Astron. Astrophys. 319, 967–972 (1997)

ASTRONOMY AND ASTROPHYSICS

Effect of chromospheric activity on the mean colours of late-type stars

P.J. Amado and P.B. Byrne

Armagh Observatory, College Hill, Armagh BT61 9DG, Northern Ireland

Received 2 July 1996 / Accepted 2 August 1996

Abstract. In this paper we show, for the first time, the effect of activity on the $(U–B)_0$ vs. $(B–V)_0$ colour-colour diagram for a large sample of late type stars. We clearly see that for single-lined spectroscopic RS CVn systems there exists an ultraviolet excess over that recorded for quiescent stars of the same spectral type. The same effect is seen in main-sequence stars but to a lesser extent. From simple arguments we demonstrate that the cause is unlikely to be unresolved flaring, the combined effect of strong chromospheric emission lines, or X-ray/UV back-heating of the photosphere. White-light faculae are a reasonable candidate for the effect however. In our investigation we have not taken into account the effect that metallicity might have on the colour indices.

Key words: stars: activity – stars: fundamental parameters – stars: late-type

1. Introduction

The solar chromosphere and corona are usually viewed as regions of the solar atmosphere whose physical conditions are controlled by magnetic heating processes originating below the photosphere. The energy content and gas density of these outer regions are orders of magnitude lower than those prevailing in the underlying photosphere. Thus photospheric processes determine the magnetic configurations which control both the heating of the corona and its morphology. To a very close approximation the chromosphere and corona have no effect on the solar photosphere. Although the same processes which heat the outer layers may give rise to heating effects visible at near-photospheric levels (e.g. white-light faculae).

Chromospherically active late-type stars exhibit all of the panoply of solar activity but on scales several orders of magnitude larger. The solar paradigm is widely (and successfully) adopted in interpreting such phenomena. It is implicitly assumed that the stellar photosphere underlying these outer atmospheric effects may be regarded as similar to that of a quiescent star of similar spectral type, at least in a global sense.

Excesses in the mean global blue colours of some young open cluster stars have been detected for some time now. Turner (1979) measured an UV excess in the members of the young (≈70 Myr) Pleiades open cluster with $(B–V)$ colour between $0.5 \leq B–V \leq 0.8$, of 0.03 magnitudes with respect to the Hyades members (≈800 Myr). He explained this as being due to an effect of metallicity, with the Pleiades members being closer in metallicity to average nearby stars and lower than that of the Hyades members.

For later Pleiades objects, Burton (1972) explained the position of members with $1.1 \leq B–V \leq 1.4$ below the ZAMS as due to gray extinction from circumstellar dust shells. Later, Stauffer (1980) ruled out the dust shell hypothesis and, in his paper, where he examined the "turn-on" point of pre-main sequence objects in the Pleiades, explained this ultraviolet excess (detected as well by Landolt (1979)) as due to flaring. He reasoned that, since many of these stars are flare stars, this might affect the blue colours, making them look bluer and, thus, producing the excess.

This UV excess has been observed in some other types of stars. For instance, the excess in the blue colours of the RS CVn single-lined spectroscopic binary HU Virgo would be fitted if a hot companion (early F) were responsible of affecting the colours (Cutispoto 1996). However, Fekel et al. (1986) did not find any evidence of a hot secondary component in their IUE spectra of HU Vir. Strassmeier (1994) confirmed the K0IV spectral classification for the primary and did not detect any sign of a secondary.

So, up to now, there have been a few attempts at explaining this excess, which we call here UV excess, seen in the blue colours of some stars. In this paper we examine several classes of chromospherically active late-type stars for evidence of an effect of activity on the mean global photospheric colours.

2. The sample

The sample of active and inactive stars was taken from several sources in the literature. We studied for all of them the

Send offprint requests to: P.J. Amado

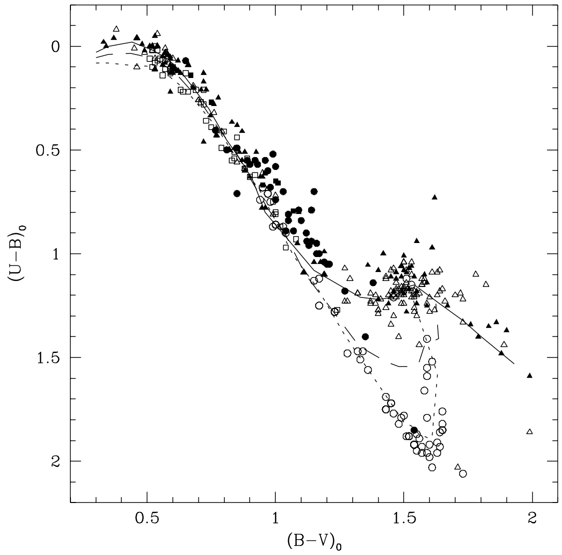

Fig. 1. $(U–B)_0$ vs. $(B–V)_0$ colour-colour diagram for active (*solid symbols*) and inactive stars (*open symbols*). Giants are represented by *circles*, subgiants by *squares* and dwarfs by *triangles*.

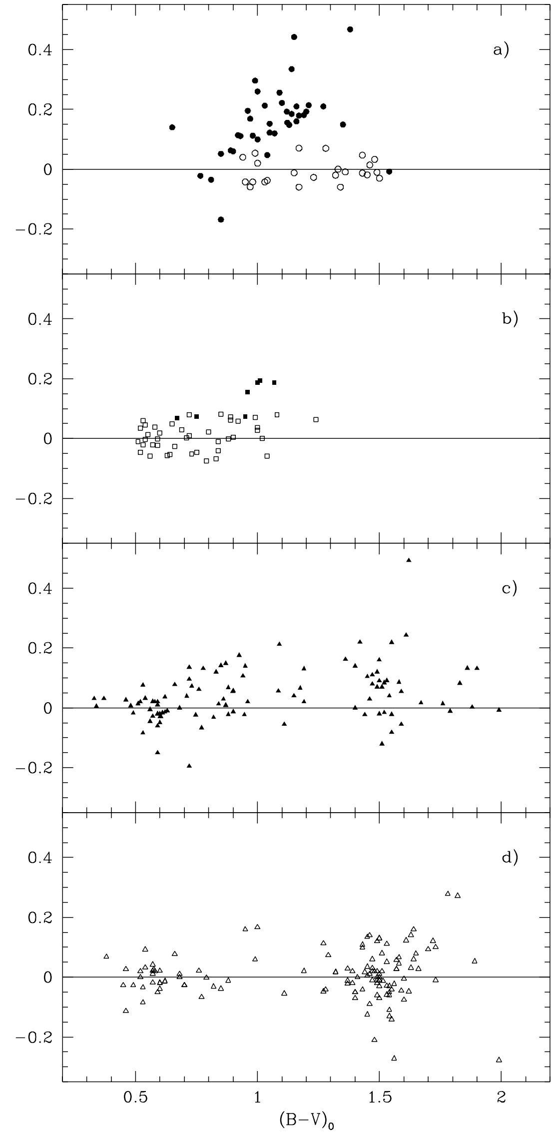

Fig. 2a–d. Ultraviolet excess $\delta(U–B)$ vs. $(B–V)_0$ diagrams for **a** class III stars, **b** class IV stars, **c** active class V stars and **d** inactive class V stars. Symbols are as in Fig. 1.

necessity of correction for interstellar extinction. The following criteria were applied. All those stars with distances d $\leq$100 pc were not corrected. It is generally agreed that, for stars nearer than 100 pc, there is no need of any correction for interstellar extinction, since this correction would be very small ($E_{B-V} < 0.04$ in the direction of the galactic center at d = 100 pc). Furthermore, if any small correction were needed, the direction of the correction would be almost parallel to the zero-reddening curve in the colour-colour diagram. Stars with galactic latitude $|b| > 20°$ and $d > 100$ pc were corrected using the expression $\bar{E}_{B-V} = 0.06\,\mathrm{cosec}(|b|) - 0.06$ derived by Woltjer (1975) for globular clusters outside the galactic absorbing layer, putting upper limits to the correction. Stars with $|b| < 20°$ and $d > 100$ pc were corrected using the expression $A_v = 0.14\,(1 - \exp\,(-10d\sin(|b|)))/\sin(|b|)$ (Van Herck 1965) where d is in kpc. We take A_v/E_{B-V}=3.2 and E_{U-B}/E_{B-V}=0.72 (Crawford & Mandwewala 1976). We also took special care with the corrections for those stars lying in directions of specially high extinction (Deutschman et al. 1976).

2.1. Active stars

The sample of active stars was taken from the catalogue of "Chromospherically Active Binary Stars" (CABS) by Strassmeier et al. (1993) and from the papers by Leggett (1992), Houdebine et al. (1996), Doyle (1996) and Mathioudakis et al. (1995).

The stars selected from the CABS catalogue are all single-lined spectroscopic binaries. We imposed this condition to prevent the UBV colours of the observed component being affected by a companion of different spectral type. CABS also provides mean colours in the standard UBV system, which were then corrected for interstellar extinction as explained above. This subsample contains stars of three different luminosity classes, namely, giant, subgiant and dwarf stars.

The subsample of stars from Leggett (1992) and Houdebine et al. (1996) are all main sequence stars with spectral types later than M0. We selected as active those stars which Leggett classified as dMe or flare stars or which showed variability, and those from Houdebine et al. (1996) with Hα in emission. Most of these objects are from the Gliese catalogue (Gliese and Jahreiss 1991) which means that they have $d < 25$ pc and therefore not needing any correction for interstellar absorption.

Mathioudakis et al.'s (1995) stars are all main sequence stars of spectral type mid-F to mid-M. They present the observed fluxes in the EUVE (Bowyer et al. 1994) Lex/B and Al/Ti/C bands, and detection in both was the criterion adopted for including them in the sample of active stars.

In his paper, Doyle (1996) uses the flux of the C IV λ1550 Å doublet observed by the IUE satellite (Boggess et al. 1978) to derive the total radiative output from the chromospheric/coronal plasma for dwarfs between early F and middle M. We used the flux of the C IV line in the IUE LORES spectra of these stars to measure the level of activity. Stars with a clear detection of the line were taken as active. None of them needed any correction for interstellar absorption since their distances were all much less than 100 pc.

2.2. Inactive stars

The sample of inactive giants is the same as that used by Amado and Byrne (1996) for the derivation of their colour-$T_{\rm eff}$ and colour-surface brightness relationships for late-type stars.

Inactive subgiants with d <100 pc were taken from the Bright Star Catalog (Hoffleit 1982) avoiding those that were referred to as binary stars or variable stars.

The sample of "inactive" main-sequence stars was selected as follows: the less active dM stars from Leggett (1992), those from Houdebine et al. (1996) with Hα in absorption, the upper limits in the IUE C IV line flux from Doyle (1996) and the 3σ levels in the EUVE Al/Ti/C band in the paper by Mathioudakis et al. (1995). We note that, since these criteria are detector based, some residual active stars may be included in the sample.

3. Results

In Fig. 1, we plot a two-colour diagram $(U-B)_0$ against $(B-V)_0$ for the sample of active and inactive stars, together with the zero-reddening curves of Schmidt-Kaler (1982), for dwarfs, subgiants and giants.

Giant stars extend over a spectral type range from G0 ($(B–V)_0$ = 0.65) to M6 ($(B–V)_0$ = 1.52), although the active giants do not extend over the full range. The active and inactive giants overlap in the range between K0 ($(B–V)_0$ = 1.00) and K4 ($(B–V)_0$ = 1.39). Subgiant stars range in $(B–V)_0$ from 0.5 to 1.2, with again a slightly more restricted range for the active stars. The main-sequence objects are distributed over all the values of $(B–V)_0$ in the plot.

Fig. 2 shows the difference between the unreddened $(U–B)_0$ colour and the intrinsic $(U–B)_0$ colour linearly interpolated from the tables of Schmidt-Kaler (1982) by using $(B–V)_0$ for each star. This plot shows that the majority of the active giants (89.50%) and all the subgiants are above the mean zero-reddening curves, thus showing a positive UV excess $\delta(U–B)$. The non-active giants, on the other hand, lie out on the line with a very small scatter (<0.1).

This UV excess is not so evident in the case of main-sequence objects, although a larger number (66.67%) lie above the mean line than below (31.53%). For the inactive dwarfs, the percentages are 47.24% above the curve and 49.61% below it. In Table 1, we give some statistics on the excess.

Table 1. Mean ultraviolet excess $\bar{\delta}_{(\rm U-B)}$, with their standard deviations, σ, for the samples of active and inactive giant, subgiant and dwarf stars. In the last two columns we give the maximum value of the deviation and the number of stars included in the subsamples.

	Lum.	$\bar{\delta}_{(\rm U-B)}$	σ	$\delta_{\rm max}$	n
	III	0.1578	0.1193	+0.4679	38
active	IV	0.1344	0.0597	+0.1942	7
	V	0.0421	0.0872	+0.4921	111
	III	0.0055	0.0405	+0.0706	24
inactive	IV	0.0070	0.0463	+0.0816	42
	V	0.0065	0.0872	−0.3100	127

4. Discussion

The question that immediately arises from this investigation is, what produces this UV excess?. We will consider next the following possibilities:

- Flaring
- Chromospheric emission
- X-ray back-heating
- Faculae

4.1. Flaring

Flares on active late-type stars show many similar characteristics to those on the Sun but are orders of magnitude more energetic and frequent. They show flux enhancement over the quiescent state at almost all wavelengths. M dwarf flare (UV Cet) stars are characterized by "white-light" emission, i.e. a continuum intensity increasing very strongly towards the blue. The possibility then arises that the mean light of individually unresolved flares of this type might produce the observed blue excess in active stars.

Lacy et al. (1976) analyzed statistically 386 flares of eight UV Cet flare stars observed by Moffett (1974), obtaining mean values for the flare energy through the U passband (E), the number of flares per interval of time (N) and the mean, time averaged, rate of energy loss due to flaring (L^*). Three of these UV Ceti stars, namely, YZ CMi, AD Leo and EV Lac were included in our sample of dMe stars. So we chose them in order to compare the extra-luminosity in the U passband necessary to match their observed UV excesses with their L^*. The result is that the UV excess luminosities, that are between 10^{28}–10^{29} erg s^{-1}, are two order of magnitudes larger than the flare luminosities, and closer to the X-ray luminosities measured in these three stars.

Lacy et al. (1976), however, realized that their *observed* flares were only the energetic end of the spectrum of flare energies from these stars. They found that the distribution of flare energies could be well represented by a power law relationship between flare energy and frequency, $\log \nu = \alpha + \beta \log E_{\rm U}$. Inte-

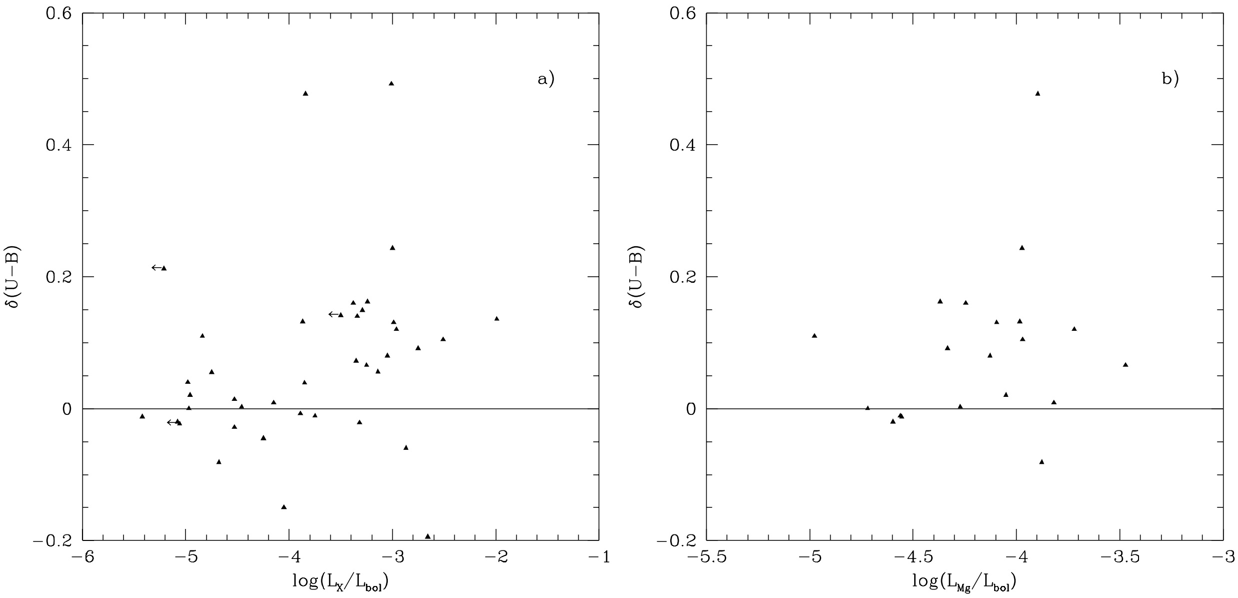

Fig. 3. UV excess for active dwarfs vs. a) the logarithm of the X-ray luminosity over the bolometric luminosity, b) the logarithm of the Mg II luminosity over the bolometric luminosity. Arrows mean upper limits.

Table 2. Effective temperatures, fluxes and filling factors for three dMe stars

Name	T_{ph} (K)	ΔF_U	F_q	$F_U = F_q + \Delta F_U$	F_{fac}	f (%)
YZ CMi	3150	$6.016\ 10^6$	$2.673\ 10^7$	$3.275\ 10^7$	$7.618\ 10^7$	12.2
AD Leo	3450	$1.040\ 10^8$	$7.618\ 10^7$	$1.802\ 10^8$	$1.847\ 10^8$	95.8
EV Lac	3300	$1.097\ 10^8$	$4.618\ 10^7$	$1.559\ 10^8$	$1.207\ 10^8$	147.2
AD Leo					$3.100\ 10^8$	44.5
EV Lac					$2.112\ 10^8$	66.5

grating this expression we obtain for the time-averaged energy per second emitted by flares in the U photometric passband

$$L' = 10^{\alpha} \frac{\beta}{\beta+1} (E_{\min}^{\beta+1} - E_{\max}^{\beta+1})$$

If we take $E_{\min} = 0.0$ and $E_{\max}$ equal to the energy of the detection threshold for each of the three stars mentioned above, we will obtain an upper limit for the energy of flares below the detection limit. In all three cases we obtain luminosities between 10^{26}–10^{27} erg s^{-1}, still two order of magnitudes below those necessary to produce the observed excesses. Thus, we conclude that small-scale flaring is unlikely to account for the observed effect.

4.2. Chromospheric emission

Ultraviolet emission lines originating in the chromospheres and transition regions of active stars are very prominent in their spectra. The presence of these strong emission lines in the wavelength range covered by the Johnson U passband would produce an increase in the flux in active stars to inactive stars where no such emission would be present. Such an effect would give rise to a shift towards the blue of the $(U–B)$ colour of the star, appearing consequently as an UV excess.

The Johnson U passband extends from 3050–4200Å peaking near 3600Å. Included in this spectral region are the following chromospheric lines: Ca II H&K λ3934/69 Å and many of the H I Balmer series lines from the series limit (λ3640 Å) to Hδ(λ4101 Å). Pettersen and Hawley (1989) give surface fluxes for many of these lines and these results demonstrate that, for the late-K and M dwarf stars the Ca II lines are the strongest emitters in this part of the spectrum (note that, at their spectral resolution Hϵ is blended with Ca II H). Their measured Ca II line surface fluxes are 10^5–10^6erg s^{-1} cm^{-2} for the most active dKe and dMe stars. These fluxes correspond to luminosities in the 10^{26}–10^{27} range, again two orders of magnitudes below those necessary to produce the observed excesses. Thus we conclude that the effect of the major chromospheric emission lines is unlikely to account for the observed effect. We cannot rule out,

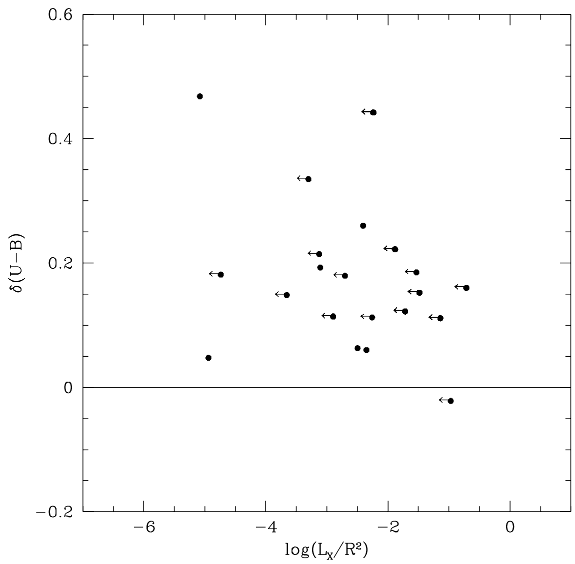

Fig. 4. UV excess for active giants vs. the logarithm of the X-ray luminosity over the squared radius of the star. Arrows mean upper limits.

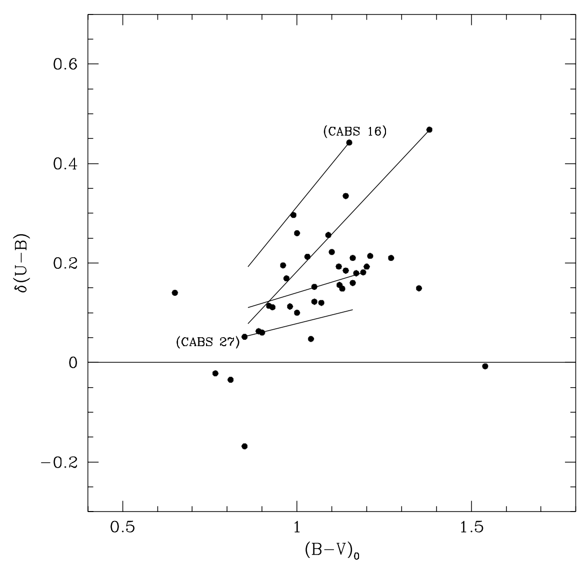

Fig. 5. UV excess for active giants vs. $(B–V)_0$ colour index. The solid lines represent the effect of contrast between the facula component and the photosphere.

however, a contribution from a distribution of a large number of metallic emission lines spread throughout the spectral region.

4.3. X-ray back-heating

Since the effect we observe is clearly associated with chromospheric and coronal activity, we have sought indications of correlation between the observed excess and some measure of this activity in individual stars. This is done in Fig. 3 and Fig. 4 where each star's $(U–B)$ excess is plotted against its X-ray and Mg II luminosity, normalized to bolometric luminosity (or surface area in the case of the giants). It is immediately apparent that no such correlation exists, the correlation coefficients being, for Fig. 3 a), 0.25786, and b), 0.24252 and for Fig. 4, 0.31912.

Furthermore, as noted above, the energy requirements of the observed excess in the U band would demand heating at a rate at least equal to the total X-ray luminosity of the star, implying 100% back-heating efficiency.

4.4. Faculae

In the Sun, faculae are patches of hot material (hotter by about 300 K from the surrounding photosphere (Phillips 1992)) within active regions. They are composed of chains or clusters of tiny bright points – facular bright points – very similar in brightness, size and lifetimes to the network bright points in quiet areas. Plages are the extension of the photospheric faculae into the chromosphere.

In active stars, where the filling factors of active regions may approach unity, the higher brightness and the hotter temperature of faculae and plages over those of the photosphere would affect the colours of the star shifting them towards the blue, thus producing an UV excess. This effect, of course, will be more enhanced for stars with lower effective temperature for which the contrast between the faculae and the photosphere will be larger.

To quantify the effect of faculae on the average colours of the stars, let us assume a temperature for the facula of $T_{\rm fac} = T_{\rm ph} + 300$ K, where $T_{\rm ph}$ is the effective temperature of the quiet photosphere and we assume black body flux distributions for both active and quiet photospheres (although these are likely to be far from the actual flux distributions, they will suffice for an order of magnitude estimate). We will take as examples for the dwarf stars the three dMe active stars mentioned above, namely, YZ CMi, AD Leo and EV Lac. In Table 2, we give all the parameters used in the calculations of the surface fluxes emitted by the quiet photosphere ($F_{\rm q}$) and the facula ($F_{\rm fac}$) in these stars. The surface flux in the U band that we would observe ($F_{\rm U}$) would be the sum of the UV excess we actually see for these stars ($\Delta F_{\rm U}$) plus $F_{\rm q}$. Making use of the equation $F_{\rm U} = fF_{\rm fac} + (1-f)F_{\rm q}$, we can derive the filling factors for the active region necessary to produce the observed UV excess. Those filling factors are also given in Table 2, where in the last two rows, we also set $T_{\rm fac} = T_{\rm ph} + 500$ K for the two most active stars. We note that the required filling factors derived are substantial fractions of the entire stellar surface.

Saar & Linsky (1985) found from Zeeman splitting in the infrared spectrum of the dMe star AD Leo that active regions covered 73%±6% of the surface of that star with a mean field strength of $B = 3800 \pm 260$G. Since the star did not show any evidence of flares at the time of the observation they concluded that this value probably represented the quiescent magnetic flux level for AD Leo. Utilizing the same technique for an optical spectrum of the dMe star EV Lac, Johns-Krull & Valenti (1996) measured magnetic fields of $B = 3800 \pm 500$ G covering 50%±13% of its surface. We note that the implied magnetic filling factors are similar to the figures we derive from the above crude estimates based on black-body faculae.

Moreover, if we take into account the effect of contrast between the facula and the surrounding photosphere of the star, we should be able to predict that the farther we move towards later spectral types, the larger the excess should become (if the temperature contrast is similar in different spectral types). We can see exactly the expected effect in Fig. 5, where we plot the excess in the $(U–B)$ colour against $(B–V)_0$ for active giant stars. The solid lines represent the effect of the contrast between the facular component and the photosphere assuming a constant excess flux in the U passband. In other words, we took the star labelled as CABS 16 (star number 16 in the CABS catalog), which is a giant star with $(B–V)_0$ = 1.15 or spectral type K0, and calculated the extra-flux in the U band necessary to produce the excess we observe in $(U–B)$. Assuming this same constant extra-flux as the effect of activity on a normal star of spectral type G5, we produced an excess in the $(U–B)$ colour that positions the star at the end of the solid line, i.e., with a $\delta(U–B)$ = 0.21. We made the same calculations for the star labelled as CABS 27, where the "parent" star is of spectral type G1 and the "descendant" star is a K2 giant star, and for two more stars. We can see that the tracks from CABS 16 and CABS 27 envelop almost all the stars in the sample of active giants, with the tracks from the other two stars falling within the previous two. This indicates that a contrast effect could play an important role in the decrease of the observed UV excess towards the earlier spectral types for active giants. In the case of the dwarfs, we saw the same trend in Fig. 2 (the third panel from the top), i.e., the earlier the spectral type the smaller the excess, but it is not so clear.

5. Conclusions

For the first time, we clearly show that activity affects the overall properties of the photosphere of a star in its intrinsic mean colours. We have demonstrated that the UV excess can be due to a contribution to the overall stellar colours of a facular component on the surface of these stars.

In our discussion here we have not, however, taken into account the effect that metallicity might have on the colour indices. Estimating such effects is beyond the scope of the present paper but would warrant a further investigation, perhaps to be undertaken spectroscopically.

Acknowledgements. Research at Armagh Observatory is supported by a Grant-in-Aid from the Department of Education for Northern Ireland. PJA acknowledges support of a Post-graduate Research Assistantship from the Armagh Observatory.

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