MAGNETOSPHERIC ACCRETION IN T TAURI STARS: OBSERVATIONAL TEST

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ABSTRACT. In the classical T Tauri stars (CTTS) the magnetic field plays an important role in the interaction between the star and the accretion disk. In 1996-2000 we have carried out an extensive spectroscopic and photometric monitoring of the extremly active CTTS RW Aur A in order to check for predictions of the magnetospheric accretion model. We find periodic rotational modulations in many spectral features, which may be explained as due to non-axisymmetric accretion, well in accordance with the model. The stable period ($2\overset{\rm d}{.}64$) was also found in the variations of the blue colours. Nevertheless, some of the important predictions of the model were not found in the star.

Key words: Stars: individual: RW Aur A—stars: pre-main sequence—stars: variables

1. Introduction

The young pre-main sequence objects of solar mass are known as irregularly variable T Tauri type stars. The classical T Tauri stars (CTTS) with strong emission spectrum, veiling and IR excess, are believed to possess accretion disk (Berout et al. 1988). The stellar magnetic field plays an important role in the interaction between the star and the disc. The concept of magnetically channeled accretion has been a guiding idea in the recent decade. The magnetospheric accretion model (Königl 1991, see also Calvet 1998 and references therein) predicts exsistence of accretion shocks at the footpoints of magnetic accretion channels. The hot spots at the stellar surface, assotiated with the accretion shocks, are believed to be responsible for the veiling and brightness variations.

In order to study the expected correlation between the veiling and brightness, we selected the most active CTTS RW Aur A, which varies in brightness in a vide range and shows clear evidences of accretion. Simultaneous spectroscopic and photometric observations were carried out during 32 nights in three seasons of 1996, 1998 and 1999, at the Nordic Optical Telescope (La Palma, Spain), with additional photometry at the Swedish telescope at the same site (for details see Petrov at al., 2001a, hereafter referred to as Paper I). During our observations the star varied in brightness within $V=9\overset{\rm m}{.}8$–$11\overset{\rm m}{.}0$, which is the most typical range of its variability.

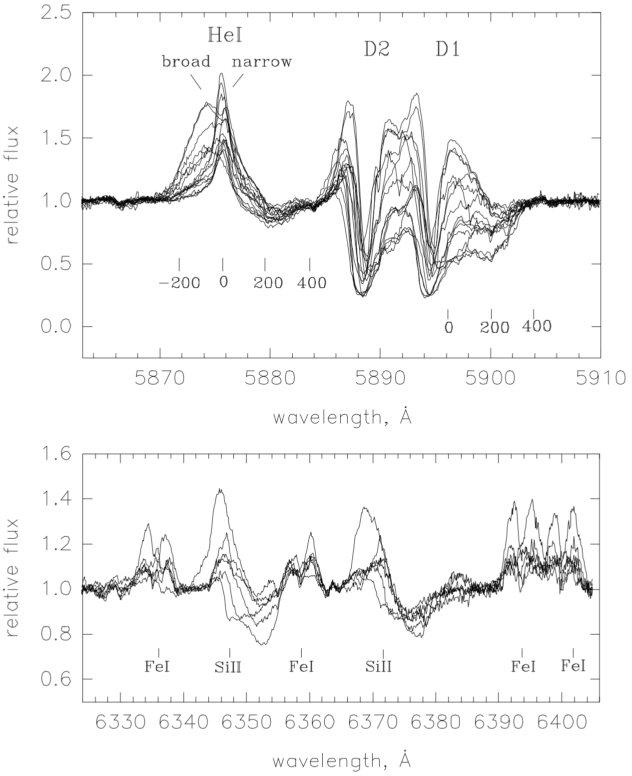

Figure 1: Two fragments of the spectrum of RW Aur A, showing the range of variability in the line profiles with accretion components. The wavelength scale is in the stellar rest frame. The radial velocity scales (in $\rm km\,s^{-1}$) are shown for the HeI and the NaI D1 lines.

2. Spectral variability

The spectrum of RW Aur A shows different components, among those are: a) highly veiled photospheric spectrum of K1-K4 star, a) broad emission lines of H, HeI, neutral and ionized metals, b) narrow emission lines of HeI and HeII, 3) red-shifted absorption components in many lines. An example of the night-to-night variability is shown on Figs. 1. The red-shifted absorptions, hearafter called the "accretion components", are present in most of the spectra. As a parameter of the accretion component we will use the equivalent width of the NaI D1 absorption within the interval of radial velicities from +200 to +400 km s−1. The HeI emission consists of the broad and narrow components (which is also observed in some other CTTS). The two components can be decomposed and the equivalent width and radial velocity of each one can be measured. The equivalent width of emission can be converted into flux using the simultaneous photometry.

From analysis of the spectra collected during the three seasons, we discovered periodic variations in many spectral features, the most pronounced are those in radial velocity and equivalent width of the narrow HeI emissions, and in the equivalent widths of the accretion components, with a period within 2.6–2.8 days. More exact value of the period, $P = 2^{\rm d}\!.641$, was found from the long time series of the photometrical data (see next Section). The phase diagrams are shown in Fig. 2. Note that the D1 accretion component vary in phase with the HeI narrow emission, while there is a phase shift, about 1/4 period, between the radial velocity and the flux of the HeI narrow emission. The period within 2.6–2.8 days is also present in radial velocity of the photospheric lines, which may be an indication that a low-mass invisible companion is orbiting the star (Gahm et al. 1999).

The veiling of the photospheric spectrum was derived in several spectral regions relatively free from the emission lines, within 5550–6050 Å, by means of cross-correlation technique using the template spectra of K-stars. The veiling factor varied irregularly within 1–10, with the average value about 3. One unexpected result is that ***no correlation between the veiling and the brightness*** was found, although both parameters varied in wide ranges. This is illustrated in Fig. 3, where two spectra shows very different levels of veiling at the same brightness of the star. Analysis of the variations in other spectral features is given in the Paper I.

3. Photometric variability

The photometry made simultaneously with our spectroscopic observations was used to convert the equivalent widths of emission lines into fluxes, and to study the correlations between spectral and photometric variability. In order to search for the periodicity in the photometrical data, we combined our data with much more extended time series available from the electronic catalogue compiled by Herbst (1994), which covers a time span over 30 years. For RW Aur A, the catalogue containes 575 observations in V and B–V and some-

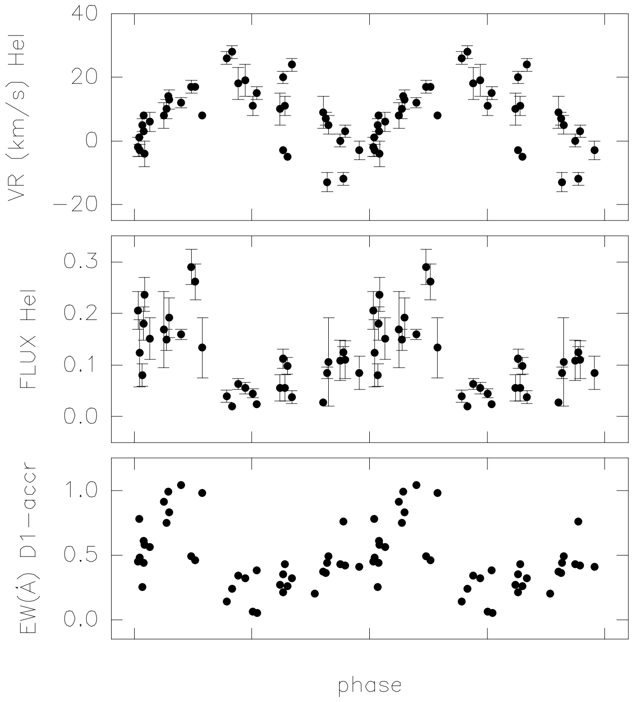

Figure 2: Phase diagrams for the period 2.641 days. Upper: radial velocity of the HeI narrow emission. Middle: flux (in $10^{-12}\,{\rm erg\,cm^{-2}\,s^{-1}}$) in the HeI narrow emission. Lower: equivalent width of the D1 accretion component.

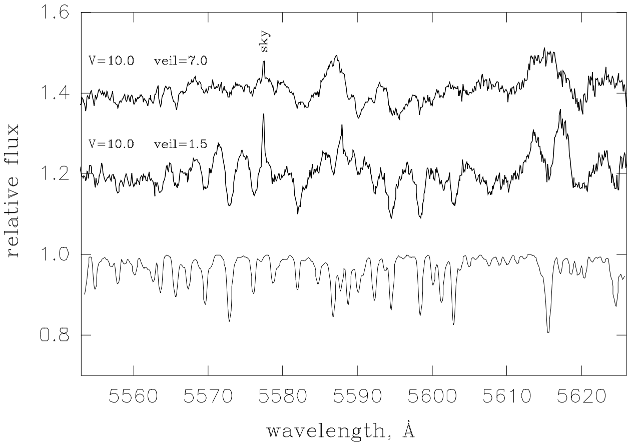

Figure 3: Two spectra with very different veiling, but with the same brightness of the star. Lower: the spectrum of γ Cep artificially veiled by factor 2

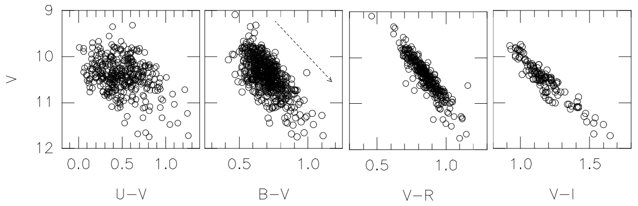

Figure 4: Colour-magnitude diagrams. The direction of the mean interstellar reddening law is shown on V ***versus*** B–V diagram. The UBVR bands are in the Johnson system, the I band is in the Cousins system.

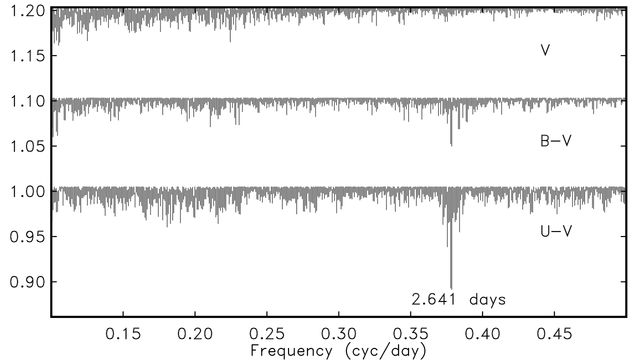

Figure 5: LS spectra for the brightness and colours in the range of periods from 2 to 10 days.

what less in other colours. The major part of the data are from the Majdanak Observatory (the ROTOR program by V.S.Shevchenko's group) and from Van Vleck Observatory (unpublished).

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 (Fig. 4). 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 $0.^{\rm m}86$–$1.^{\rm m}05$. With $A_V = 0.^{\rm m}3$ (Paper I) the observed photospheric colour B–V is expected to be within $0.^{\rm m}95$–$1.^{\rm m}14$. Most of the observed B–V colours are 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 contribution of the emission lines to the photometric bands also accounts for a part of the excessively blue colours. From the spectra with the strongest emission lines we estimate the maximal contribution to the B-V colour as $0.^{\rm m}2$.

The search for periods in the brightness and colours variations was made using the LS-statistic (Pelt 1992): variance of the least square fit residual divided by original variance of the data. As a model to be fitted we used a single harmonic curve. No periodicity was found in the V-magnitude within a region of periods from 1 to 100 days, while the blue colours reveal a significant period around 2.64 days, in accordance with that found from the spectral analysis. The LS spectra are shown in Fig. 5.

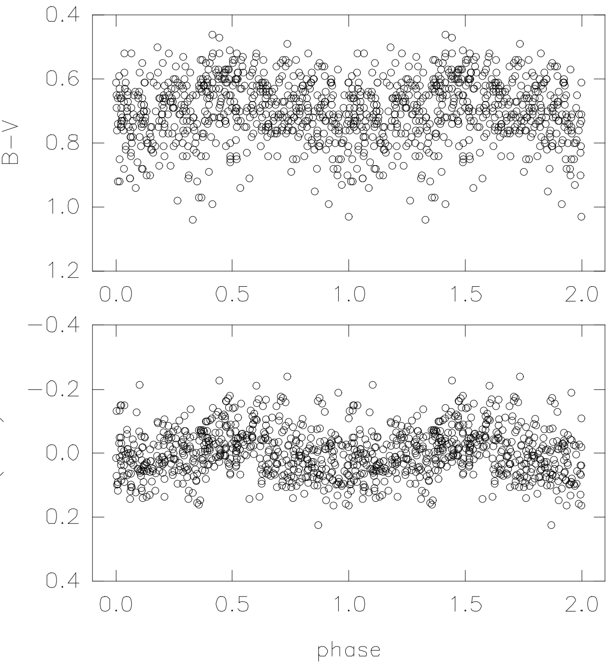

Figure 6: Phase diagram for the period 2.641 days. Upper panel: variations in the observed colour. Lower panel: variations in the residual colour (see text).

From the colour-magnitude diagrams (Fig. 4) we can conclude that the total variability of RW Aur consists of at least two components: a large-scale variability in all the colours within about $0.^{\rm m}5$, and a scatter around the linear trend on the diagrams. This scatter is very small in the red colours but steeply increasing towards the UV, which indicates the presence of a hot variable source of radiation. We can eliminate the linear trend in the colour-magnitude diagrams and investigate the time variations in the ***residual*** colours, which can be defined as δ(B–V)=(B–V)–C·V+*const* for B–V and in a similar way for other colours. The period 2.641 days is better seen in the residual colours (see Fig. 6). When the whole data set is used, the full amplitude of the sinusoidal variations is: $0.^{\rm m}21$ in U–V, $0.^{\rm m}07$ in B–V, and about $0.^{\rm m}02$ in V–R and V–I. More detailed analysis of this periodicity is given in Petrov et al.(2001b).

4. Discussion

The correlated periodic variations in the HeI narrow emission and the D1-accretion components (Fig. 2) is the most important finding of our research. The vari-

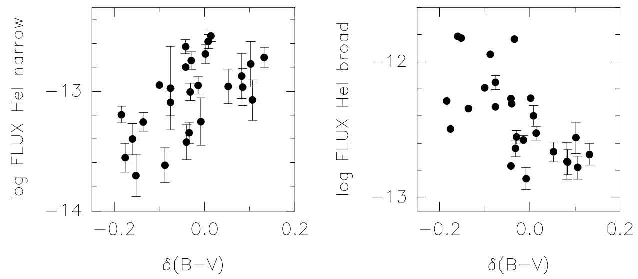

Figure 7: Correlation between the resudual B–V colour and the fluxes in the HeI narrow and broad emission lines.

ations are most probably caused by rotational modulation of the non-axysimmetric accretion, as it is described below.

The quater-period phase-shift between the radial velocity and the flux variations is a clear indication to the spot-like region of the HeI narrow emission: the radial velocity is minimal when the spot is face on to the observer, and maximal when the spot is at the limb (all the velocities discussed here are in the stellar rest frame). Note, that the average radial velocity of the HeI narrow emission is not zero, but positive: +10 km s^{-1}. This emission may arise from the post-shock region at the footpoint of the accretion column (Calvet & Gullbring 1998). The accretion components of NaI D and many other lines indicate the inflow velocity up to +450 km/s, which is consistent with the free-fall velocity to the star. The broad emission lines may originate from the global magnetosphere of the star threaded by streams of gas flowing towards the star (Calvet 1998). At the moments when the star is seen through the accretion column, both the strength of the accretion components and the flux in the HeI narrow emission are enhanced. The rotational modulation arise due to the presence of one or two dominating columns of accretion, that is accretion is non-axisymmetric. The asymmetry may arise due to a misalignment of the magnetic and rotational axes (Königl 1991). An alternative hypothesis (a binary star) is discussed in Paper I.

So far, the results of our research seem to support the magntically channeled accretion model. Since the model predicts the existence of a hot photospheric spot below the accretion shock, we should expect periodic modulations in brightness and colours as well. The amplitudes of the periodic colour variations (Section 3) rising steeply towards the UV indicate the presense of a hot source of radiation, which might be identified with the expected hot spot. 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. With $T_{\rm phot}$=4800 K, and the amplitudes given in Section 3, we get $T_{\rm spot}$=15000 K and the covering fraction 0.1%. Such a small spot gives only a $0\overset{\mathrm{m}}{.}05$ amplitude in the V magnitude. Then, we should expect the bluer colour when the HeI narrow emission is stronger. However, quite the opposite is observed: when the residual colours are bluer, the flux in the narrow HeI emission is lower (Fig. 7). The "normal" correlation exists between the colour and the ***broad line*** flux: the larger the broad line flux, the bluer the colour.

Hence, the residual blue colours vary in "anti-phase" to the strength of the accretion components and to the flux in the narrow HeI 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-uniformely distributed hot gas, which also radiates in the broad emission lines.

In the case of RW Aur A we met with the following contradiction. On the one hand, the large level of the veiling of the photospheric spectrum and the large amplitude of the irregular light variations suggest the presence of strong accretion shocks. On the other hand, the strong spectroscopic evidences of accretion do not show any relation to the brightness of the star. In addition, no correlation between the veiling and brightness was found, when both parameters varied in a wide range.

The apparent absence of the hot spot related to the accretion column is really puzzling. Either the accretion shock is absent indeed, i.e. all the kinetic energy of the infalling gas dissipates before it reaches the stellar surface, or the complicated geometry of the flows and possible extinction of light within the gas streams makes the observed variations so complicated.

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