Doin' the twist: Secular changes in the surface differential rotation on AB Doradus

A. Collier Cameron1 *, J.-F. Donati2
1 School of Physics and Astronomy, Univ. of St Andrews, St Andrews, Scotland KY16 9SS
2 Laboratoire d’Astrophysique, Observatoire Midi-Pyrénées, Avenue E. Belin, F-31400 Toulouse, France

Accepted 2001 November 12. Received 2001 November 12; in original form 2001 November 6

ABSTRACT
We present measurements of the rotation rates of individual starspots on the rapidly rotating young K0 dwarf AB Doradus, at six epochs between 1988 December and 1996 December. The equatorial rotation period of the star decreased from 0.5137 to 0.5129 days between 1988 December and 1992 January. It then increased steadily, attaining a value of 0.5133 days by 1996 December. The latitude dependence of the rotation rate mirrored the changes in the equatorial rotation rate. The beat period between the equatorial and polar rotation periods dropped from 140 days to 70 days initially, then rose steadily. The most rigid rotation, in 1988 December, occurred when the starspot coverage was at a maximum. The time-dependent part of the differential rotation is found to have $\Delta \Omega / \Omega \approx 0.004$, which should alter the oblateness of the star enough to explain the period changes observed in several close binaries via the mechanism of Applegate (1992).

Key words: stars: activity – stars: imaging – stars: individual: AB Dor – stars: rotation – stars: spots

1 INTRODUCTION
The back-reaction of Lorentz forces on the fluid circulation in the convective zone of a rotating late-type star is of fundamental importance in theories of stellar magnetic-field generation. Over the last decade or so, a consensus has emerged among dynamo theorists that this back-reaction could have a significant influence on the differential rotation pattern in the convective zones of the Sun and active late-type stars (see, e.g. Brandenburg et al. 1991; Moss et al. 1995; Kitchatinov et al. 1999).

The quasi-cyclic orbital period changes observed among short-period binaries with magnetically-active components provide further indirect evidence that substantial changes in differential rotation could be taking place on active binary components. Work by Applegate (1992), Lanza, Rodono & Rosner (1998) and Lanza & Rodonò (1999) suggests that small, magnetically-modulated changes in stellar differential rotation will alter the gravitational quadrupole moment of the active star. This can be sufficient to produce orbital period changes as large as the fractional $\delta P / P \approx 1.5 \times 10^{-4}$ observed in HR 1099 by Donati (1999).

In this paper we report observations of long-term changes in surface differential rotation on the young, rapidly rotating K0 dwarf AB Doradus, providing independent support for this theory. We apply a new method for determining the latitudes and rotation rates of individual starspots (Collier Cameron, Donati & Semel 2002) to six sets of archival time-resolved echelle spectroscopy of AB Dor, spanning the period from 1988 December to 1996 December.

2 OBSERVATIONS AND DATA REDUCTION
The details of the instruments and observing procedures used to secure the six data sets have been published elsewhere, so we give only a brief summary in Table 1.

The observations from the three earliest runs were re-extracted from the raw data using the Starlink ECHOMOP optimal extraction routines, to ensure consistency with the later data. The spectra from all 6 years included the Hα region, in which numerous weak, narrow telluric lines of H2O and O2 are present. We used spectral subtraction (Collier Cameron et al. 2001) to isolate the travelling distortions produced by starspots in the mean profile, and least-squares deconvolution (Donati et al. 1997) to stack up the residual profile information in the large number of known photospheric lines recorded in the echellograms. The number $N$ of lines used in each year ranges from 140 to 2000, and is given in Table 1, column 3. Since the spectra in all years were ex-
posed to a signal-to-noise (S:N) ratio of 100 to 120, the S:N of the deconvolved profiles scales approximately with \( \sqrt{N} \).

The deconvolved profiles were placed in the heliocentric reference frame, to an accuracy better than 100 m s\(^{-1}\), using the telluric lines as velocity references during the deconvolution procedure. The resulting time-series of residual profiles were subjected to a matched-filter analysis, yielding measures of the spot area, radial velocity amplitude about the stellar centre of mass, and rotation period, together with estimates of their uncertainties. More detailed descriptions of the deconvolution, spectral subtraction and matched-filter analysis procedures are given by Collier Cameron et al. (2001) and Collier Cameron, Donati & Semel (2002). As in this earlier paper, we used a limb-darkening coefficient \( u = 0.77 \) and \( v \sin i = 91 \) km s\(^{-1}\) in constructing the matched filter.

### 3 RESULTS

The rotation periods of the spots detected in each season’s data are plotted against their rotational velocity amplitudes \( K = \Omega(\theta)R_\star \cos \theta \sin i \) in the left-hand panels of Figure 1. Here \( \Omega(\theta) \) is the rotation rate at latitude \( \theta \), and \( R_\star \) is the stellar radius.

In the 1995 and 1996 seasons, outlying points caused by aliasing between closely-spaced pairs of spots observed several days apart can be seen (Collier Cameron, Donati & Semel 2002). These were excluded from the next stage of the analysis.

The stellar radial velocity \( v_r \simeq 32.5 \) km s\(^{-1}\) and \( v \sin i = 91 \) km s\(^{-1}\) are both uncertain by \( \pm 1 \) km s\(^{-1}\) or so. The systematic errors in the derived quantities \( K \) and \( P \) due to these uncertainties are smaller than the 1σ error bars shown in Figure 1.

As Collier Cameron, Donati & Semel (2002) noted, there is an intrinsic scatter of the individual spot rotation rates about the mean differential rotation pattern. The rms magnitude of this scatter is equivalent to an additional uncertainty of \( \pm 0.00017 \) day in the rotation period of each spot. After adding this error in quadrature to the measured uncertainty in each spot’s period, we fitted a differential rotation law of the form

\[
\Omega(\theta) = \Omega_{\text{equator}} - \Omega_{\text{beat}} \sin^2 \theta
\]

(1)

to each season’s data. The optimal solutions for the equatorial rotation period \( P_{\text{equator}} = 2\pi/\Omega_{\text{equator}} \) and the equator-pole beat period \( P_{\text{beat}} = 2\pi/\Omega_{\text{beat}} \) are shown together with their 68.3% and 95.4% confidence regions in the right-hand panels of Fig. 1. The inner contour is the locus \( \chi^2 = \chi^2_{\text{min}} + 1.0 \), whose extremities in \( P_{\text{equator}} \) and \( P_{\text{beat}} \) give the one-dimensional 1σ error bars on the two periods. The outer contours, at \( \chi^2 = \chi^2_{\text{min}} + 2.3 \) and 6.17, contain 68.3% and 95.4% of the joint probability respectively.

The fits to the six years’ data are summarized in Table 2 and Fig. 2. The equator-pole beat period of AB Dor displays significant variability from one observing season to the next. Between 1988 December and 1992 January the differential rotation rate in the star’s surface layers doubled, with the beat period falling from 140 to 70 days. The equatorial rate increased and the high-latitude rotation rate dropped. This increased shear pattern persisted into 1993. In 1994 and 1995 the rotation rate at latitude 40° and northward increased while the equator continued to rotate rapidly. In 1996 the high latitudes continued spinning up as the equator began to show signs of slowing down. The smallest variation in rotation period is seen at 40° (latitude \( \sim 40° \)), but nowhere on the star is the rotation rate constant.

### 4 DISCUSSION AND CONCLUSIONS

We have found that the differential rotation rate of the young K0 dwarf AB Dor varies by a factor 2 on a timescale of a few years. While the 8-year timespan of the observations presented here is too short to determine whether we are seeing a cyclic phenomenon, the apparent smoothness of the increase and decline in the differential rotation suggests that the changes occur on a timescale of order a decade or two. The variation resembles a wave of excess rotation, originating at the equator in 1992 and propagating poleward.

Applegate (1992) and Lanza, Rodono & Rosner (1998) have shown that changes in magnetic flux threading the con-

---

**Table 1.** Summary of observing runs. Details of the observations are given in the papers listed. The phase ranges in the fourth column are those in which the complete signatures of individual spots could be observed on at least two nights of the run observing concerned.

<table>
<thead>
<tr>
<th>UT Dates</th>
<th>Telescope/Instrument</th>
<th>No of lines</th>
<th>Phase coverage</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988 Dec 16, 19</td>
<td>3.9-m AAT/UCLES</td>
<td>139</td>
<td>0.09:0.40</td>
<td>Collier Cameron et al. (1990)</td>
</tr>
<tr>
<td>1988 Dec 21, 23</td>
<td>3.6-m ESO/CASPEC</td>
<td>326</td>
<td>0.00:0.38, 0.94:1.00</td>
<td>Collier Cameron et al. (1990)</td>
</tr>
<tr>
<td>1992 Jan 18, 19, 20</td>
<td>3.9-m AAT/UCLES</td>
<td>1134</td>
<td>0.08:0.62</td>
<td>Collier Cameron &amp; Unruh (1994)</td>
</tr>
<tr>
<td>1993 Nov 23, 24, 25</td>
<td>3.9-m AAT/UCLES</td>
<td>1566</td>
<td>0.40:0.85</td>
<td>Unruh, Collier Cameron &amp; Cutispoto (1995)</td>
</tr>
<tr>
<td>1994 Nov 15, 16, 17</td>
<td>4.0-m CTIO/echelle</td>
<td>619</td>
<td>0.04:0.18, 0.28:0.63</td>
<td>Collier Cameron et al. (1999)</td>
</tr>
<tr>
<td>1995 Dec 07, 11</td>
<td>3.9-m AAT/UCLES</td>
<td>1936</td>
<td>0.55:0.95</td>
<td>Donati &amp; Collier Cameron (1997)</td>
</tr>
<tr>
<td>1996 Dec 23, 25, 27, 29</td>
<td>3.9-m AAT/UCLES</td>
<td>1964</td>
<td>0.50:1.00</td>
<td>Donati et al. (1999)</td>
</tr>
</tbody>
</table>

---

**Table 2.** Differential rotation parameters derived from 2-parameter fits to the rotation rates of individual spots in 1988 December, 1992 January, 1993 November, 1994 November, 1995 December and 1996 December. The second column gives the number of spots contributing to each fit.

<table>
<thead>
<tr>
<th>JD</th>
<th>No of spots</th>
<th>( P_{\text{equator}} ) (days)</th>
<th>( P_{\text{beat}} ) (days)</th>
<th>( \chi^2 \</th>
</tr>
</thead>
<tbody>
<tr>
<td>47517.1</td>
<td>12</td>
<td>0.51367 ± 0.00010</td>
<td>136 ( ^{+18}_{-16} )</td>
<td>32.4</td>
</tr>
<tr>
<td>48640.9</td>
<td>12</td>
<td>0.51285 ± 0.00012</td>
<td>69 ( ^{+10}_{-10} )</td>
<td>11.2</td>
</tr>
<tr>
<td>49316.3</td>
<td>15</td>
<td>0.51290 ± 0.00010</td>
<td>71 ( ^{+6}_{-6} )</td>
<td>47.1</td>
</tr>
<tr>
<td>49672.5</td>
<td>13</td>
<td>0.51299 ± 0.00020</td>
<td>94 ( ^{+26}_{-26} )</td>
<td>55.2</td>
</tr>
<tr>
<td>50061.2</td>
<td>16</td>
<td>0.51292 ± 0.00008</td>
<td>88 ( ^{+7}_{-7} )</td>
<td>15.9</td>
</tr>
<tr>
<td>50443.7</td>
<td>19</td>
<td>0.51326 ± 0.00007</td>
<td>109 ( ^{+9}_{-9} )</td>
<td>53.3</td>
</tr>
</tbody>
</table>

© 0000 RAS, MNRAS 000, 000–000
Variable differential rotation on AB Dor

Figure 1. The left-hand panels show rotation period $P$ versus rotational velocity amplitude $K$ for candidate starspots in each year of observation. “Threshold” denotes the $\chi^2$ threshold below which spurious spots have been rejected. “Phi” denotes the phase range searched, as given in column 4 of Table 1. The fitted differential rotation curve is shown for each year. The right-hand panels show the contours $\Delta\chi^2 = 1.0, 2.3$ and 6.17 as a function of equatorial rotation period and equator-pole lap time, both in days.
Figure 1 – continued
Variable differential rotation on AB Dor

4.50
4.25
4.00

Figure 2. The equator-pole beat period $P_{\text{beat}}$ (upper panel) and equatorial rotation period $P_{\text{eq}}$ (lower panel) versus Julian date. The data points are shown for (left to right) 1988 December, 1992 January, 1993 November, 1994 November, 1995 December and 1996 December.

The viscous transport during a stellar magnetic cycle may alter the viscous transport of angular momentum sufficiently to produce substantial changes in differential rotation. AB Dor was rotating most rigidly in late 1988, at a time when the star’s maximum light level was depressed by 0.2 mag or so relative to photometry secured in the early 1980s and mid-1990s (Küster et al. 1997). The increase in differential rotation between 1988 and early 1992 coincides with a 0.1-mag rise in the maximum brightness of the star. The maximum brightness of the star remained steady between 1992 and late 1996, as the differential rotation began gradually to decrease again. The timescales of the long-term changes in starspot coverage and differential rotation thus appear to be comparable, though we cannot yet determine how closely the spot coverage and differential rotation rate are linked.

These departures from the time-averaged differential rotation pattern are between one and two orders of magnitude greater than the waves of excess and deficit rotational velocity — sometimes described as “torsional oscillations” — that migrate equatorward during the solar spot cycle (Howard & Labonte 1980; Labonte & Howard 1982). These departures from the mean solar rotational velocity have amplitudes of order 5 m s$^{-1}$. At the equator of AB Dor, however, a change in period from 0.5137 to 0.5128 days corresponds to a 200 m s$^{-1}$ change in $v \sin i$. If we consider the full change $\Delta \Omega = 0.048$ radian d$^{-1}$ in the equator-pole beat frequency, we find that $\Delta \Omega / \Omega \simeq 0.004$.

Such a large modulation of the surface differential rotation will alter the star’s oblateness sufficiently that, if AB Dor were in a close binary system, it would be expected to produce observable long-term orbital period changes. By way of comparison, the K2V primary of the binary system V471 Tau has a spectral type and rotation period very similar to those of AB Dor. Applegate (1992) points out that the observed 20-year, $\Delta P / P \simeq 10^{-6}$ modulation of the orbital period in V471 Tau (Skillman & Patterson 1988; Ibanoglu et al. 1994) would require a variable differential rotation in the K star, with $\Delta \Omega / \Omega = 0.0032$. The observed changes in AB Dor’s differential rotation are of precisely the magnitude required by the Applegate (1992) model to explain the orbital period variations in V471 Tau.

ACKNOWLEDGMENTS

This paper is based on observations made using the 3.9-m Anglo-Australian Telescope, the 3.6-m telescope at ESO and the 4-m telescope at CTIO. The project made use of support software and data analysis facilities provided by the Starlink Project which is run by CCLRC on behalf of PPARC. We thank the referee, Dr. Martin Küster, for suggesting several improvements to the paper. ACC acknowledges the support of a PPARC Senior Research Fellowship.

REFERENCES


© 0000 RAS, MNRAS 000, 000-000