

# *UBVRI* photometric monitoring of 7 rapidly rotating late-type dwarfs in the Alpha Persei cluster<sup>\*,\*\*</sup>

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**Abstract.** — The *UBVRI* light curves of 7 late-type dwarfs amongst the fastest rotators of the Alpha Per cluster ( $v \sin i \geq 140 \text{ km s}^{-1}$ ) are presented. The shape of the light curves suggests that the photometric variations are most often dominated by a single group of cool spots located at intermediate or high latitude on the stellar surface. Assuming that starspots are good tracers of the stellar magnetic field, the smooth light curves indicate the existence of a large scale, slowly varying magnetic structure at the surface of these ultrafast rotators.

**Key words:** stars: magnetic fields — stars: rotation — stars: activity — stars: late type — open clusters and associations: individual: Alpha Persei

## 1. Introduction

The axial rotation periods of several tens of late-type dwarfs belonging to young clusters have been measured to date (see Prosser et al. 1993a,b, 1995; O'Dell & Cameron 1993; O'Dell et al. 1995; Allain et al. 1996a,b for the more recent studies and references therein). These measurements are useful to investigate the rotation rates of stars that begin their life on the main sequence, thereby bringing observational constraints on models of stellar angular momentum evolution. They are also useful to relate the degree of chromospheric and coronal activity that young solar type stars exhibit to their rotation rate in order to investigate the efficiency of the internal dynamo over a vast range of rotation rates from a few  $\text{km s}^{-1}$  to more than  $200 \text{ km s}^{-1}$ .

The stellar rotational periods are derived by monitoring the photometric variations which result from the modulation of the stellar luminosity by surface inhomogeneities. Because all the previous studies were primarily aimed at measuring rotational periods, which requires a tight temporal sampling of the light curve especially for fast rotators, the observations were usually obtained at

one (*V*-band), sometimes 2 (*V* and *I*-band), wavelengths. While quite enough to derive accurate rotational periods, monochromatic monitoring tells little on the properties of the spots that are responsible for the modulation.

We therefore decided to monitor a sample of fast rotators of the Alpha Persei cluster over the wide wavelength range encompassed by the *UBVRI* Cousins filters. All the stars included in this study had previously known photometric periods of a few hours. The aim of the present study was i) to characterize the photometric variations of the rapid rotators simultaneously in several filters over the wavelength range from 0.36 to 0.8 microns, ii) to investigate the stability of the light curves on a timescale of a few hours, i.e., from one rotational cycle to the other, as well as on a timescale of a few years, by comparing the present study with previous ones, and iii) to infer the general properties of the starspots both from the multiwavelength information gathered and from the overall shape of tightly sampled light curves.

The acquisition of the light curves and the data reduction are described in Sect. 2. The *UBVRI* light curves of each of the 7 stars observed are presented in Sect. 3. The properties of the underlying starspots are inferred from the shape, wavelength dependency, and temporal evolution of these light curves and are discussed in Sect. 4.

\*Based on observations made at Observatoire de Haute-Provence (CNRS), France

\*\*Data Table in electronic form available at CDS via anonymous ftp cdsarc.u-strasbg.fr or 130.79.128.5

## 2. Observations

Data were acquired at the 120 cm telescope of Observatoire de Haute-Provence using a Tek 512 CCD providing a square field of view of 6.5 arcmin. Care was taken to center every AP star so as to maximize the number of field stars in the same frame that could later be used as comparison stars to perform differential photometry. The Journal of Observations is given in Table 1.

**Table 1.** Journal of the observations

| Star   | JD-2449000.00 | Date (1993)  | Instrument  |
|--------|---------------|--------------|-------------|
| AP 100 | 300.30–301.70 | Nov.8, Nov.9 | T120+Tek512 |
| AP 139 | 300.30–300.70 | Nov.8        | id.         |
| AP 124 | 301.30–301.70 | Nov.9        | id.         |
| AP 226 | 303.25–303.70 | Nov.11       | id.         |
| AP 258 | 303.25–303.70 | Nov.11       | id.         |
| AP 95  | 304.25–304.70 | Nov.12       | id.         |
| AP 118 | 304.25–204.70 | Nov.12       | id.         |

The observations were obtained as part of a backup program as adverse weather at OHP in November 1993 would not allow us to perform the main program dedicated to the search for very slow rotators in the Alpha Persei cluster (see Allain et al. 1996b). The data presented here were thus obtained during the 4 nights of our run that benefited from good photometric conditions.

The standard reduction of CCD images (bias correction, flat-fielding) was done using the IRAF/CCDPROC package at CFHT. Differential photometry was performed using the IRAF/DAOPHOT package for photometry in crowded fields. The photometry was computed by first deriving an empirical PSF from a bright and isolated star in the image, then by fitting this PSF to the other stars in the image. The PSF radius was adapted to the instantaneous seeing by setting it equal to 2.5 times the average FWHM of the stars in the image.

The light curves of several comparison stars were set to zero mean and added in order to increase the  $S/N$  ratio of the comparison light curve. From 1 to 7 comparison stars were thus combined depending on the object and the wavelength. The resulting comparison light curve was then subtracted to the zero mean light curve of the AP star. The error bars displayed in the figures of Sect. 3 show the rms deviation of the comparison stars in the image. In most images, stars under study had a peak intensity between 30 and 80% of the CCD saturation limit, thus yielding a very good signal-to-noise ratio. The resulting photometric error varies between 0.005 and 0.01 mag in all filters except for a few images taken through clouds whose  $S/N$  is lower.

## 3. Results

The light curves of Alpha Per dwarfs were searched for periodicities using 3 methods: the CLEANed periodogram, the string length minimization algorithm, and a least-square sine curve fit (see Allain et al. 1996a for details). The light curves in each of the *UBVRI* filters were analyzed independently. In all cases, the same results were found by the 3 methods in all 5 filters. The mean error on the period derived in this way is 0.3 hours.

The results are listed in Table 2. The period listed is the average of the periods found by the different methods in the various filters (which always agreed to better than 10%). The amplitude of modulation in the *UBVRI* filters are derived from a non-linear least-square fit of the light curves by a sine curve with the free parameters being the origin of phase, the period, the mean light level, and the amplitude of modulation.

The amplitude of modulations measured in the *UBVRI* filters and the spot model discussed in Bouvier et al. (1993) were used to get estimates of the spot temperature and size that are listed in Table 2. In most cases, the model reproduces the observed amplitudes to better than 10%. However, it should be emphasized that the estimated spot size is a lower limit to the actual fractional coverage of the stellar surface by spot groups. This is because the model assumes that the spot faces the observer at minimum brightness and disappears out of view at maximum brightness. As discussed below, this is unlikely to be the case for the stars studied here, most of which seem to have high latitude spots. Then, the spot size listed in Table 2 may largely underestimate the actual areal coverage by spots. The spot temperature is not affected by such geometric effects and mainly depends upon the variation of the photometric amplitude with wavelength. The spot temperature, however, is sensitive to the choice of limb-darkening coefficients. As a result, the uncertainty on the spot temperature is of the order of 200 K. The *UBVRI* coefficients listed in Diaz-Cordoves et al. (1995) and Claret et al. (1995) as a function of effective temperature and gravity were used here. In order to derive the stellar effective temperature, the star's spectral type was derived from the dereddened  $(B - V)$  color index ( $E(B - V) = 0.1$  mag) using Johnson's (1966) Sp.T.-( $B - V$ ) scale, and the effective temperature was deduced from the spectral type using the  $T_{\text{eff}}$ -Sp.T. scale listed in Cohen & Kuhi (1979).

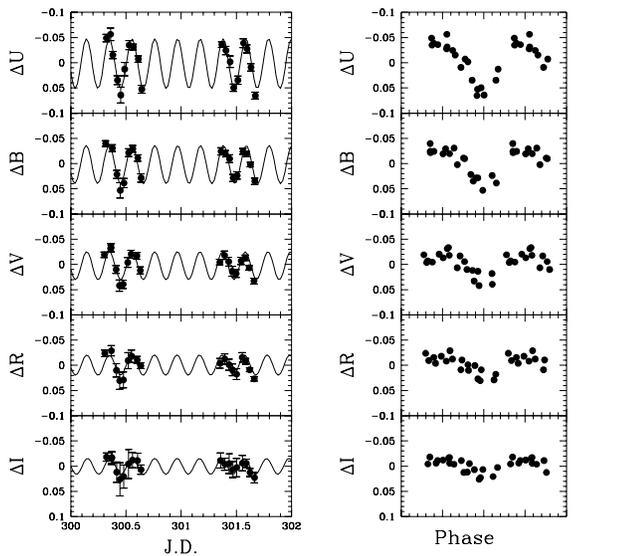
The results are presented and discussed below for each of the 7 stars in turn in the order they were observed.

**AP100:** The light-curve of AP 100 was obtained over 2 consecutive nights in the *UBVRI* filters and is shown in Fig. 1. Five comparison stars were used in the *BVRI* images to derive AP 100's photometry and 2 in the *U* images. The results of the period analysis are very consistent: all 3 methods (sinus fit, CLEANed periodogram, string-length) yield the same period of 4.9h for each of the *UBVRI* light

**Table 2.** Photometric period and *UBVRI* amplitudes. Spot properties

| Star   | Period<br>(h) | Photometric amplitudes |          |          |          |          | $(B - V)$ | $T_{\text{eff}}$<br>(K) | $T_{\text{spot}}$<br>(K) | $S_{\text{spot}}$<br>(%) | $v \sin i$<br>( $\text{km s}^{-1}$ ) |
|--------|---------------|------------------------|----------|----------|----------|----------|-----------|-------------------------|--------------------------|--------------------------|--------------------------------------|
|        |               | <i>U</i>               | <i>B</i> | <i>V</i> | <i>R</i> | <i>I</i> |           |                         |                          |                          |                                      |
| AP 100 | 4.9           | 0.10                   | 0.075    | 0.055    | 0.04     | 0.03     | 1.13      | 4775                    | 5500                     | 4                        | 205                                  |
| AP 139 | 5.9           | 0.10                   | 0.10     | 0.09     | 0.085    | 0.085    | 0.90      | 5236                    | 2600                     | 6                        | 170                                  |
| AP 124 | 4.4           | 0.185                  | 0.165    | 0.14     | 0.115    | 0.08     | 1.27:     | 4395                    | 4000                     | 21                       | 190:                                 |
| AP 226 | 5.7           | 0.04                   | 0.03     | 0.025    | 0.025    | 0.02     | 0.86      | 5445                    | 4900                     | 4                        | 181                                  |
| AP 258 | 3.1/6.3       | 0.035                  | 0.03     | 0.02     | 0.04     | 0.02     | 0.83      | 5445                    | 3500                     | 2                        | 170                                  |
| AP 95  | 8.6           | 0.14                   | 0.115    | 0.105    | 0.095    | 0.08     | 0.88      | 5236                    | 4100                     | 10                       | 140                                  |
| AP 118 | 8.0           | 0.06                   | 0.055    | 0.06     | 0.05     | 0.05     | 0.81      | 5588                    | $\leq 2500$              | 4                        | 160                                  |

$(B - V)$  values are from Stauffer et al. (1989), Prosser (1992), Prosser et al. (1993), and O’Dell et al. (1995)  
 $v \sin i$  values are from Stauffer et al. (1989), Prosser (1992), and Prosser et al. (1993)

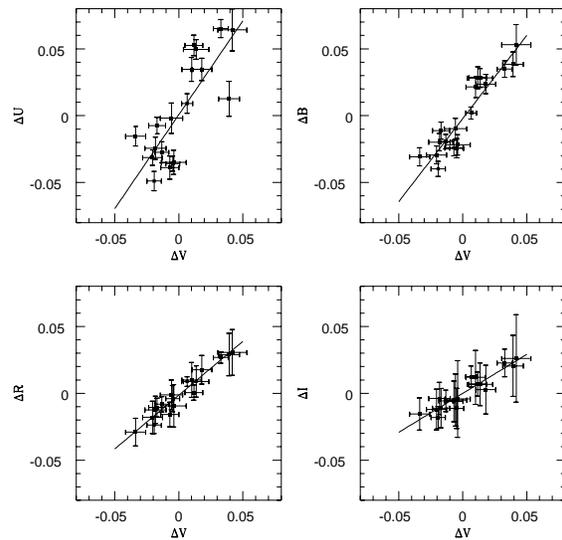


**Fig. 1.** AP 100: *UBVRI* light curves. *Left*: direct light curves obtained over 2 consecutive nights and least-square fitted by a 4.9h-period sinus curve. *Right*: same light curves folded in phase with a period of 4.9h

curves analyzed independently. The *UBVRI* light curves of AP 100 folded in phase with a period of 4.9h are shown in Fig. 1.

The amplitudes of modulation in the *UBVRI* filters were derived by fitting a 4.9h-period sinus curve to the observed light curves in each filter. The results of the fit are shown in Fig. 1 and the amplitudes are listed in Table 2.

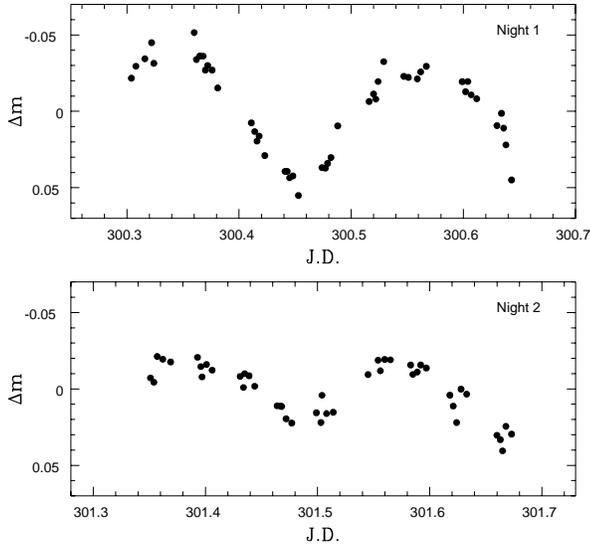
Flux-flux plots are shown in Fig. 2. They very clearly show that the photometric variations observed in the different filters are strongly linearly correlated, with the star becoming redder when fainter. We may thus assume that the *UBVRI* light curves all have the same shape and differ only in amplitude. We take advantage of this to build a “gray” (i.e., non wavelength-dependent) light curve which contains all the measurements as follows: each of the



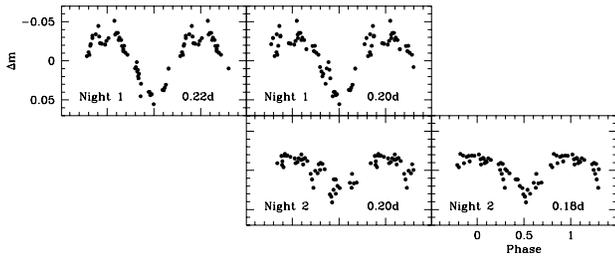
**Fig. 2.** AP 100: Relationships between the photometric variations observed in the various filters. Solid lines show linear least-square fits to the points

*UBRI* light curve is first rescaled to the amplitude of the *V*-band light curve by applying a multiplicative coefficient equal to  $dV/dm$  with  $m=U,B,R,I$ . The  $dV/dm$  coefficients are derived from a linear least-square fit to the diagrams shown in Fig. 2. The 5 light curves thus renormalized to the same arbitrary amplitude are then combined to yield the “gray” light curve shown in Fig. 3.

Because the period is of a few hours only and the time delay between measurements in different filters is up to 30 minutes, the “gray” light curves provides a much better sampling of the photometric variations of AP 100 than any of the individual light curves. In particular, it bears evidence for changes occurring in the shape of the light curve on a timescale of a few hours only. This is best seen on the first night where the second maximum is significantly lower and flatter than the first one that occurred only 5



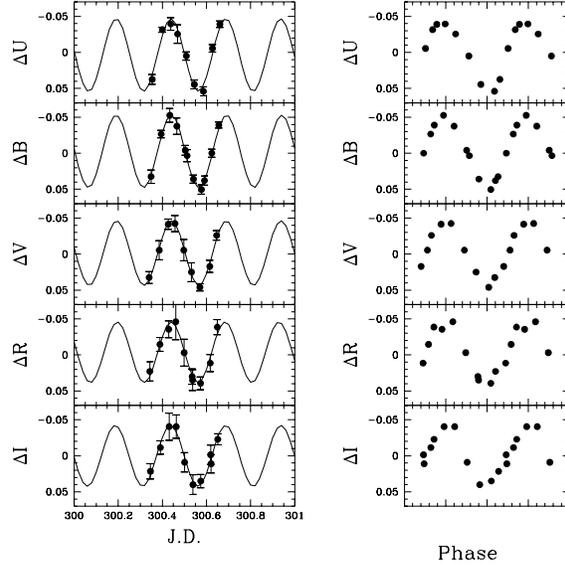
**Fig. 3. AP 100:** “Gray” light curve (see text for explanations). The first and second observing nights are shown in the upper and lower panels, respectively. Changes in the amplitude of variations seem to occur on a timescale of a few hours



**Fig. 4. AP 100:** Gray light curves obtained on the first night (upper panels) and on the second night (lower panels) of observation. The light curves are folded in phase with periods of 5.3h (left), 4.9h (middle), and 4.3h (right). See text for details

hours earlier. On the second night, the amplitude of modulation appears to be smaller than on the first night. Such rapid changes in the light curve’s amplitude and shape indicate that the properties of the stellar spots responsible for the modulation may change on a timescale of only a few hours. Alternatively, such rapid changes could result from flaring activity at the stellar surface. However, the changes are observed to equally affect the light curves at all wavelengths from *U* to *I*, while flares may be expected to be seen predominantly only at the shortest wavelengths.

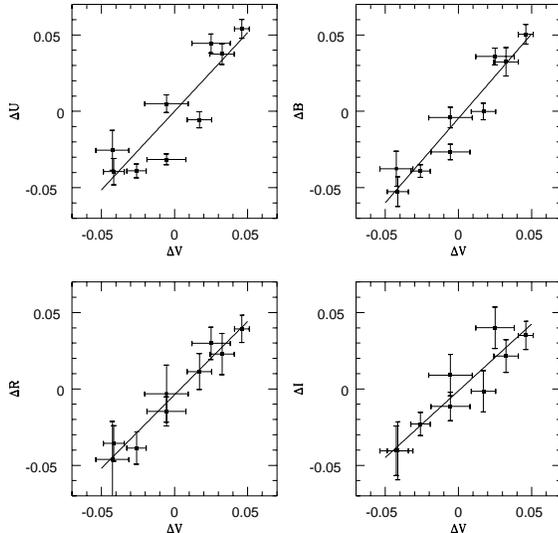
We also find marginal evidence for a period change occurring between the 2 nights of observations. When the first and second nights are analyzed separately, different periods are consistently found by the various methods in all filters, namely: 5.3h for the first night and 4.3h for the



**Fig. 5. AP 139:** Direct and phased *UBVRI* light curves. The solid curve is a least square sinus fit to the observations

second night. Whether or not this difference is significant is difficult to assess with only about 1.5 periods being covered each night, leading to an uncertainty of 0.3h on the period determination. As an illustration we show in Fig. 4, the light curves obtained on the first and second nights separately. They are folded in phase with different periods: 4.9h (best period for the whole data set), 5.3h (best period for the first night), and 4.3h (best period for the second night). The scatter on the first night appears to be significantly reduced when adopting a 5.3h period instead of the 4.9h period derived for the whole data set. On the second night, the improvement of a 4.3h period over a 4.9h period may also be seen. We mention this point mostly to draw attention on the fact that very short-term variations, i.e., on a timescale of the rotational period of these fast rotators, might occur both in amplitude and period. This clearly deserves more study as it would imply rapidly changing spot properties and large amount of surface differential rotation.

AP 100 is the only star of the sample which exhibits such short term variations in its light curve. It is also the only one whose photometric modulation appears to be due to a spot hotter rather than colder than the photosphere. We have no interpretation to offer as to what could be the origin and nature of such a hot spot on the surface of a late-type ZAMS dwarf. As discussed in Bouvier et al. (1993), such a high spot temperature could be an artefact of the spot model if AP 100 had an unresolved red companion. If real, however, the short term variability of AP 100 could be the direct consequence of its modulation being driven by a hot spot since stars with cool spots appear



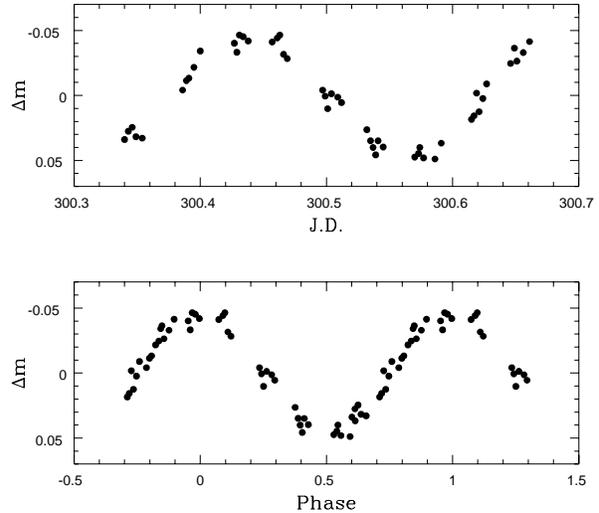
**Fig. 6. AP 139:** Correlated photometric variations in the *UBVRI* filters. Solid lines are linear least-square fits to the data

to have much more stable light curves on a timescale of a few hours (see below).

Prosser et al. (1993a) derived a 4.97h period for AP 100 while O’Dell & Collier Cameron (1993) reported the period to be 5.5h in the *V*-band and 6.0h in the *I*-band from simultaneous *V* & *I* observations. Our measurement of 4.9h agrees well with Prosser’s one. Both, however, are inconsistent with the longer period found by O’Dell & Cameron. The origin of this discrepancy is unclear, especially when considering the fact that Prosser’s and O’Dell & Cameron’s observations were obtained only one month apart in the fall of 1991. The 0.5h difference between the *V*-band and *I*-band period measurements in O’Dell & Cameron probably reflects the true uncertainty on their period determination (instead of the 0.07h error bar quoted in their Table 15), which would then possibly solve the discrepancy. The amplitude of modulation in the *V* and *I*-band listed by O’Dell & Cameron are a factor of 3 larger than those reported by Prosser and here.

**AP139:** On the one night it was observed, AP 139 exhibited very smooth sinusoidal-like variations. The 3 period-determination algorithms yield a period of 5.9h in all 5 filters. The monochromatic light curves as a function of time and as a function of phase are shown in Fig. 5.

Relationships between the photometric variations observed in the various filters are shown in Fig. 6. The least-square slopes are very close to unity indicative of an almost constant amplitude of modulation over the wavelength range from 0.36 to 0.80 microns. From these diagrams, as explained above for AP 100, we built a “gray” light curve for AP 139 which is shown in Fig. 7.



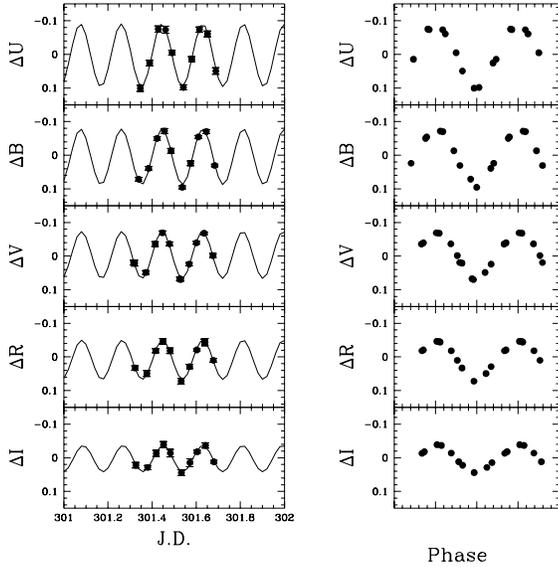
**Fig. 7. AP 139:** “Gray” light curve plotted as a function of time (upper panel) and folded in phase with a period of 5.9h (lower panel)

The shape of the light curve is remarkably close to a pure sinus curve (the rms deviation about the sinus fit is 0.006 mag). Only two spots configurations are likely to produce such a smooth-looking light curve for a star seen at such a high inclination ( $\sin i=1.0$ , Prosser et al. 1993a): either a large circular spot straddling the stellar pole but whose center is slightly offset from the pole, or a continuous distribution of spots over the stellar surface whose areal coverage smoothly varies across the stellar disk. In any case, the observed light curve does exclude the presence of isolated spot groups located at intermediate or low latitudes which would produce significant departure from a sine wave.

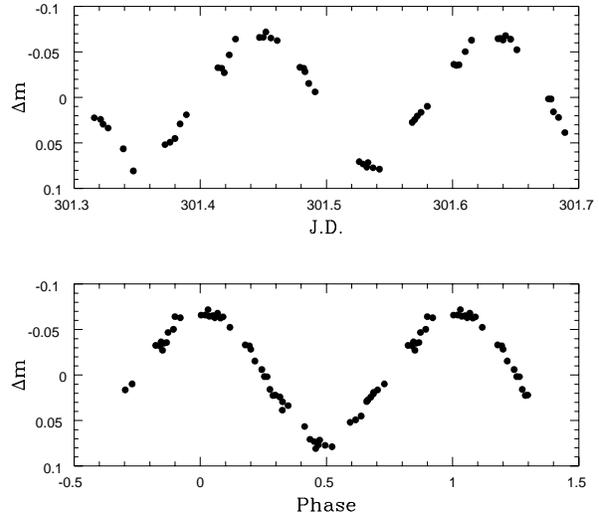
Prosser et al. (1993a) and O’Dell & Collier Cameron (1993) reported a period of 6.2h and 6.3h, respectively, for AP 139. Both estimates are consistent with our 5.9h measurement. Comparing the various sets of data, neither the amplitude of modulation nor the shape of the light curve seem to have changed over the 2-year timescale between Nov. 91 and Nov. 93.

**AP124:** The photometric variations of AP 124 were monitored over 10h within one night. The *UBVRI* light curves are shown in Fig. 8. The amplitude of modulation decreases from about 0.2 mag in the *U*-band to 0.08 mag in the *I*-band. The 3 period-search methods agree in finding a period of 4.4h in all filters. The corresponding phased light curves are shown in the right panels of Fig. 8. Flux-flux plots are shown in Fig. 9 from which the gray light curve shown in Fig. 10 is derived.

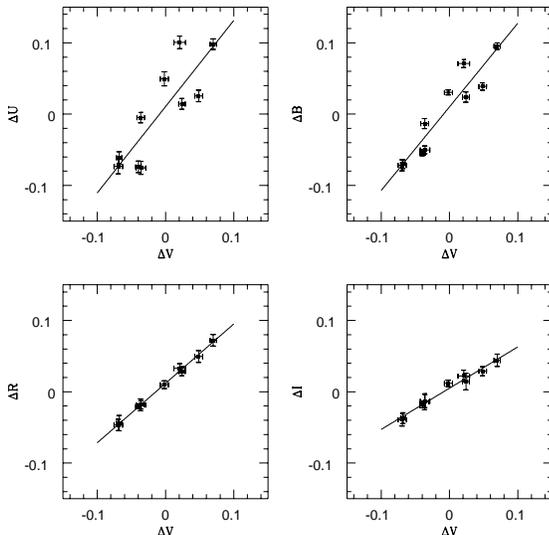
As for AP 139 above, the light curve of AP 124 is remarkably sinusoidal in shape with an rms deviation of



**Fig. 8. AP 124:** Direct (left) and phased (right) *UBVRI* light curves



**Fig. 10. AP 124:** Direct (upper) and phased (lower) “gray” light curve. The period is 4.4h



**Fig. 9. AP 124:** Relationships between the photometric variations observed in the various filters

only 0.006 mag around the sinus fit. The light curve covers exactly 2 rotational periods and bears no evidence for any change occurring between the first and second period neither in amplitude nor in shape.

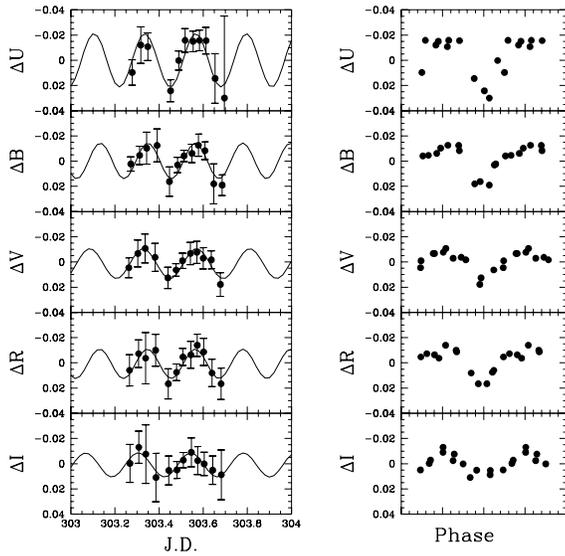
The 4.4h period found here agrees very well with the determination of Prosser et al. (1993b) who reported a period of 4.39h from a heavily sampled light curve obtained in Nov. 92. There are slight but noticeable differences between the two light curves obtained 1 year apart. In Nov.

93, the light curve was more symmetric around minimum brightness than it was in Nov. 92 and the amplitude of modulation was 0.14 mag while it was only 0.08 mag one year earlier. The evolution of the light curve toward a more symmetric shape and a larger amplitude may result from the slow drifting of spot groups relative to each other on the stellar surface.

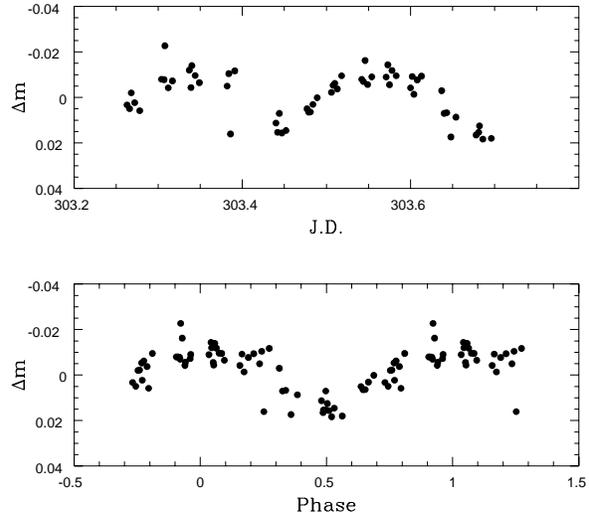
**AP 226:** From 4 to 7 comparison stars were used in every image to derive the differential light curve of AP 226 in the *UBVRI* filters shown in Fig. 11. AP226 exhibits very small amplitudes of variations, not exceeding 0.04 in the *U*-band and decreasing to 0.02 mag in the *I*-band. Nevertheless, a very clear period of 5.7h is found from all 3 period-search algorithms in all filters and is illustrated in Fig. 11. The scatter the light curves exhibit when folded in phase is due in part to the small amplitude of modulation, which amounts to only a few times the average photometric error, and for another part to the fact that AP 226 is a visual binary with a faint, very close companion. Although the DAOPHOT photometric reduction package used here is able to handle the effects of faint companions, its presence nevertheless adds some noise in the photometry of AP 226.

Flux-flux plots are shown in Fig. 12 whose slopes were used to renormalise the *UBRI* amplitudes of modulation to that of the *V* filter, thus leading to the gray light curve shown as a function of time as well as folded in phase in Fig. 13.

The 5.7h period found here confirms the previous estimates of 5.35h reported by Prosser et al. (1993b) and 5.45h by O’Dell et al. (1995). The most obvious difference between Prosser’s data set and ours (no light curve



**Fig. 11.** AP 226: *UBVRI* light curves shown as a function of time (left panels) and folded in phase with a period of 5.7h (right panels). Solid curves show least-square sinusoidal fits to the observations



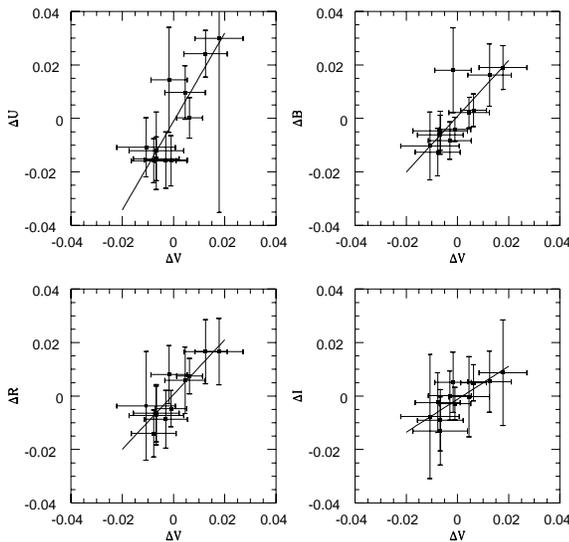
**Fig. 13.** AP 226: “Gray” light curve as a function of time (upper panel) and folded in phase with a period of 5.7h (lower panel). Note the small amplitude of modulation

is shown in O’Dell et al.’s paper) is that the amplitude of modulation in Nov. 93 was only a third of what it was in Oct. 92. It also appears that the Nov. 93 light curve is much flatter close to maximum brightness than it was one year earlier. These two differences, both in amplitude and shape, may result from the size of the spots having considerably shrunk between the two epochs of observations.

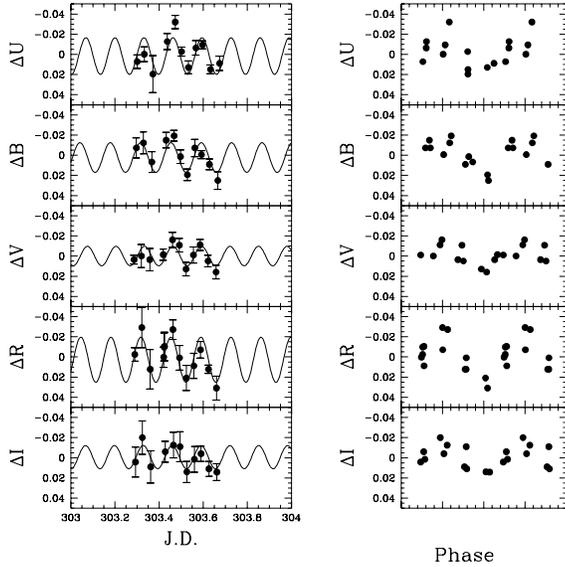
**AP 258:** AP 258 exhibits an extremely low-level of photometric variability with an amplitude of modulation which ranges between 0.02 and 0.04 mag in the *UBVRI* filters (see Fig. 14). Nevertheless, the various period-search algorithms consistently find a period of 3.1h in all filters. Direct and phased light curves are displayed in Fig. 14. The amplitude of modulation seems to be larger in the *R*-band than in the *V*-band, which is somewhat unexpected since stellar spots always induce light modulation whose amplitude monotonically decreases toward longer wavelengths. Because the amplitudes of modulation are so small, amounting to only 2 or 3 times the photometric error, the seemingly larger *R*-band amplitude compared to the *V*-band is likely to be merely the result of photometric uncertainties.

Flux-flux plots are shown in Fig. 15 and were used to compute the “gray” light curve of AP 258 which is shown in Fig. 16. The direct light curve covers 3 photometric periods and there is some evidence for a change in the mean brightness level from one period to the next. In particular, the third brightness maximum appears to be 0.01 mag fainter than the second one.

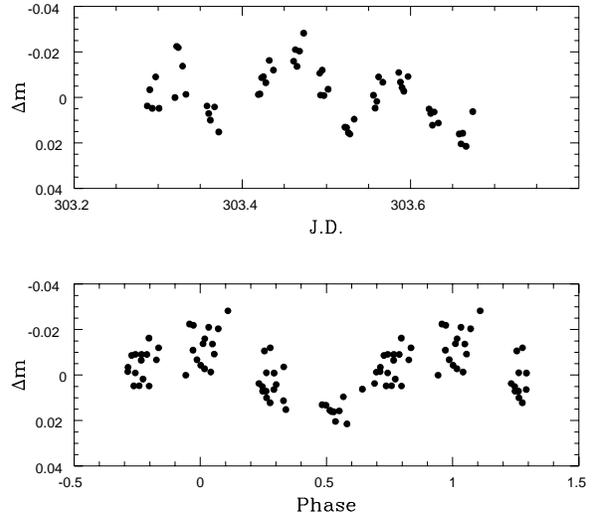
These changes likely reflect the presence of several spot groups on the stellar surface. In fact, Prosser et al. (1993a)



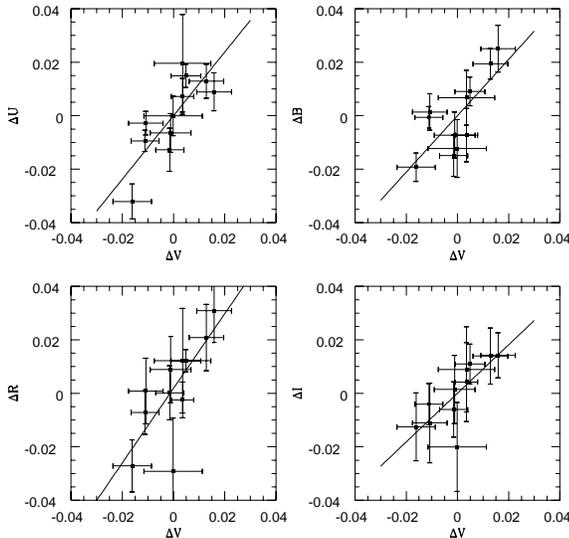
**Fig. 12.** AP 226: The photometric variations in the *UBRI* filters are plotted against the *V*-band measurements. Solid lines are linear least square fits to the data



**Fig. 14.** AP 258: Direct and phased *UBVRI* light curves

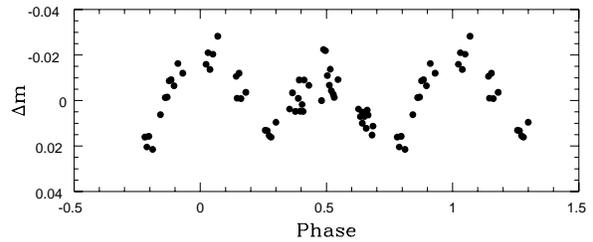


**Fig. 16.** AP 258: Direct and phased “gray” light curve with a period of 3.1h



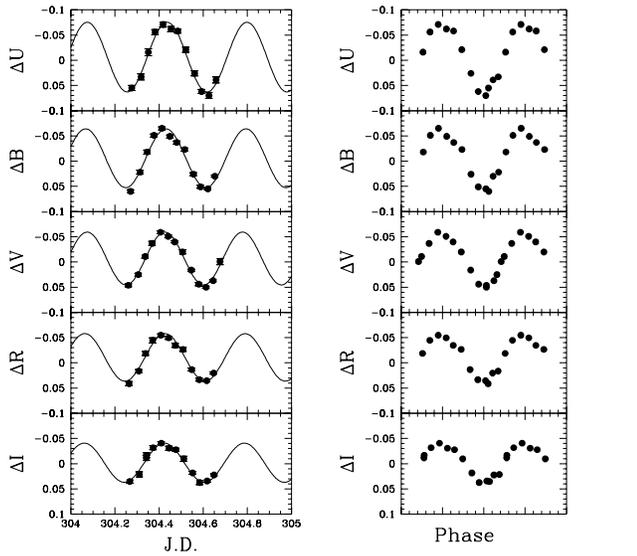
**Fig. 15.** AP 258: Correlated photometric variations in the 5 filters

reported a period of 6.3h for AP 258 which is twice as long as the 3.1h period reported here. Prosser’s data clearly excludes the existence of a 3.1h period in Dec.91. We therefore conclude that the 3.1h period present in the Nov. 93 data set is due to the existence of 2 major spot groups located at opposite longitudes on the stellar surface. The two spot groups thus produce a photometric modulation whose period is twice as short as the true stellar rotational period.

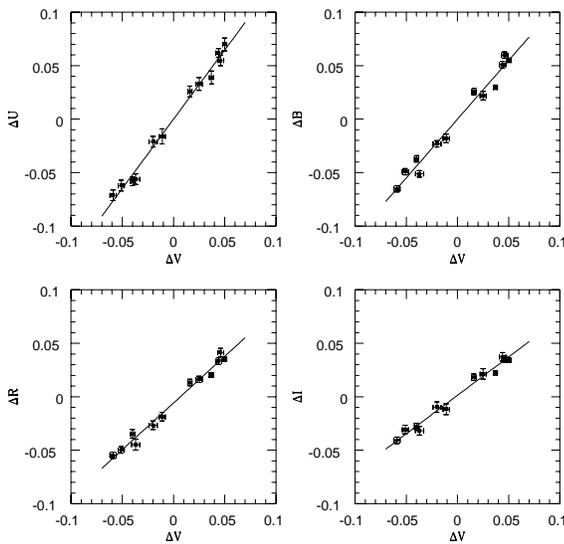


**Fig. 17.** AP 258: “Gray” light curve folded in phase with a period of 6.3h as found by Prosser et al. (1993a)

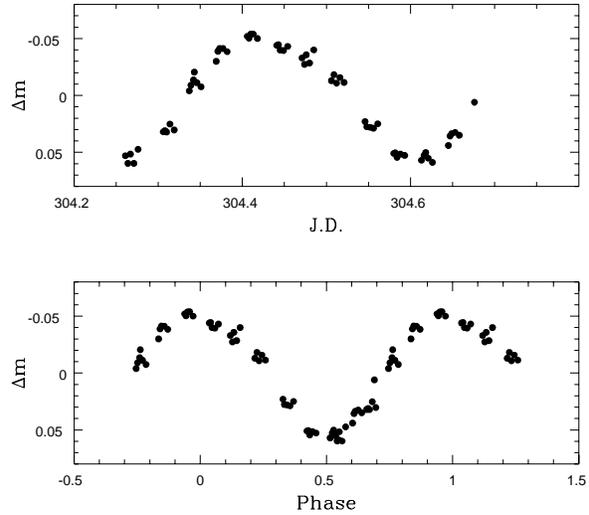
The gray light curve of AP 258 folded in phase with a period of 6.3h is shown in Fig. 17. The brightness minimum at phase 0.25 is due to one spot group and the second minimum a phase 0.75, is caused by another spot group. There are several striking features in this light curve. First, the phase difference between the two successive minima is exactly 0.5 rotational period. This indicates that the two spot groups are located on opposite longitudes at the stellar surface. Second, the minimum brightness level and the overall amplitude of modulation are quite similar for the 2 spot groups. This indicates that the two spot groups must have roughly similar sizes and temperatures and are located either at the same or at opposite latitudes since AP 258 is viewed almost equator-on ( $\sin i = 1$ , Prosser et al. 1993a). This is further required by the symmetry of the light curve shape around  $\Phi = 0.5$ . Finally, the presence of two spot groups at opposite longitudes on the stellar surface implies that, at any phase of the rotational cycle,



**Fig. 18. AP 95:** *UBVRI* light curves as a function of time (left panels) and folded in phase with a period of 8.6h (right panels). The error bars shown in the left panels are hardly visible as they are usually not larger than the size of the filled circle symbols



**Fig. 19. AP 95:** Linear relationships between the photometric variations in the 5 filters



**Fig. 20. AP 95:** “Gray” light curve as a function of time (upper panel) and folded in phase with a period of 8.6h (lower panel)

one of the spot groups is visible. This may explain why the amplitude of modulation is only 0.03 mag while it was 0.10 mag at the time of Prosser’s observations.

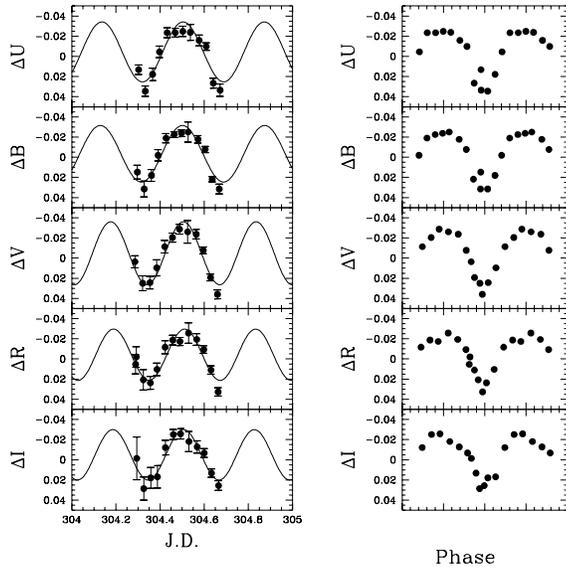
All this is strongly suggestive of a dipolar-like configuration for the 2 major spot groups at the surface of AP 258.

**AP 95:** AP 95’s *UBVRI* light curves are shown in Fig. 18 and exhibit a clear 8.6h period in all filters even though the observations cover hardly more than one complete period. A sine curve provides a remarkably tight fit to the observed light variations from which we derive amplitudes of modulation that smoothly decrease from 0.14 mag in the *U*-band to 0.08 mag in the *I*-band.

As for all other stars in this sample, there is a tight correlation between the photometric variations occurring in the different filters as illustrated by the flux-flux plots displayed in Fig. 19. The “gray” light curve built by normalizing the amplitude of modulation in each of the *UBRI* filters to that of the *V*-filter and then combining all the data points is displayed in Fig. 20. Again, the light curve is almost a pure sinusoid (rms scatter of 0.007 mag around the sine fit) and there is no evidence for any changes in the level of the 2 light minima observed during that night.

The 8.6h period found above is in good agreement with the early determination of 8.47h by Stauffer et al. (1989) from observations performed in Nov. 86. The amplitude of modulation varied from 0.3 mag in Nov. 86 to 0.1 mag in Nov. 93.

**AP 118:** AP118’s *UBVRI* light curves are shown in Fig. 21. The amplitude of modulation is small, amounting to about 0.04 mag in all filters. While the observations



**Fig. 21. AP 118:** *UBVRI* light curves against time (left panels) and phase (right panels) when folded with a period of 8.0h. Solid curves in the left panels are sinus fits to the observations

cover only slightly more than one period, all 3 period-search algorithms converge to indicate a clear 8.0h periodicity in all filters.

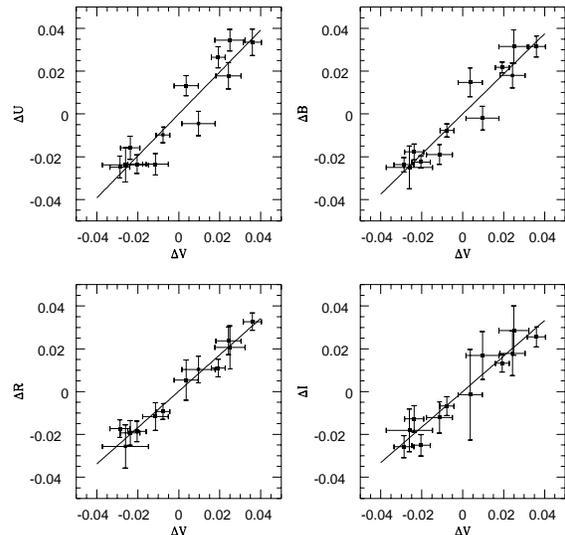
The shape of the light curve of AP 118 differs significantly from a sine wave. This is best seen in the “gray” light curve constructed from the flux-flux plots shown in Fig. 22. The gray light curve folded in phase with a period of 8.0h (Fig. 23) exhibits a flat-topped part at maximum light and a deep and narrow minimum centered at phase 0.5. This shape is strongly suggestive of a spot located at intermediate latitudes on the stellar surface which disappears from view during a small fraction of the rotational cycle around maximum brightness.

Another striking difference between AP 118’s light curve and those of most stars in this study is that the amplitude of modulation barely varies over the whole wavelength range from 0.36 to 0.8 microns, indicative of an essentially black spot being responsible for the modulation (see Table 2).

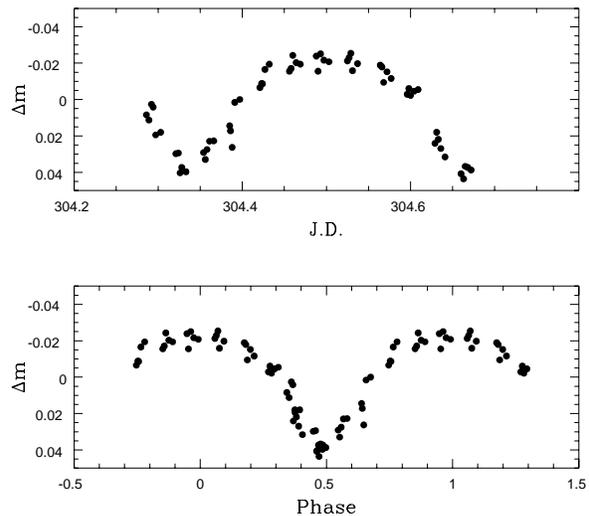
The only previous determination of AP 118’s period is that of O’Dell & Collier Cameron (1993) who found 7.6h still consistent with the 8.0h-period reported here. The amplitude of variability was 0.16 mag in the *V*-band on Oct. 91 and only 0.06 mag in Nov. 93. The shape of the light curve has changed as well between the 2 observing runs, being much more sinusoidal-like during the former.

#### 4. Discussion

The stellar sample studied here is rather homogeneous as it includes G5-K5 dwarfs of the same age that all are



**Fig. 22. AP 118:** Relationships between the photometric variations observed in the *UBVRI* filters. Solid lines are unweighted linear least-square fits to the data



**Fig. 23. AP 118:** “Gray” light curve. The shape of the light curve differs from a sine wave in that it exhibits a flat-topped part at maximum light and a narrow minimum at opposite phase

rapid rotators, with  $v \sin i$  from 140 to more than 200 km s<sup>-1</sup>. All the stars are also seen at high inclination with  $\sin i \geq 0.9$  (Prosser et al. 1993a,b; O'Dell et al. 1995), i.e., almost equator-on, so that geometric effects ought to be the same in all the light curves. Yet, the light curves of the 7 stars exhibit a large variety of amplitudes (from 0.02 to 0.14 mag), shapes (from strictly sinusoidal to flat-topped, from one to several light minima), and evolution timescales (from a few hours to years). This may not be surprising, however, since rapidly-rotating, late-type stars likely have long-term activity cycles, so that the variety of light curves observed here may reflect the different phases of a typical activity cycle for such stars (e.g., Baliunas & Vaughan 1985). For instance, Innis et al.'s (1988) long-term photometric monitoring study of AB Dor, whose properties are similar to the stars studied here, shows the star to exhibit over the years most of the different types of light curve shapes and amplitudes reported here.

The amplitude of variability varies by a factor of almost 10 from star to star and indeed covers most of the range of amplitudes observed for late-type dwarfs in young clusters, slow and rapid rotators alike (Prosser et al. 1993a,b; O'Dell et al. 1995, Allain et al. 1996a,b). Thus, no correlation is found between the amplitude of modulation and either rotation or spectral type within this sample.

The observed amplitudes, and their variations with wavelength over the *UBVRI* domain, result from the modulation by starspots that cover more than a few percent of the stellar disk and whose temperature, except for AP 100, are between a few hundred and a few thousand K colder than that of the photosphere. In AP 100, the spots responsible for the modulation appear to be hotter than the photosphere.

The spot properties, as derived from the spot model and listed in Table 2, show that the amplitude of modulation primarily depends on the spot size and not on the spot temperature. The actual size of the spots may be much larger than the lower limits listed in Table 2. This is very likely to be the case at least for the light curves that exhibit smooth sinusoidal-like variations which probably result from modulation by circumpolar spots. Therefore, the spot sizes listed in Table 2 are best understood as being the net difference in the area of the stellar disk covered by spots between minimum and maximum brightness.

There appears to be an interesting correlation between the amplitude of modulation and the shape of the light curve. The 3 stars (AP 139, AP 124, AP 95) with the largest photometric amplitudes, around 0.1 mag in the *V*-band, exhibit remarkably sinusoidal light variations. In contrast, AP 226 and AP 118, amongst the stars with the lowest photometric amplitudes (AP 258 is another one discussed below), bear evidence for flat-topped light curve near maximum brightness. This amplitude-shape correlation may be related to both the spot size and the spot latitude on the stellar surface as discussed below.

The sinusoidal-like light curves of the large amplitude variables AP 139, 124, and 95 suggest that the stars are covered by large, high latitude spots that straddle the stellar poles. The circumpolar spot group is seen throughout the rotational cycle and the stellar brightness is modulated only due to the fact that the spot is tilted relative to the stellar rotational axis, thus naturally leading to the observed sinusoidal shape of the light curve. The sinusoidal shape of the light curve further suggests that there are no additional low latitude spots. Because the stars are seen almost equator-on, the appearance of a small, low latitude spot covering a few percent of the stellar disk would yield a distinct signature in the light curve in the form of a bump seen during half or less of the rotational cycle superimposed onto the sine wave due to circumpolar spots. Such a signature is not seen in the light curves of the 3 stars. And while a very large, low-latitude spot could conceivably lead to a sinusoidal light curve, the amplitude of modulation would then be much larger than observed here.

The modulation of large amplitude variables thus appears to result from a large circumpolar spot group. In contrast, the light curves of low amplitude variables, such as AP 226 and AP 118, suggest that the modulation is due to relatively small spots located at intermediate latitudes and which disappear from view during part of the rotational cycle. Such a spot configuration accounts for both the low level of variability and the flat part of these light curves around maximum brightness.

Quite noticeable as well is the fact that, with the remarkable exception of AP 258 discussed below, the light curves exhibit only one brightness minimum during a rotational period and the phase delay between maximum and minimum brightness is exactly half of the rotational period. Both features indicate that the photometric modulation is driven by *one single* spot group. In the case of dipolar spots, and owing to the high inclination of the stars, one would expect to observe 2 brightness minima occurring over a complete rotational period, one associated with each of the polar spots. That this is not the case implies that the spot distribution is usually not dipolar.

The exception of AP 258 is most intriguing. Two brightness minima are seen during the 6.3h rotational cycle and both the shape and the depth of the minima are fairly similar. This is best explained by assuming a dipolar geometry for the distribution of active regions at the stellar surface, in turn strongly suggestive of an associated magnetic stellar dipole. Such a dipolar structure, if indeed linked to the stellar magnetic field, would be expected to be very stable. This, however, is denied by the observations of Prosser et al. (1993a) obtained 3 years earlier and which reveal only one brightness minimum during the 6.3h rotational cycle. As an alternative to dipolar spots, the occurrence of two brightness minima could result from active longitude belts located at low latitudes roughly

similar to those observed at the surface of the young, rapidly rotating K0 dwarf AB Doradus (Collier Cameron 1995). However, the high degree of symmetry in the starspot distribution implied by the light curve makes this alternative less likely.

The evolution of the light curves is fairly unpredictable. Comparing the above results with light curves obtained a couple of years earlier by Prosser's and O'Dell's groups, it is seen that both the amplitude of modulation and the shape of the light curve can (but not always do) vary on this timescale. This suggests that the lifetime of the spots responsible for the modulation is of the order of a few years. In the case of AP 100, however, the light curve changes on a timescale of a few hours only. Such a short timescale may be characteristic of hot spots – or a long-duration optical flare of the type occasionally observed in RS CVn systems – since none of the other stars, whose variability is dominated by cool spots, exhibit such a short term variability. In particular, we do not find any evidence for very short timescale variations which could have been associated with solar-type UV flaring activity.

Finally, in spite of clear variations of the light curves shape and amplitude over the years, the photometric period appears to remain constant in all the stars covered with cool spots. We therefore find no evidence for strong surface differential rotation in the present set of rapid rotators.

## 5. Conclusion

The photometric variability of the fastest rotators of the Alpha Persei cluster is dominated by starspot modulation. Most stars exhibit very smooth photometric variations, suggestive of one major spot group being responsible for the modulation rather than a large number of small spot groups distributed over the stellar surface. This result is somewhat surprising since both theoretical dynamo models and inferences from the rotational decay of late-type dwarfs on the ZAMS suggest that the magnetic field structure of fast rotators should be quite complex. Provided that the dark spots are good tracers of the surface

magnetic field, the light curves of the fast rotators instead suggest the existence of a large-scale magnetic structure which slowly evolves on a timescale of years.

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