Astron. Nachr. / AN **326**, No. 3/4, 292–295 (2005) / **DOI** 10.1002/asna.200410392

Modelling the colour-brightness relation of chromospherically active stars

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Received 18 October 2004; accepted 7 December 2004; published online 11 March 2005

Abstract. The photometric flux of chromospherically active, spotted stars generally becomes redder and fainter when large starspots rotate into view on the stellar disc. However, some of the most active RS CVn systems show a bluer flux as they get fainter. Modelling of one such system (UX Ari) has shown that hot, bright, photospheric facular regions accompanying the cool, dark spots on the cooler, more active component are a possible explanation. The bluer flux of the hotter, less active component does not appear to be sufficient to explain the observed behaviour. We have begun a search for additional chromospherically active stars with a similar relation between colour and brightness, to investigate whether these relations can be explained in the same way. Our results for V711 Tau and RS CVn are presented here, and we conclude that the photospheric faculae remain the most probable explanation for the observed behaviour.

Key words: stars: activity – stars: atmospheres – stars: spots – techniques: photometric

1. Introduction

Some of the most active, late-type binary stars, e.g. UX Ari, V711 Tau and MM Her, show a bluer photometric colour with fainter photometric magnitude (Catalano et al. 1996; Taş, Evren & İbanoğlu 1999; Aarum Ulvås & Henry 2003); opposite to what one would expect from stars covered by cool spots. Amado (2003) found that active giants (from chromospherically active single-lined spectroscopic binaries) with spectral types later than G8 have a bluer $B-V$ colour than inactive giants of the same spectral type. The effect on $B-V$ is smaller than the one on $U-B$ reported by Amado & Byrne (1997). The most probable explanation, according to both papers, is a facular component in the photosphere of the active star. Previously published modelling of the RS CVn system UX Ari (Aarum Ulvås & Engvold 2003) has shown that photospheric faculae are a likely explanation, rather than the bluer flux of the hotter, unspotted companion becoming more dominant as the active regions of the cooler, active star rotate into view.

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We have begun a search for other active stars with the same relation between colour and brightness to investigate likely explanations. Our results on two other RS CVn binaries, V711 Tau and RS CVn, are presented here.

V711 Tau (HR 1099, HD 22468) is one of the most active and well studied RS CVn stars. The spectroscopic binary is the primary (A) component of the visual binary ADS 2644 and consists of a K1 IV primary component and a G5 V secondary component. The secondary component of the visual binary, ADS 2644B, is a K3 V single star located 6″ away in the sky. In our discussion we follow the notation used by Fekel (1983): Components Aa and Ab refer to the more active K1 IV primary component and the less active G5 V secondary component, respectively, of the spectroscopic binary. Component A refers to the primary component of the visual binary (i.e. ADS 2644A) and will also be used for any combined properties of Aa and Ab. Finally, component B refers to the K3 V secondary component of the visual binary.

RS CVn (HD 114519) is the prototype of the class of active stars that bears its name. The class was first defined by Hall (1976). RS CVn is a spectroscopic binary where the primary and secondary components have spectral classifications K2 IV and F5 V, respectively.

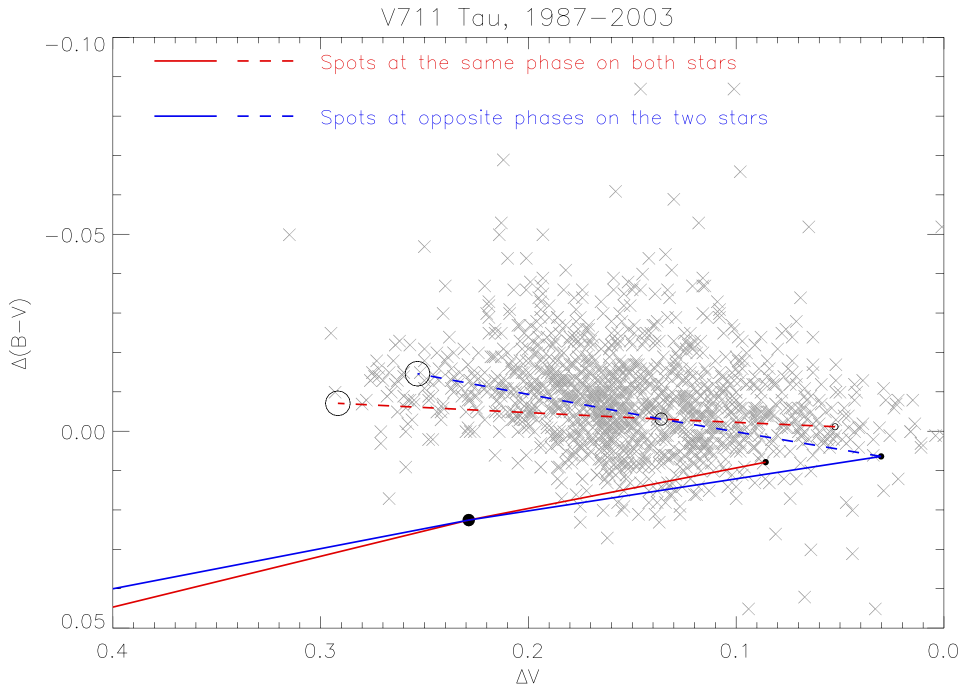

Fig. 1. (online colour at www.an-journal.org) Modelling the colour-brightness relation of V711 Tau. The differential magnitude ΔV along the abscissa is measured relative to the brightest observation. The differential colour $\Delta(B-V)$ along the ordinate is measured relative to the mean colour of those observations having $\Delta V < 0.05$. The observations are represented by grey $\times$ symbols. The modelling results are represented by open or filled circles with varying sizes, and red or blue, solid or dashed lines. Filled circles and solid lines represent models where the active regions consist of cool spots only. Open circles and dashed lines represent models where the active regions of component Aa consist of both spots and faculae. Red lines represent models where the active regions are at the same phase on both components. Blue lines represent models where the active regions are at opposite phases on the two components. Along both the red lines, the circle size reflects the relative stellar surface area of the active regions. The plotting circle where the blue lines intersect, corresponds to the case where only the active regions of component Ab are visible (with maximum extension). The largest plotting circles along the blue lines (the filled one being outside the plot) correspond to the case where only the active regions of component Aa are visible (with maximum extension), i.e. half a rotation later.

2. Modelling the photometric observations

We used a slightly modified version of the modelling technique described by Aarum Ulvås & Engvold (2003) to calculate the change in photometric magnitude and colour for V711 Tau and RS CVn when active regions rotated into and out of view. The modelled active regions would consist of either cool spots only or a combination of cool spots and hot, photospheric faculae. The calculated changes in magnitude and colour were subsequently compared to the observed range in magnitude and colour of the star systems.

The model calculated the differential magnitude ΔV and the differential colour $\Delta(B-V)$ in the sense spotted system minus unspotted system. The total flux of the system was first calculated as a function of wavelength, and then we used the photometric transmission coefficients described by Bessell (1990) to obtain the Johnson B and V magnitudes. The flux calculations used the stellar, spot and facular parameters listed along with their sources in Table 1 (for V711 Tau) and Table 2 (for RS CVn).

The observations were obtained with the T3 0.4 m automatic photoelectric telescope (APT) at Fairborn Observatory[1] (Henry 1995a, 1995b) operated by the Tennessee State University. Parts of the V711 Tau observations have been published by Henry et al. (1995), and parts of the RS CVn observations have been published by Eaton et al. (1993). The observations were obtained using a 55″ diaphragm, which implies that the observations of V711 Tau include compo-

Table 1. Stellar, spot and facular parameters used in the V711 Tau model calculations. The temperature $T_{\rm B}$ and radius $R_{\rm B}$ were taken from Gray (1992), given its K3 V spectral classification. $T_{\rm s}$ is the spot temperature. The facular temperature $T_{\rm f}$ was set 250 K higher than the Aa effective temperature $T_{\rm Aa}$, consistent with previous modelling (Aarum Ulvås & Engvold 2003).

Parameter	Source
$T_{\rm Aa} = 4800$ K	García-Alvarez et al. 2003
$R_{\rm Aa} = 3.3 R_\odot$	García-Alvarez et al. 2003
$T_{\rm Ab} = 5400$ K	García-Alvarez et al. 2003
$R_{\rm Ab} = 1.1 R_\odot$	García-Alvarez et al. 2003
$T_{\rm B} = 4925$ K	Gray 1992
$R_{\rm B} = 0.73 R_\odot$	Gray 1992
$T_{\rm s} = 3800$ K	García-Alvarez et al. 2003
$T_{\rm f} = 5050$ K	Aarum Ulvås & Engvold 2003

[1] http://www.fairobs.org/

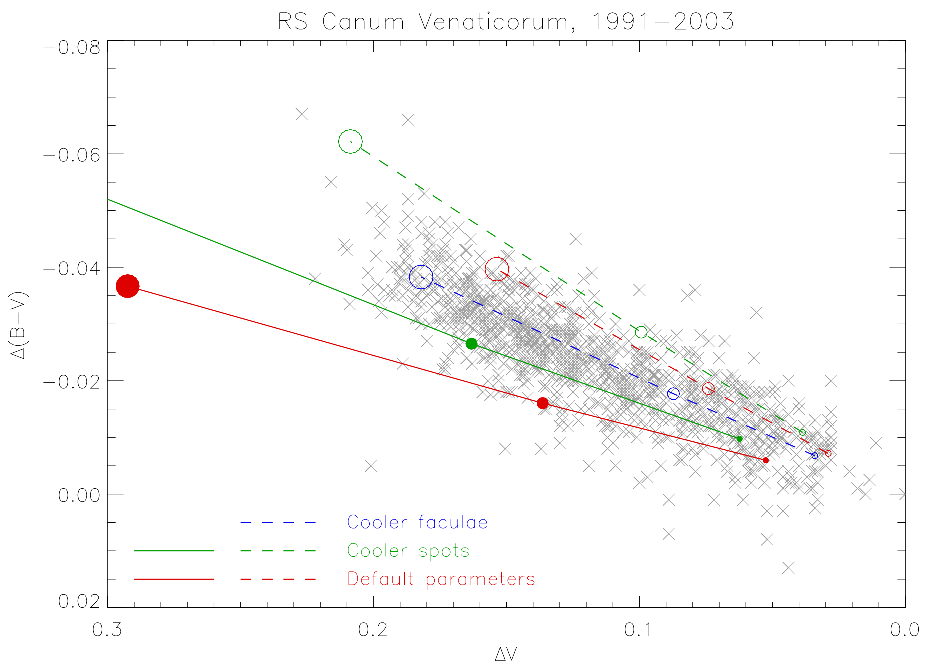

Fig. 2. (online colour at www.an-journal.org) Modelling the colour-brightness relation of RS CVn. The differential magnitude along the abscissa and the differential colour along the ordinate are measured relative to the brightest observation. As in Fig. 1, the observations are represented by grey $\times$ symbols, and filled circles and solid lines represent the 'spot-only' case, whereas open circles and dashed lines represent the 'spot-and-faculae' case. The sizes of the plotting circles reflect the sizes of the active regions. The line colours are explained in the figure, and the default parameters are the ones listed in Table 2. 'Cooler spots' means models with $T_s = 3000$ K, i.e. 450 K cooler than default. 'Cooler faculae' means a model with $T_f = 4733$ K, i.e. 50 K lower than default, and 200 K hotter than the photosphere.

Table 2. Stellar, spot and facular parameters used in the RS CVn model calculations. The temperatures T_1 and T_2 and the radii R_1 and R_2 were taken as the averages of the two sources. The facular temperature T_f was set 250 K higher than the effective temperature T_1 of the primary component, consistent with previous modelling (Aarum Ulvås & Engvold 2003).

Parameter	Source(s)
$T_1 = 4533$ K	Reglero, Giménez & Estela 1990; Eaton et al. 1993
$R_1 = 3.85 R_\odot$	Reglero et al. 1990; Eaton et al. 1993
$T_2 = 6510$ K	Reglero et al. 1990; Eaton et al. 1993
$R_2 = 1.89 R_\odot$	Reglero et al. 1990; Eaton et al. 1993
$T_s = 3450$ K	Eaton et al. 1993
$T_f = 4783$ K	Aarum Ulvås & Engvold 2003

nent B. This component was therefore also included in our modelling. The reduction procedure of the T3 data has been described in several papers, e.g. Henry et al. (1995).

The observed changes in magnitude and colour of active stars are the result of the rotation of a spotted stellar surface. Our model mimics the rotational modulation by varying the relative areas of the active regions.

3. Results

In order to compare the modelling results to the observations, we transformed the observed V magnitude to the differential magnitude ΔV in the sense observed magnitude minus the brightest observed magnitude. The observed $B-V$ colour was transformed to the differential colour $\Delta(B-V)$ in the sense observed $B-V$ minus a zero-point value of $B-V$. The zero-point $B-V$ value was taken as the average $B-V$ of the brightest measurements (see Figs. 1 and 2 for how the zero-point values were derived for V711 Tau and RS CVn, respectively). The brightest observation is the closest we can get to an unspotted system in the data.

3.1. V711 Tau

V711 Tau is different from UX Ari in the sense that also the secondary component (V711 Tau component Ab) shows strong enough spot activity to be mapped by Doppler imaging. García-Alvarez et al. (2003) mapped the spot distributions on both components Aa and Ab simultaneously and found that both stars were spotted. The modelling in the present paper was done in two cases:

1. The active regions lie at the same phase on both stars.
2. The active regions lie at opposite phases on the two stars.

Only the later and more luminous Aa component was assumed to have faculae, following the findings by Amado & Byrne (1997) and Amado (2003).

The modelling results are presented in Fig. 1. We see that the models where the active regions consist of spots only (filled circles and solid lines) cannot explain the observed behaviour, even when the Ab component is unspotted as the spots on the Aa component are in view (blue, solid line). The bluer flux of the hotter Ab component appears to be insufficient to compensate for the redder flux of the starspots.

In both cases with faculae (open circles and dashed lines) the modelling results fall within the observed range in colour. It is hard from Fig. 1 to distinguish between the two cases mentioned above, represented by the red and blue dashed lines.

3.2. RS CVn

RS CVn is different from both UX Ari and V711 Tau in the sense that the secondary component is $\approx$ 1000 K hotter and has $\approx 0.8R_\odot$ larger radius. This makes the two RS CVn components more equal in terms of B and V band flux. Only the brighter, cooler primary component was assumed to have active regions in the modelling.

The modelling results are presented in Fig. 2. We see that the models where the active regions contain spots only (filled circles and solid lines) result in a too red colour compared to the observations. This is the case even when the spots are made cooler than default (green line and circles). Also, the minimum magnitude is too faint in both cases.

The model that best fits the observations, is one where the active regions contain both spots and faculae (open circles and dashed lines). However, the best fit is obtained when the faculae are made cooler than default (blue as opposed to red line). This case also reproduces nicely the observed range in magnitude.

4. Discussion

The fact that both components Aa and Ab show activity makes V711 Tau particularly interesting, since it results in a complicated colour-brightness relation as the activity varies on two stars simultaneously on a timescale of years. In their Doppler imaging García-Alvarez et al. (2003) found spots at the same phase on both components. This would correspond to the red, dashed line in Fig. 1. However, the case of spots at opposite phases (blue, dashed line in the figure) agrees equally well with the observations. The active regions on the two components are likely to be visible at the same orbital phase during some observing seasons, and at opposite phases during other seasons. This variation in spot location is likely to cause the large spread in the observed colour for all magnitudes in Fig. 1. The spread is also suggested by the dashed lines in the figure. Finally, we note that some measurements towards redder colour with fainter system can represent cases where the active regions of the Aa component contain spots only, and no faculae, which was also found for UX Ari (Aarum Ulvås & Engvold 2003).

All the models of RS CVn in Fig. 2 become bluer as they become fainter. There are hardly any measurements showing a redder and fainter system, as was the case for V711 Tau (Fig. 1) and UX Ari (Aarum-Ulvås & Engvold 2003). The reason for this is that the secondary component is hotter and larger than for V711 Tau and UX Ari (see Tables 1 and 2; the secondary component of UX Ari is similar in temperature and radius to the Ab component of V711 Tau). The same effect is the cause of the smaller differences between the models that have (dashed lines) and the ones that do not have (solid lines) faculae. The flux of the primary component, and thereby the active regions, is less dominant for RS CVn compared to V711 Tau and UX Ari. The secondary component contributes enough to the total flux to make the system as a whole bluer as the cool spots of the primary component come into view. It matters less whether or not the active regions contain faculae. In such cases the modelling technique used here becomes less able to distinguish between active regions with faculae and active regions without faculae. Still, the bluer flux of the hotter secondary alone appears not to be quite enough to explain the observed relation. The colour could be made to fit by making the spots cooler than the observed spot temperature (suggested by the green, solid line in Fig. 2), but the side effect is that the minimum magnitude becomes far too faint compared to the observations. The observed range in colour and magnitude are much more easily reproduced simultaneously when faculae are included in the model.

Hot faculae surrounding cool spots appear to be necessary to explain the observed relation between photometric magnitude and colour in the most active of the chromospherically active stars. However, the stars that have been examined so far (UX Ari, V711 Tau and RS CVn) are all binary stars with a relatively bright secondary component. If this is indeed a facular effect, it should be observed also in binaries with faint secondary components as well as in single stars. Future work will aim to answer this question and investigate other possible explanations for the effect (Aarum-Ulvås et al., in prep.).

Acknowledgements. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. This work is supported by the German Research Foundation under project number TW9249–DFG STR 645/1–2. GWH acknowledges support from NASA grant NCC5–511 and NSF grant HRD–9706268.

References

Aarum-Ulvås, V., Engvold, O.: 2003, A&A 399, L11
Aarum-Ulvås, V., Henry, G.W.: 2003, A&A 402, 1033
Amado, P.J.: 2003, A&A 404, 631
Amado, P.J., Byrne, P.B.: 1997, A&A 319, 967
Bessell, M.S.: 1990, PASP 102, 1181
Catalano, S., Rodonò, M., Frasca, A., Cutispoto, G.: 1996, in: K.G. Strassmeier, J.L. Linsky (eds.), *Stellar Surface Structure*, IAU Symp. 176, Kluwer Academic Publishers, Dordrecht, p. 403
Eaton, J.A., Henry, G.W., Bell, C., Okorogu, A.: 1993, AJ 106, 1181
Fekel, F.C.: 1983, ApJ 268, 274
García-Alvarez, D., Barnes, J.R., Collier Cameron, A., Doyle, J.G., Messina, S., Lanza, A.F., Rodonò, M.: 2003, A&A 402, 1073
Gray, D.F.: 1992, *The observation and analysis of stellar photospheres*, 2nd ed., Cambridge University Press
Hall, D.S.: 1976, in: W.S. Fitch (ed.), *Multiple Periodic Variable Stars*, IAU Coll. 29, Reidel Publishing Company, Dordrecht, p. 287 (invited papers)
Henry, G.W.: 1995a, ASP Conf. Ser. 79, 37
Henry, G.W.: 1995b, ASP Conf. Ser. 79, 44
Henry, G.W., Eaton, J.A., Hamer, J., Hall, D.S.: 1995, ApJS 97, 513
Reglero, V., Giménez, A., Estela, A.: 1990, A&A 231, 375
Taş, G., Evren, S., İbanoğlu, C.: 1999, A&A 349, 546