-2^{\text{d}}9$. The period was stable over several years of observation. A model of non-axisymmetric magnetically channeled accretion seems to explain most of the observed variations. The asymmetry of the accretion can be caused either by a close, low-mass, invisible companion (Gahm et al. 1999), or by a misalignment of the magnetic and rotational axes.

The presence of an asymmetric accretion shock at the stellar surface should modulate the strengths of the He I and He II emission lines presumably formed in the post-shock region (Calvet & Gullbring 1998), while the hot photospheric spot (10^4 K) below the shock should modulate the brightness of the star. In case of RW Aur A, clear periodic modulations in He I, Fe II and other emissions were observed (Paper I) which gives a unique opportunity to study the expected periodic modulation of the brightness.

In this paper we search for periodicities in the variations of the brightness and the colours of RW Aur A, using all the available photometric data collected over three decades.

2. Observational data

The data were taken from the catalogue of UBVR photometry of TTS compiled by Herbst et al. (1994). For RW Aur A, the catalogue contains 575 observations in V and $B-V$, and fewer in other colours. The major part of the data are from the Maidanak Observatory (the ROTOR program by V. S. Shevchenko's group), and from Van Vleck Observatory (unpublished), other sources are Kardopolov & Filip'ev (1985), Rydgren et al. (1984) and Herbst et al. (1983). We also used the photometric data of 1996–99, presented in Paper I. Since the information about the observational errors is not available in all cases, we adopt equal weights for all data. The light curve is shown in Fig. 1, and the colour-magnitude diagrams are shown in Fig. 2.

There is a good correlation between V and the colours $B-V$, $V-R$ and $R-I$, with the slopes roughly corresponding to the mean law of interstellar extinction. It looks very much like the result of variable circumstellar extinction. Note, however, that for the spectral type of RW Aur A (K1–K4 V) the normal photospheric colour $B-V$ should be $0^{\text{m}}86-1^{\text{m}}05$. With $A_V = 0^{\text{m}}3$ (Paper I) the observed photospheric colour $B-V$ is expected to be within $0^{\text{m}}95-1^{\text{m}}14$. Most of the observed $B-V$ colours are

Send offprint requests to: P. P. Petrov,
e-mail: Peter.Petrov@Oulu.Fi

* On leave from the Crimean Astrophysical Observatory.

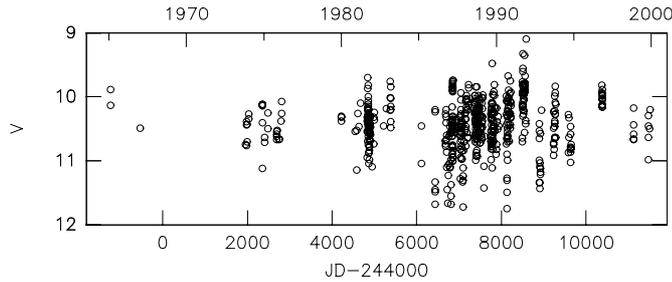


Fig. 1. Light curve of RW Aur A from 1965 to 1999.

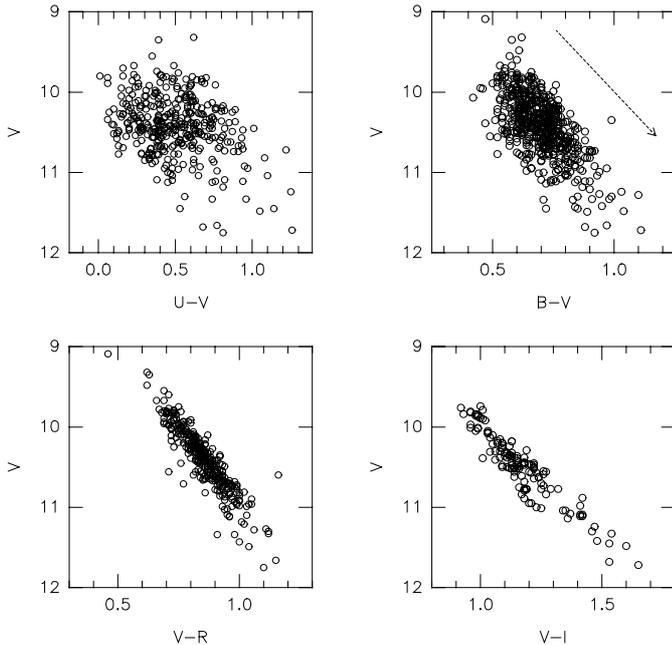


Fig. 2. Colour-magnitude diagrams. The direction of reddening is shown in the V vs. $B-V$ diagram according to the mean law of interstellar extinction. The $UBVR$ bands are in the Johnson system, the I band is in the Cousins system.

much bluer. This effect is also known for other CTTS: the stars typically have closest to normal photospheric colours when they are at minimum brightness, while becoming overly blue at maximum light (Vrba et al. 1993). This is believed to be due to an additional, variable non-photospheric hot continuum which also accounts for the veiling of the photospheric line spectrum. The continuum may belong either to hot photospheric spots at the base of the accretion columns, or to plage-like regions of hot gas above the stellar surface. The contribution of the emission lines to the photometric bands also accounts for a part of the excessively blue colours.

3. Time series analysis

3.1. Feature at $P = 2^d.641$

The compiled data set of RW Aur A is very inhomogeneous. It contains large gaps and several dense subregions. To avoid any complication due to methodological artefacts, we selected for frequency analysis the simplest

statistic available: the variance of the least squares fit residuals divided by the original variance of the data. As the model to be fitted we used a single harmonic curve $\mu + A \cos(2\pi t w_k) + B \sin(2\pi t w_k)$, where μ is the mean level of the light curve and w_k , ($k = 1, 2, \dots, K$) is one of the trial frequencies. The computed row of K variance ratios forms the least squares (LS) frequency spectrum (see Pelt 1992).

The overall picture of the time variability of the star in the range of periods 0.8–1000 days is presented in Fig. 3. For the channels V , B and U , most of the variability is well concentrated around the zero frequency (the bunch of peaks around frequency 1 cyc/day is a result of aliasing from zero frequency). The relatively small peak at $2^d.641$ in the U band is just the feature we are going to analyse in more detail. As it is well seen from the same figure, the strength of the peak for $B-V$ is significantly amplified, and for the $U-V$ colour (computed as $(U-B) + (B-V)$) the peak becomes the strongest in the full range of frequencies. Its statistical significance can be demonstrated using different methods. For instance, when we carried out 1000 Monte-Carlo runs in the range of periods 2–3 days, the reshuffled data never showed peaks of this strength. For the full displayed range this gives a false alarm probability which is less than 0.0075. Due to the bad spacing of the data, any more detailed analysis can give only formally better levels of significance. This is why we tried to test the $2^d.641$ feature by using a careful analysis of separate subsets of the full data. The peak at $1^d.609$ in $U-V$ (see Fig. 3) is a result of aliasing ($\frac{1}{1.609} \approx 1 - \frac{1}{2.641}$), and we do not consider it further.

3.2. General and specific variability

From the colour-magnitude diagrams (Fig. 2) we can conclude that the total variability of RW Aur A consists of at least two components: general variability (GV), which is a large-scale variability in all the colours within about $0^m.5$, and specific variability (SV), which can be best seen in the colour-magnitude diagrams for $U-V$ and $B-V$, as the scatter of the points around the linear trend. This scatter is very small in the red colours but steeply increasing towards the UV. Figure 3 shows that the feature at $P = 2^d.641$ belongs to SV (it is totally absent from the V band). In order to investigate the SV more closely, we should eliminate the linear trend in the colour-magnitude diagrams and investigate the residual time variations in the colours, which can be defined as $(B-V)_{\text{res}} = (B-V) - C \cdot V + \text{const.}$ for $B-V$ and in a similar way for other colours. Thus, we included an extra term into the LS fit of the harmonics: $\mu + A \cos(2\pi t w_k) + B \sin(2\pi t w_k) + C \cdot V(t)$, and allowed coefficient C to vary together with the other model parameters μ, A, B . As a result we obtained a new statistic for the period search which allows to optimally separate SV from GV.

The results of such a procedure can be seen in Fig. 4, where short fragments of the LS spectra are depicted.

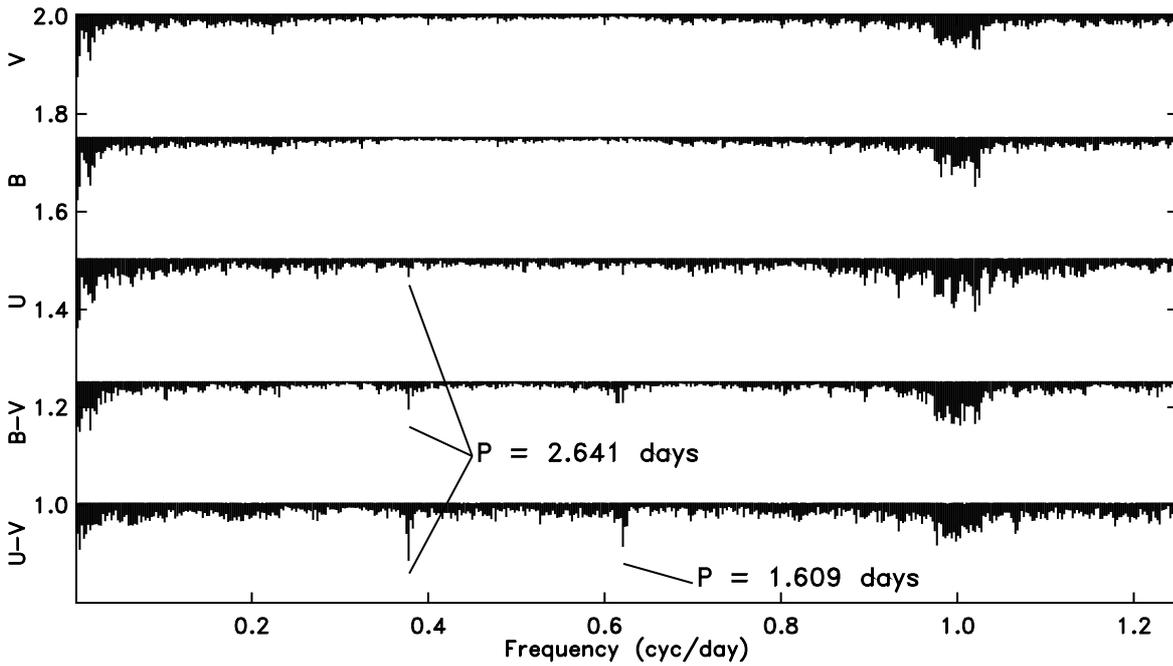


Fig. 3. Least squares spectra for magnitudes and colours. Due to the long time base, the actual spectra contain more than 300 000 points each, so that the plot is somewhat schematic. For every pixel of the plot, the minimum and maximum value of the spectra covered by that pixel was computed, and the spectral content for the corresponding pixel was plotted as a vertical line from minimum to maximum.

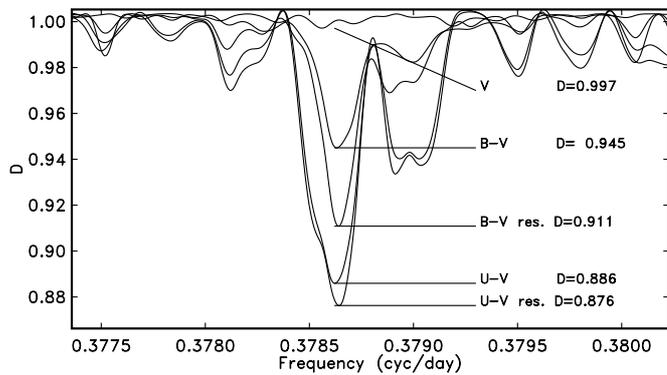


Fig. 4. Details of the LS spectra around period $P = 2^d641$. Specific values of the test statistic (denoted here by D) are also displayed. It is well seen that the peaks are amplified in the spectra of the residual variances.

One can see that a strong improvement is obtained for the $B-V$ colour. The improvement is even more dramatic in the red colours, where the amplitude of the periodic signal is very small ($SV \ll GV$). The phase diagrams with $P = 2^d641$ for the residual variations $(U-V)_{\text{res}}$ and $(B-V)_{\text{res}}$ are depicted in Fig. 5. The scatter is still quite significant so that we need to look at the data in more detail.

3.3. Stability of the period

Here, we will focus on the analysis of the residual variation $(U-V)_{\text{res}}$. The largest number of observations are concentrated in the following four seasons: 1981–82, 1987–88,

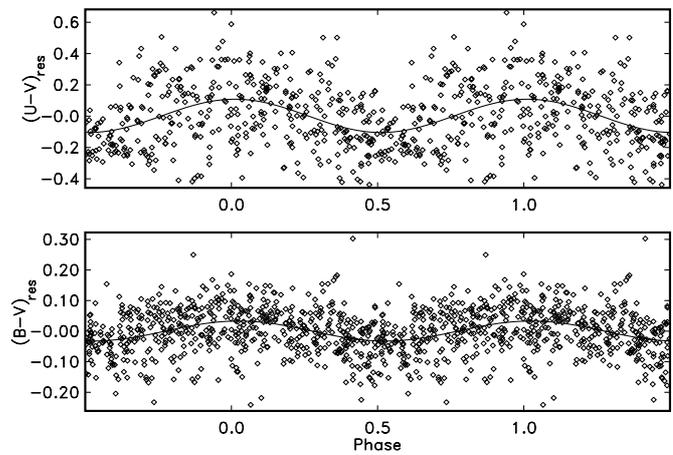


Fig. 5. The phase diagram for $(U-V)_{\text{res}}$ and $(B-V)_{\text{res}}$ with the period 2^d641 . The best fit harmonic is also given as a continuous line.

1988–89 and 1989–90. In Fig. 6 we plotted the results of the LS fits of a single harmonic with the period $P = 2^d641$ for each of the four seasons separately. The scatter for two seasons (1981–82 and 1988–89) is reasonably small, but for season 1987–88 it is much larger, and for the last season with the small number of points it is very high. However, the amplitudes (maximum–minimum) are still significant (0^m33 , 0^m20 , 0^m40 , 0^m15 , respectively), especially if compared to the amplitude 0^m21 of the full data fit (see Fig. 5). There is also a reasonably good phase stability: the phase shifts around the full fit phase are 20%, 5.7%, 3.3%, 8.3%, respectively.

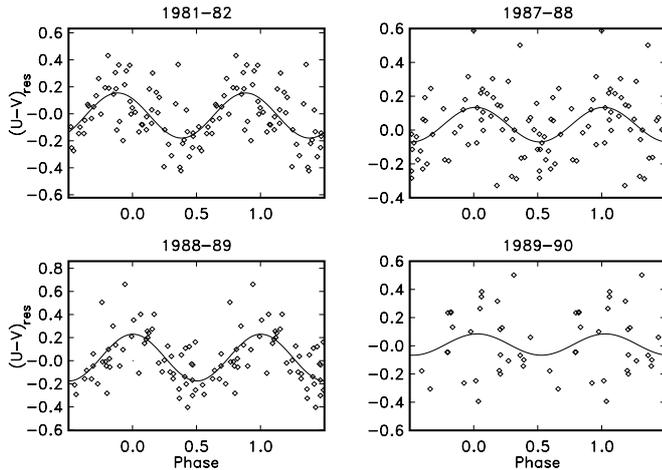


Fig. 6. Local fits for $(U-V)_{\text{res}}$ with the period 2.641 days. There are 59 points for the 1981–82 season, 54 points for 1987–88, 54 points for 1988–89, and 27 points for 1989–90.

As can be seen from Fig. 4 the feature around the period $2^{\text{d}}641$ consists of two main depressions in the LS frequency spectra. The smaller peak right from the main peak ($P = 2^{\text{d}}639$) is a result of a cycle count ambiguity between seasons 1981–82 and 1987–88. If we computed the LS spectrum for the three subsets from 1981–1989 together, ignoring all other data points, the peaks around $2^{\text{d}}641$ and $2^{\text{d}}639$ occurred to be comparably deep. Consequently, the last digit in the value of the accepted period depends on wildly scattered points outside the above mentioned seasons and must be taken only as the best approximation.

In conclusion, we can say that the most prominent feature in the frequency spectrum of the $U-V$ colour is certainly a real regularity which is more or less persistent at least during eight years (see Fig. 6).

4. Discussion: Is there a hot spot?

The periodic variations of the blue colours are most probably related to the periodicities in the spectral lines discussed in Paper I. The spectroscopic data set used in Paper I covered only four years (1996–1999), which allowed to find a period within the range $2^{\text{d}}6-2^{\text{d}}9$. The period of $2^{\text{d}}77$ was selected as the best one for demonstration of the phase diagrams in Paper I, although with a period of $2^{\text{d}}64$ the diagrams look similar. In this paper, using the much larger time span of the photometric data we confirm the period and prove that it was relatively stable over at least several years. The stability of the period probably excludes the possibility that the periodicity is caused by a local asymmetry in the magnetospheric structure, which is supposed to be a short-lived phenomenon. We still cannot distinguish between the binary hypothesis and the hypothesis of the inclined magnetic rotator (misalignment of the magnetic and rotational axes), discussed in Paper I.

The amplitudes of the periodic colour variations rising steeply towards the UV indicate the presence of a hot

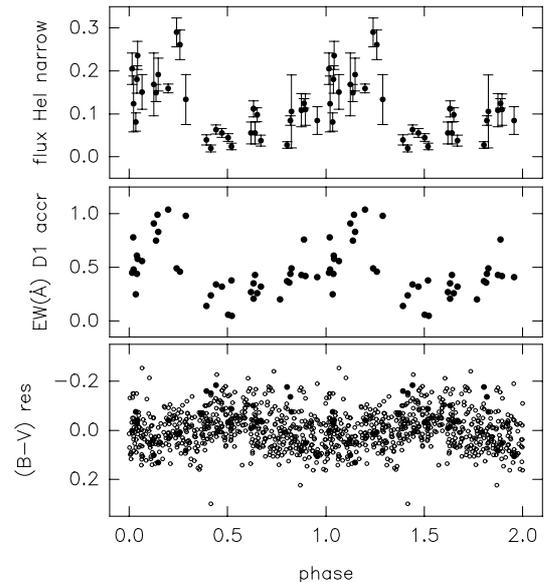


Fig. 7. Phase diagrams with the period $2^{\text{d}}641$. Upper: flux (in $10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$) in the narrow HeI emission. The errors are due to uncertainties in the decomposition of the HeI emission profile into the narrow and broad components. Centre: equivalent width of the NaI D1 accretion component. Lower: the residual $B-V$ colour (filled circles: the photometry made simultaneously with the spectroscopy; open circles: the whole set of the photometric data).

source of radiation (hot spot). When the whole data set is used, the full amplitudes of the sinusoidal oscillations are: $0^{\text{m}}21$ in $U-V$, $0^{\text{m}}07$ in $B-V$, and about $0^{\text{m}}02$ in $V-R$ and $V-I$. Using black body approximations for the fluxes from the photosphere and the hot spot, one can estimate the temperature of the hot spot and the fraction of the visible stellar disc covered by the spot (Vrba et al. 1993). With $T_{\text{phot}} = 4800 \text{ K}$, and the amplitudes given above, we get $T_{\text{spot}} = 15000 \text{ K}$ and the covering fraction 0.1%. Such a small spot gives only a $0^{\text{m}}05$ amplitude in the V magnitude.

In Paper I we presented strong arguments in favour of the magnetospheric accretion model. The accelerated gas stream(s) flowing toward the star is clearly seen in the red-shifted components of many spectral lines. The strengths of the red-shifted components vary periodically, being increased considerably at the phase when the accretion stream is in the line of sight. We found that the narrow HeI emission varies in correlation with the red-shifted accretion components, and concluded that the narrow emission originates from the shock region(s) at the bottom of the accretion stream, near the stellar surface. The broad emissions are believed to be formed in the global magnetosphere of the star. The two relevant phase diagrams are reproduced here with the new period $2^{\text{d}}641$ and compared to the colour phase diagram (Fig. 7).

We might now identify the small hot spot with the accretion shock at the stellar surface. Then we would expect the bluer colours when the narrow HeI emission is stronger. However, from Fig. 7 one can notice that quite

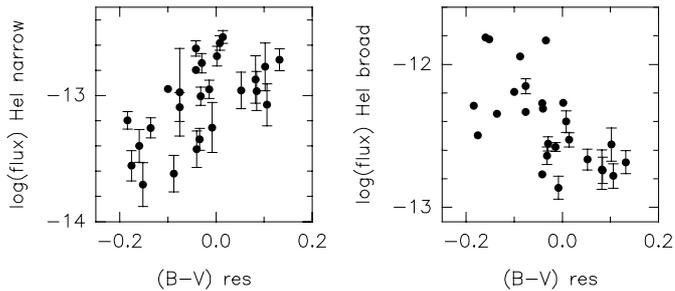


Fig. 8. Fluxes in the narrow and broad components of the He I emission vs. the residual $B-V$ colours.

the opposite is observed: when the colours are bluer, the flux in the narrow He I emission is lower. This inverse correlation is better seen in the Fig. 8 with the logarithmic scale for the flux. The “normal” correlation exists between the colour and the broad line flux: the larger the broad line flux, the bluer the colour (see also Paper I).

Hence, the colour varies in “anti-phase” to the strength of the accretion components and to the flux in the narrow He I emission, in the sense that the star is redder when the shock region is facing the observer. There is no doubt that magnetospheric accretion is going on in RW Aur A, and that the accretion column(s) exists, but the expected hot spot at the base of the accretion column does not reveal itself in our series of data. The small hot spot, discussed above, may belong to the non-uniformly distributed hot gas, which also radiates in the broad emission lines.

The apparent absence of the hot spot related to the accretion column is really puzzling. Either the accretion

shock is absent indeed, or the complicated geometry of the flows and possible extinction of light within the gas streams makes the observed variations so complicated. Simultaneous spectroscopic, photometric and polarimetric monitoring of the star could clarify the situation.

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