AG Dor: Spot Parameters From Simultaneous Optical and Infrared Photometry and TiO Spectroscopy

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Abstract:
As a continuation of our project to derive the distribution and temperature of the modulating component of spots on active late-type stars, the authors have observed a number of RS CVn, BY Dra and dMe stars photometrically (optical $UBV(RI)_c$ and infrared $HJK$) and spectroscopically (TiO band) simultaneously in Dec. 1996 and Jan. 1997. The simultaneity of these observations allows us to apply two of the currently available techniques with which spot temperatures, sizes and locations can be obtained, viz., the light-curve modelling technique and the TiO band technique. We present here the photometric and spectroscopic data for one of our targets, AG Dor, and the spot model that best fits the observed light and colour curves and the depth of the $\lambda7055$ Å titanium oxide band for this active star.

1. Introduction
Many stars show variations in their V-band light curve which can be accounted for by assuming that cool parts of the stellar photosphere (starspots) are carried on, across and off the stellar disk by the star’s rotation. These variations in light can also be seen in colour indices like $(V-R)_c$, $(V-I)_c$ or $(V-K)$, usually in phase with the V curve, showing a reddening at light minimum (maximum spot visibility) and, thus, supporting the cool spot hypothesis.

Further evidence of such a hypothesis comes from the fact that some spectral features, especially molecular bands (e.g. TiO bands), characteristic of the cooler spots are visible at some or even at all phases throughout the rotation of the star. The presence of these bands reveals the existence of these spots since at the effective temperature of the unspotted photosphere, none should be seen.

2. Observations
The data presented in this paper were collected at the South African Astronomical Observatory between 24 December 1996 and 6 January 1997.

The $UBV(RI)_c$ data were taken with the 0.5 m telescope and the $JHK$ magnitudes with the 0.75 m telescope. The observations were corrected for atmospheric extinction and transformed into the standard system.

In order to obtain accurate differential photometry for the variable stars (v), comparison (c) and check (ck) stars were chosen with magnitudes and spectral
Table 1. Mean value of the \( V \) magnitude and colours for our targets and the standard deviations (\( \sigma \)) in units of 0.001 magnitudes of the \( v-c \) and \( c-k-c \) differences in the \( V \)-band

<table>
<thead>
<tr>
<th>Program Star</th>
<th>( V_{\text{max}} )</th>
<th>( U-B )</th>
<th>( B-V )</th>
<th>( V-R_c )</th>
<th>( V-I_c )</th>
<th>( \sigma_{V} ) ( (v-c) )</th>
<th>( \sigma_{V} ) ( (c-k-c) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>AG Dor</td>
<td>8.674</td>
<td>0.658</td>
<td>0.961</td>
<td>0.552</td>
<td>1.086</td>
<td>6.186</td>
<td>32</td>
</tr>
</tbody>
</table>

Types as close to those of the variable stars as possible. Each star was measured long enough to get a signal-to-noise of 1000 in each filter and according to the sequence \( c-v-v-c-c-k \). The variable star measurements were averaged to obtain one data point per sequence. The sky background was also measured, specially carefully during the periods of bright moon. In Table 1, the maximum \( V \) and \( K \) magnitudes and mean \( (U-B) \), \( (B-V) \), \( (V-R)_{C} \) and \( (V-I)_{C} \) colours for AG Dor are reported along with the standard deviations (\( \sigma \)) for the \( v-c \) and \( c-k-c \) mean differential \( V \)-band magnitudes in units of 0.001 magnitudes. The standard error of the \( V \) magnitude for these observations is of the order of \( \sim 0.01 \), due to extinction and transformation errors, the typical single measure standard error being of a few milli-magnitudes.

The spectroscopic data for AG Dor and standard stars were collected with the 1.9 m telescope. These data were flat-field corrected, sky subtracted and wavelength calibrated using the IRAF astronomical software package. The wavelength calibration was achieved by collecting arc spectra from a copper-argon lamp. The data were also corrected for the presence of telluric lines. In order to do so, we observed rapidly rotating B and A stars as close in time and on the sky to our target stars as possible. Measurements of arc lines gave an instrumental resolution of \( \sim 1.7 \) Å.

3. Results: Photometry

AG Dor (HD 26354) is a non-eclipsing, double-lined spectroscopic binary (SB2) which was classified as an RS CVn-type system by Kholopov et al. (1989), though a tentative BY Dra-type classification seemed to be feasible as well. Recently, from an extensive high resolution spectroscopic study, Washüttl & Strassmeier (1995) computed \( v \sin i \) of \( 17 \pm 2 \) and \( 10 \pm 5 \) km s\(^{-1} \) for the primary and secondary components respectively. These values translate to minimum radii of 0.86 and 0.50 \( R_\odot \) for the components, thus strengthening the BY Dra classification of K1V + K5V. The secondary star of such a system would be about 1.2 magnitudes fainter in the \( V \)-band than the primary (Cutispoto 1996). The system has an orbital period of 2.562 days (Balona 1987) and its photometric variability was found by Lloyd-Evans & Koen (1987). They reported \( V \)-light variations with a period of 2.533 days with an amplitude of 0.09 magnitudes. This system is listed with number 34 in the “Catalog of Chromospherically Active Stars” (CABS) (Strassmeier et al. 1993), which also gives an X-ray flux...
AG Dor: Starspot Parameters

Figure 1. Light and colour curves for AG Dor. The solid squares represent the data from between December 1996 and beginning of January 1997 and the solid triangles the data from the end of January and beginning of February 1997. The lines correspond to different fits with the solid lines representing Model 1 (thick) and Model 2 (thin) and the dashed lines Model 3 (thick) and Model 4 (thin). The parameters for each model are given in Table 2.

of $0.65 \times 10^{30}$ erg s$^{-1}$ (Dempsey et al. 1993) and a radio flux density of 6.6 mJy (Slee & Stewart 1989). It shows Ca II H and K weak in emission.

The phases were calculated from the ephemeris HJD= 2447587.52 + 2.533E (Lloyd-Evans & Koen 1987). We selected the standards HD 26779 and HD 25901 as the comparison and check stars respectively. In Fig. 1, the $V$ light curve and $(U-B)$, $(B-V)$, $(V-R)_c$, $(V-I)_c$ and $(V-K)$ colour curves for this star are given by the solid symbols (see caption for more details). The $V$ curve has a shape similar to that of the 1989 season (Cutispoto 1992) but with the peak shifted and a maximum brightness of 8.67, making it 0.1 magnitudes fainter than the
Table 2. Spot parameters for AG Dor

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polar</td>
<td>Radius (°)</td>
<td>62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lat. (°)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long. (°)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_{\text{eff}}$ (K)</td>
<td></td>
<td>4000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spot 1</td>
<td>Radius (°)</td>
<td>14</td>
<td>22</td>
<td>15</td>
</tr>
<tr>
<td>Lat. (°)</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Long. (°)</td>
<td>252</td>
<td>252</td>
<td>252</td>
<td>252</td>
</tr>
<tr>
<td>$T_{\text{eff}}$ (K)</td>
<td>4300</td>
<td>4600</td>
<td>4450</td>
<td>4650</td>
</tr>
<tr>
<td>Spot 2</td>
<td>Radius (°)</td>
<td>18</td>
<td>22</td>
<td>16</td>
</tr>
<tr>
<td>Lat. (°)</td>
<td>10</td>
<td>0</td>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td>Long. (°)</td>
<td>352.8</td>
<td>352.8</td>
<td>352.8</td>
<td>352.8</td>
</tr>
<tr>
<td>$T_{\text{eff}}$ (K)</td>
<td>4550</td>
<td>4550</td>
<td>4350</td>
<td>4600</td>
</tr>
<tr>
<td>Relative $\chi^2$</td>
<td>1</td>
<td>1.02</td>
<td>1.22</td>
<td>1.04</td>
</tr>
</tbody>
</table>

maximum recorded by Cutispoto (1996). This implies that the contribution of the non-modulating distribution of spots must have increased between the two epochs. $(V-R)_c$, $(V-I)_c$ and $(V-K)$ show variations in phase with those of the $V$ curve.

We used a FORTRAN code named SPOTPIC to model the light and colour curves of AG Dor. This code allows for different values of the spot and photospheric surface gravity (to allow for magnetic evacuation), uses new surface brightness–$(I_c-K)$ and $T_{\text{eff}}$–colour relationships (Amado & Byrne 1996) to determine the spot and photospheric fluxes, and includes the $V-K$ colour in the modelling of starspots. For a more comprehensive description refer to Amado (1997). The spot model fits are given by the lines in Fig. 1. It was necessary to use two spots in the models because there seemed to be some indication for structure in the minima of the $V$, $(V-I)_c$ and, specially, $(V-K)$ curves, otherwise the fit could have been attempted with only one spot. The spot parameters are given in Table 2 for four different models. Models 1 and 2 (solid thick and thin lines) were computed assuming a photospheric surface gravity ($\log g_{\text{ph}}$) and a spot effective gravity ($\log g_{\text{sp}}$) of 5.0, and a photospheric effective temperature ($T_{\text{ph}}$) of 5000 K and 4800 K respectively. Models 3 and 4 (dashed thick and thin lines) were computed assuming a $\log g_{\text{ph}}$ of 5.0, a $\log g_{\text{sp}}$ of 4.5 and a $T_{\text{ph}}$ of 5000 K for Model 3, and 4800 K for Model 4. The inclination of the star, $i$, was set to 90°.

A non-modulating component of the spot distribution was included in the models by assuming a polar spot (although also an equatorial belt might have been considered) whose parameters are given in Table 2. It is interesting to note that the temperature of this component is much lower than the temperature of the modulating spots. However, the temperature and the area might have had different values if an equatorial belt was used in the models. The zero level
of the magnitudes for the unspotted surface were taken from Cutispoto (1996), where the star was observed in Feb.–Mar. 1990, and the magnitudes appeared brighter, at light maximum, than in any previous epoch.

4. Results: Spectroscopy

In Fig. 2, we show the spectra recorded on every clear night over the region around the TiO band at $\lambda 7055$ Å. The uppermost spectrum is an overall mean of the nightly spectra. Usually, another TiO band at $\lambda 8860$ Å is also recorded in order to uniquely determine effective temperature and areas, but this was not possible here because of the low sensitivity of the instrument at those wavelengths.

On these spectra, we took measurements of the TiO band-head depth. These measurements were made in two 5 Å-wide regions to the blue ($\lambda\lambda 7043 – 7048$ Å) and red ($\lambda\lambda 7060 – 7065$ Å) of the band-head as in Neff et al. (1995). We plotted the results of this measurements but we did not find any rotational modulation of the band depth. This was probably mostly due to the low resolution of our data which was not good enough to attempt this kind of measurements.

We used also our standard star spectra (HR 1003 M3–4 III and HD 19285 M5 III) to synthesize the spectra of a K5 III, M1 III and M7 III stars. Once this was done, we used these data to simulate spot spectra. The star HR 953 (K0 III) was used as the model for the unspotted photosphere of AG Dor. A better model would have been a star of spectral type K1 V but we did not observed any star of luminosity class V.

The excess absorption in AG Dor is weak but clearly present. To model its mean spectrum, we used the equation

$$F_{\text{total}} = \frac{f_s R_{\lambda} F_s + (1 - f_s) F_Q}{f_s R_{\lambda} + (1 - f_s)}$$

where $f_s$ is the filling factor, $R_{\lambda}$ is the flux ratio between the photosphere and the spot and $F_s$ and $F_Q$ are the fluxes emitted by the unspotted photosphere and the spot.

In Fig. 3, we show the results of fitting the simulated spectra to the observed one, varying the filling factor and the temperature of the spots. Green circles mean a relatively (taking into account the quality of the data) good fit and red squares poor fits. We also show the solutions from our two best photometric models. Since we only observed one band head, it was not possible to constraint the temperature and the filling factor of the spots simultaneously from the spectroscopic data. Also, due to the weakness of the band and to the low resolution of our data, it was not clear which of the simulated spectra having a spot temperature of $\sim 4000$ K fitted the observed spectrum the best. However, we can conclude that, at the temperature of the “photometric” spots (see Table 2), their contribution to the depth of the TiO band is probably negligible. Therefore, the non-modulating component of the spot distribution, which is cooler than the modulating one, must be responsible for the presence of the $\lambda 7055$ Å TiO band.
Figure 2. AG Dor’s nightly spectra in the region of the TiO molecular band. The spectra have been normalized to the local continuum and shifted for clarity. The spectrum at the top is the overall mean for all the nights. The TiO (specially the λ7053) and CaH molecular bands and the telluric O₂ and H₂O have been marked.

5. Conclusions

We have modelled simultaneously optical, near-infrared and far-infrared colour curves to try to remove the non-uniqueness of the solution of the spot problem, thus obtaining $T_{\text{eff}}$, size (radius) and location (latitude and longitude) of the spots with good accuracy for the star AG Doradus. Applying the photometric modelling code SPOTPIC (Amado 1997), we find two modulating spots together with a non-modulating component, which we recreated with a polar spot, on the photosphere of AG Dor in Dec. 96/Jan. 97. The spot temperatures were constrained to be between 4300 K and 4600 K for the modulating component, and cooler, viz., 4000 K, for the non-modulating one. From the photometric data, we
determined the filling factor of AG Dor’s total coverage of spots to be between 4% (Model 1) and 7% (Model 2) for the modulating component and 26.5% for the non-modulating one, which was consistent with the value determined from the spectroscopic data. Therefore, we hold the non-modulating component of spots on AG Dor at this epoch to be totally responsible for the presence of the λ7055 Å TiO band in the spectra of this K1 dwarf with photospheric temperature of 5000 K.

Acknowledgments. 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. PJA would like also to acknowledge here the support and helpfulness of the staff at the SAAO and specially of Francois van Wyk and Fred Marang who obtained some photometric data for this work under the supervision of Dr. David Kilkenny and Dr. Patricia Whitelock respectively.
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