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Magnetic activity of the spotted dwarf AP149 in the α Persei open cluster *

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Abstract The simultaneous photometric and spectroscopic observations of the spotted G dwarf AP149 in the young open cluster α Persei are analyzed here. We reconstruct the observed light curves with a two-starspot model by means of a light curve modeling technique, and find that the active regions shift oppositely along longitude on a time scale of one day. Combining with the observational data obtained by other groups, we discuss the evolution of spotted regions in the photosphere, and find that its starspots evolve not only on a short time scale but also on a long time scale. The pure chromospheric emissions for Ca IIHK and H_β lines are derived by using the spectral subtraction technique. The variation of Ca IIHK lines' excess emission is spatially correlated to the starspot regions. There is no clear rotational modulation for the H_β line's excess emission, probably due to the contamination of prominence emission.

Key words: stars: activity — stars: late-type — stars: spots — stars: individual: AP149

1 INTRODUCTION

α Persei is a young open cluster with an age of about 50 Myr (Mermilliod 1981), which consists of several hundred members (Prosser 1992). In this cluster, a significant fraction of low mass stars are rotating rapidly (Stauffer et al. 1985; Stauffer et al. 1989), exhibiting evident rotational modulation due to inhomogeneities in surface brightness (O'Dell & Collier Cameron 1993; Prosser et al. 1993). Hence, it is an ideal candidate to study the stellar activity-rotation relationship for these young late-type stars (Randich et al. 1996).

As a member of α Persei, AP149 (GSC 03320–01643) is a rapidly rotating spotted late G dwarf ($v \sin i$=102 km s^{-1}) with an inclination of 30° (Barnes et al. 2001). As early as the 1990s, O'Dell & Collier Cameron (1993) and Prosser et al. (1993) successively derived its rotational period, on the basis of its rotational modulation of surface inhomogeneities in the V band. The starspot distribution

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of AP149 was discussed in detail by Barnes et al. (2001), as well as the existence of prominences in emission based on the H_α emission features. The H_α emission variations of AP149 were also detected by Savanov et al. (2003) in Oct. 2002.

Although AP149 has been known as a spotted late-type star since the 1990s, up to now, the evolution of its starspot and chromospheric activity has not been well studied. Thus, we made new simultaneous photometric and spectroscopic observations of AP149 in Nov. 2008, in order to better understand its magnetic activity. In this paper, we first present the information regarding observations and data reduction. Then, we analyze and discuss the photometric and spectroscopic results. The conclusions are presented last.

2 OBSERVATIONS AND DATA REDUCTION

The new photometric observations of AP149 were carried out with the 85 cm telescope at the Xinglong station of National Astronomical Observatories, China, over two consecutive nights: 2008 Nov. 5–6. The photometer was equipped with a 512×512 pixel CCD and the standard Johnson-Cousin-Bessell set BVRI filters (see Zhou et al. 2009 for details) were used during our observing nights. GSC 03320–00493 and GSC 03320–00777 served as comparison and check stars respectively. All raw CCD frames were processed by using the IRAF package in a standard way, and the instrumental magnitudes of AP149, the comparison and check stars were obtained by using the IRAF/APPHOT package. The standard deviation of the magnitude difference between the comparison and check star is lower than $0.005^{\rm m}$ in the V band, indicating that our photometric data have high accuracy. The corresponding light curves of AP149 in the $BVRI$ bands are displayed in Figure 1.

The new spectroscopic observations of AP149 were made with the 2.16 m telescope at the Xinglong station at the same time: 2008 Nov. 5–6. The OMR spectrograph centered at about 4280 Å

Table 1 Observing Log of AP149 (Exp. time = 900.00 s)

Date	Start time (UT)	Phase	S/N Ca II HK	S/N H_β
2008–11–05	13:44:24.00	0.670	28	61
2008–11–05	14:23:54.00	0.755	30	66
2008–11–05	15:02:28.00	0.838	35	73
2008–11–05	15:37:47.00	0.914	36	72
2008–11–05	16:14:52.00	0.944	38	76
2008–11–05	16:51:33.00	0.074	35	68
2008–11–05	18:57:01.00	0.344	41	81
2008–11–05	19:34:47.00	0.425	35	74
2008–11–05	20:12:31.00	0.507	32	71
2008–11–05	20:48:57.00	0.586	27	64
2008–11–06	12:43:27.00	0.644	29	71
2008–11–06	13:19:40.00	0.723	28	65
2008–11–06	13:54:43.00	0.798	33	71
2008–11–06	14:31:43.00	0.878	36	74
2008–11–06	15:09:38.00	0.960	36	72
2008–11–06	15:49:20.00	0.045	39	75
2008–11–06	16:27:33.00	0.128	38	73
2008–11–06	17:06:35.00	0.212	38	72
2008–11–06	17:42:57.00	0.290	36	70
2008–11–06	18:15:29.00	0.361	35	68
2008–11–06	18:50:14.00	0.436	34	65
2008–11–06	19:26:29.00	0.514	30	60
2008–11–06	20:01:03.00	0.588	28	59
2008–11–06	20:38:10.00	0.668	26	56
2008–11–06	21:14:07.00	0.746	25	56

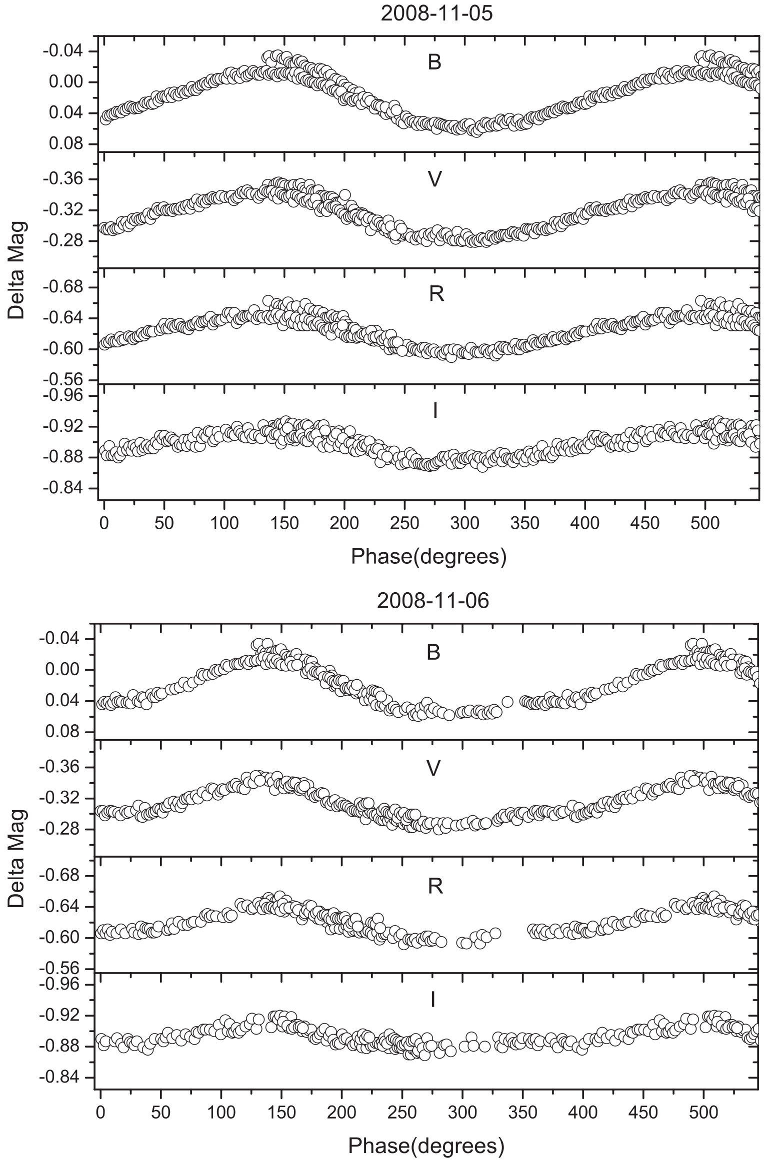

Fig. 1 $BVRI$ light curves of AP149 on 2008 Nov. 5 and 2008 Nov. 6.

with a reciprocal dispersion of 1.03 Å pixel^{-1} and a 1340×240 pixel CCD were used. The observing log is listed in Table 1, where we show the information about spectroscopic observations, such as the observing date, start time, exposure time and so on. In addition, several very slowly rotating and inactive late-type stars HR 222 (K2V), HR 3309 (G5V) and HR 3750 (G2V) were observed using the same instrument configuration, which were used as reference stars.

The spectral images were reduced by using the IRAF package in a standard fashion. The wavelength calibration was made by taking the spectra of an He-Ar lamp. By comparison, we found that HR 222 and HR 3309 are better templates for AP149, which indicates the spectral type of AP149 is between K2V and G5V; this is similar to the result of spectral type G8V given by Barnes et al.

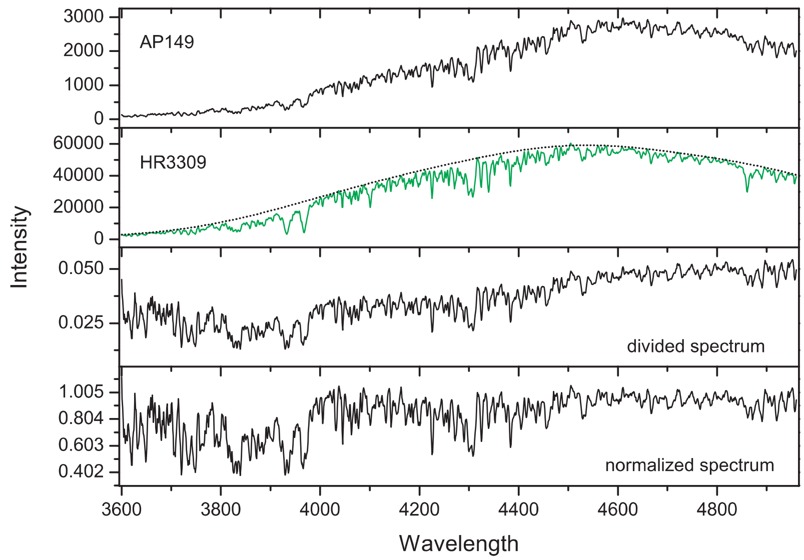

Fig. 2 An example of spectral normalization procedure.

(2001). For our analysis, we finally used HR 3309 as the reference star. Since the spectra of AP149 suffer from severe blending of the photospheric absorption lines because of its rapid rotation, it is difficult to normalize the spectra with respect to continuum fitting. Therefore, we first obtained the continuum fit to the template spectrum (HR 3309) with a spline3 function, then each target spectrum was divided by the continuum fit to HR 3309, in order to remove the low-order variation of the spectrum and obtain a relatively flat residual spectrum. Further fitting to this divided spectrum using a low-order polynomial was easy to do, consequently the final normalization to the corresponding original spectrum was finished. Such a procedure is similar to that used by other authors, such as Collier Cameron & Unruh (1994) and Barnes et al. (2001). Figure 2 shows an example of such a procedure, where we display the observed spectrum of AP 149, the continuum fit to HR 3309's observed spectrum, and the divided and normalized spectra of AP149. All one dimensional normalized spectra of AP149 are displayed in Figure 3.

3 LIGHT CURVE ANALYSIS

3.1 Period Analysis

The previous period determination of AP149 only relied on a small quantity of observations; O'Dell & Collier Cameron (1993) and Prosser et al. (1993) derived its periods of 7.694 h and 7.6 h based on 21 and 30 points in the V band, respectively. Considering that our new photometric observations have a much higher time resolution and full phase coverage (e.g., 444 data points in V band), hence, we calculate its period again on the basis of our new observations. Using the PDM method (Stellingwerf 1978), we obtain its period: $P = 0.322\,\mathrm{d}$, which is essentially the same as previous results mentioned above, also in agreement with the result ($P = 0.3200\,\mathrm{d}$) derived by Barnes et al. (2001). Figure 4 gives the relation between the phase dispersion statistic quantity theta and the period; note that the minimum of theta corresponds to the period $P = 0.322\,\mathrm{d}$.

The phases of our new observations are calculated by using the following ephemeris formula:

$$T \;=\; \mathrm{HJD}2448548.50 + 0.^{\mathrm{d}}322E. \tag{1}$$

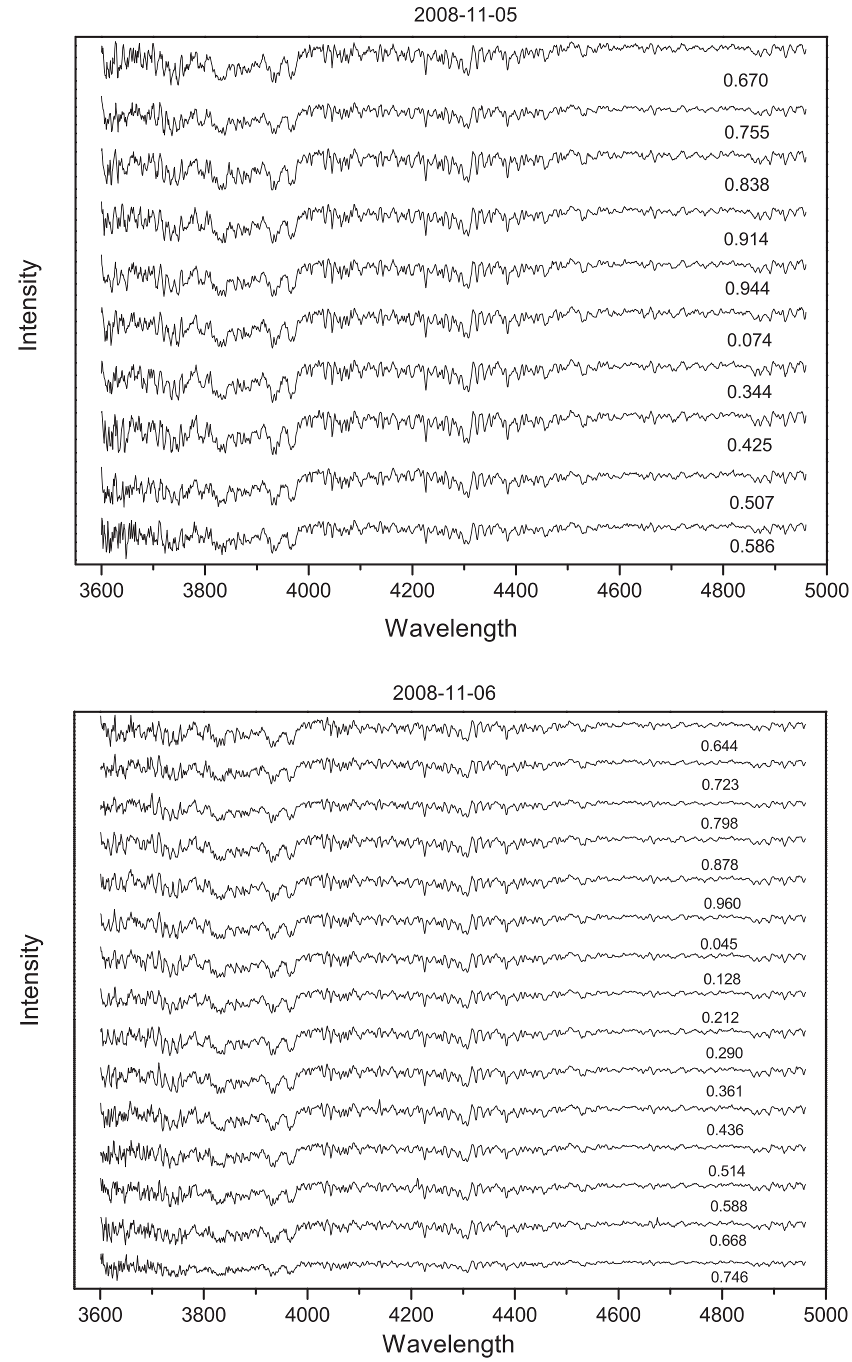

Fig. 3 One dimensional normalized spectra of AP149 on 2008 Nov. 5 and 2008 Nov. 6.

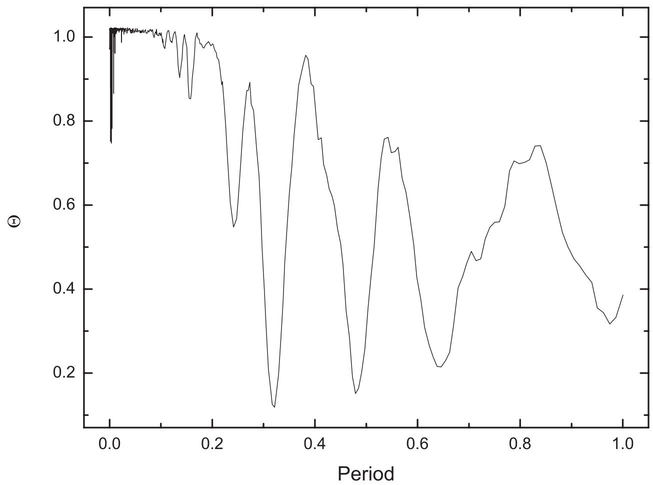

Fig. 4 Relation between the phase dispersion statistic quantity theta and the period; note that the minimum of theta corresponds to the period $P = 0.322$ d.

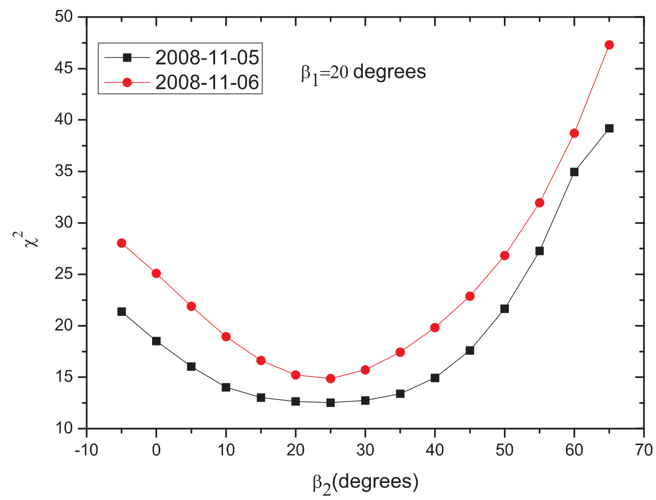

Fig. 5 χ^2 of solutions with different latitudes (β_1, β_2) fixed in the fitting runs, where $\beta_1 = 20°$ and β_2 varies from –5° to 65°.

In addition, using the same ephemeris formula, we re-calculate the phases for the V band photometric observations of O'Dell & Collier Cameron (1993), which were made in the run on dates 1991 Oct. 18–23.

3.2 Starspot Modeling

Although multi-color photometry contains information about the effective temperature of starspots, we only perform an analysis for light curves in the V band by means of the spot fitting program of

Budding et al. (Budding 1977; Budding & Zeilik 1987), since this program cannot process multi-color light curves simultaneously. More importantly, rather than the spots' physical natures (e.g., effective temperature), we look only at their positions, from which we can derive their evolutions, such as the movements along longitude. The program provides the configuration of the spotted star on the basis of the observed light curve, by applying a model with one or two dark, circular spots. The problem in performing the fitting is that there are many parameters, not only describing the spots (e.g., size, position) but also describing the star (e.g., inclination), furthermore, several parameters are correlated in the fitting run (Budding & Zeilik 1987). Fortunately, three parameters have been effectively determined for our case as follows:

(1) Inclination of star i: based on the result derived by Barnes et al. (2001), we set it as 30°.
(2) The limb darkening coefficient u: for photometry in the V band, the effective temperature of about 5500 K (Barnes et al. 2001) indicates $u = 0.69$ according to the model of Claret & Hauschildt (2003) with $\log g = 4.5$ and solar metallic abundance. In fact, the limb-darkening coefficient affects the starspot modeling results very little, for example, we found almost the same starspots by using different values corresponding to photospheric temperatures 5300 K and 5700 K.
(3) The intensity of the spot K_λ: it is defined as the ratio of the flux in the spot to the flux in the photosphere at λ (the effective wavelength). We simply set this value as 0.0, which means the spot is black (relative to the photosphere). Actually, the spot temperature is correlated to the spot radius, as well as its position. In general, such an assumption will result in smaller spots, while the positions of spots will only be affected very little. For instance, we got slightly larger spots concentrated at almost the same positions using $K_\lambda = 0.3$, which is a representative value in most cases for the V-band observations, since the temperature difference between the spots and the photosphere is about 1000–2000 K for G-K dwarfs, based on the statistics of the spot temperature contrast with respect to the photospheric temperature (Berdyugina 2005).

These three parameters mentioned above are fixed during the light curve fitting. The remaining adjustable parameters are the longitude (α), latitude (β) and radius (ρ) of the spot. From the asymmetric light curves taken in both nights (see Fig. 1), we perform the spot fitting using a model with two spots. Hence, there are six adjustable parameters: α_1, α_2, β_1, β_2, ρ_1 and ρ_2. In order to derive the optimized values for these parameters in an objective way, we carry out the spot fitting as follows: Given the initial values for these six adjustable parameters, we keep the latitudes of the two spots (β_1, β_2) fixed in the fitting runs, while we release their longitudes and radii to find out the best fit. By adjusting the longitudes (α_1, α_2) and radii (ρ_1, ρ_2), we obtain the optimized longitudes and radii for the latitudes (β_1, β_2). Similarly, another solution of longitudes and radii of the two spots is derived for new latitudes (β'_1, β'_2). Finally, by examining the values of χ^2 of all the solutions and the fittings between the theoretical curves and observed data points by eye, we find that the solution with latitudes (20°, 25°) is the best one. Figure 5 gives an example of this procedure, where we show the variation of χ^2 in solutions at different latitudes β_2 when the latitude β_1 is fixed.

For the purpose of comparison, we apply the same procedure to the V band observations of O'Dell & Collier Cameron (1993). We also find that the model with two spots located at low latitudes represents the observed data points better. For this dataset, the latitudes (20°, 20°) are the best solution. The adopted parameters of the spots for these three datasets are given in Table 2, where their latitudes, longitudes and radii are listed, together with the χ^2 values. Correspondingly, Figures 6 and 7 show the plots of the theoretical light curves with observed data points superimposed on the three datasets. The locations of the spots on a Mercator projection of the star's surface are shown in Figure 8, where the notations "0," "5" and "6" correspond to the datasets 1991 Oct. 18–23, 2008 Nov. 5 and 2008 Nov. 6, respectively.

Table 2 Adopted Parameters of Spots

Dataset	Number of data points	$\beta_1(^\circ)$ $\beta_2(^\circ)$	$\alpha_1(^\circ)$ $\alpha_2(^\circ)$	$\rho_1(^\circ)$ $\rho_2(^\circ)$	χ^2
2008–11–05	143(binned)	20.00	264.70 ± 5.23	14.11 ± 0.55	12.53
		25.00	367.50 ± 7.43	11.65 ± 0.56	
2008–11–06	127(binned)	20.00	255.06 ± 4.04	14.34 ± 0.35	14.88
		25.00	379.71 ± 5.25	12.20 ± 0.34	
1991–10–18∼23	21	20.00	94.16 ± 8.19	17.57 ± 0.98	19.84
		20.00	348.64 ± 14.92	12.71 ± 1.34	

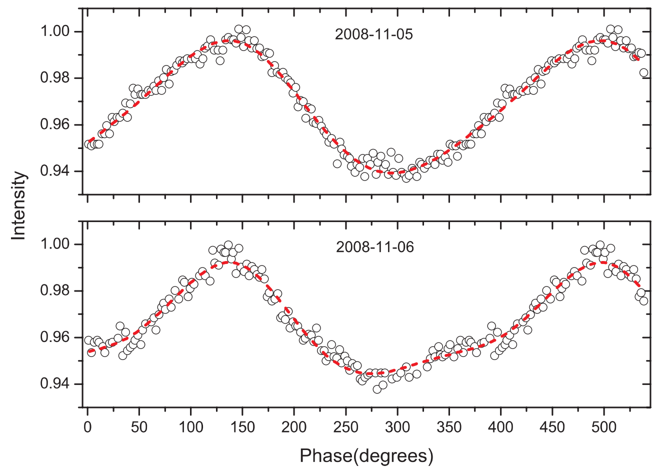

Fig. 6 Plots of the theoretical light curves with observed data points superimposed. Note that the observations are in intensity units and are binned values, and the maximum level is one unit (1 corresponding to "unspotted" light level of the star).

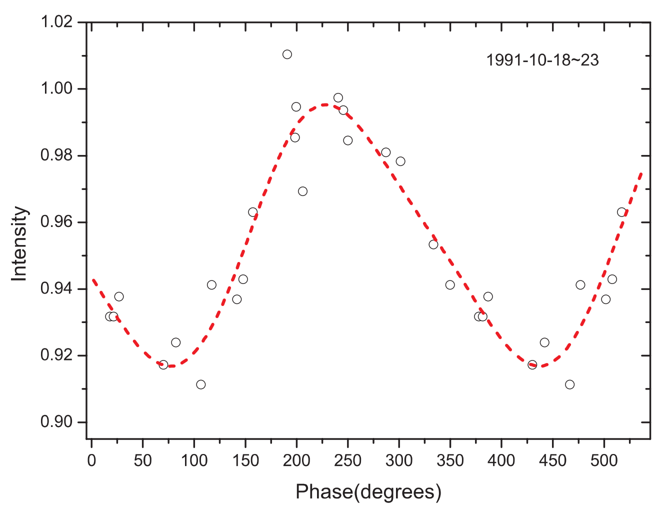

Fig. 7 Same as Fig. 6, but for the dataset on 1991 Oct. 18–23.

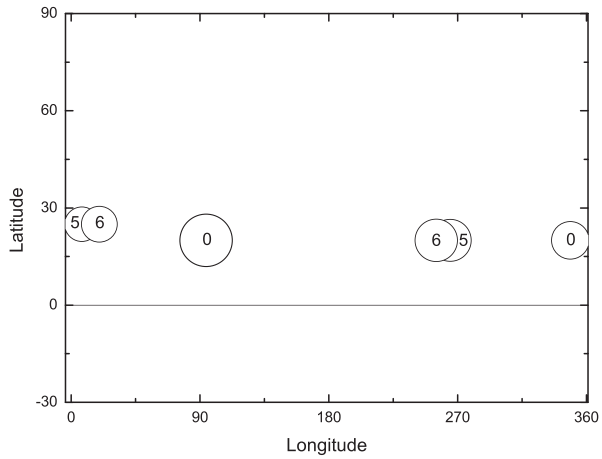

Fig. 8 Locations of the spots on a Mercator projection of the star's surface, where the notations "0," "5" and "6" correspond to the data observed on 1991 Oct. 18–23, 2008 Nov. 5 and 2008 Nov. 6, respectively.

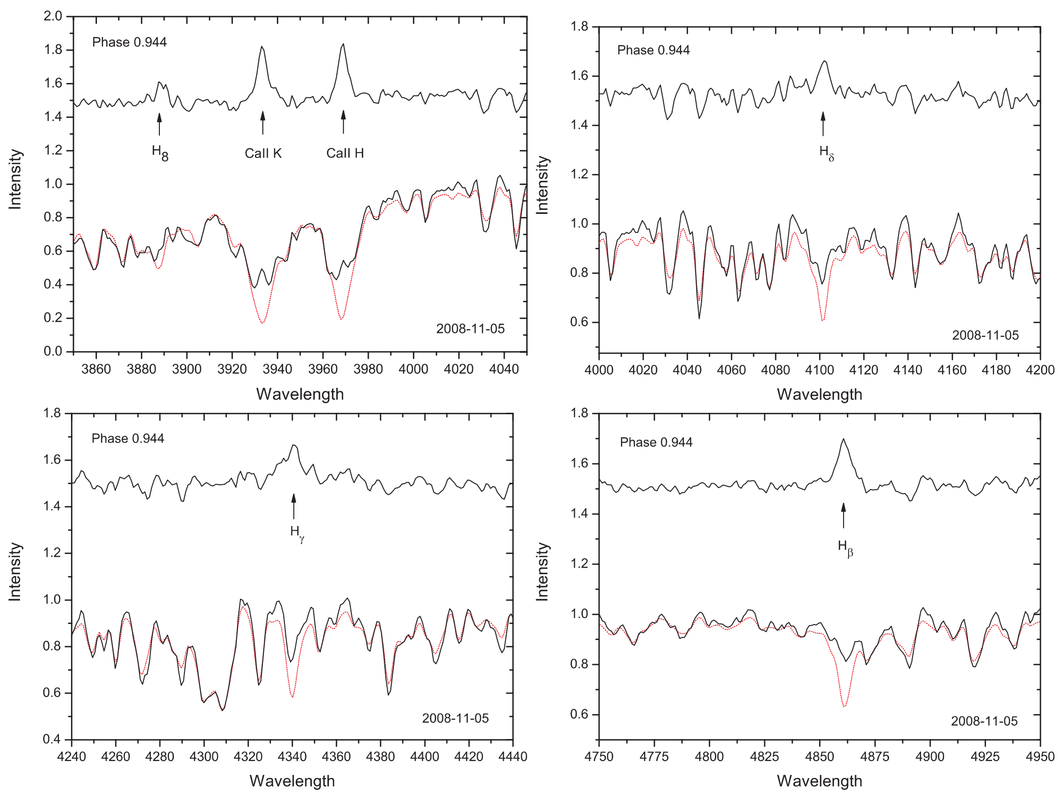

Fig. 9 An example of the synthesized, observed and subtracted spectra for the Ca IIHK, H_8, H_δ, H_γ and H_β lines. The upper solid lines represent the subtracted spectra, while the lower solid lines and dotted lines indicate the observed and synthesized spectra, respectively. Note that the subtracted spectra are vertically offset for better display.

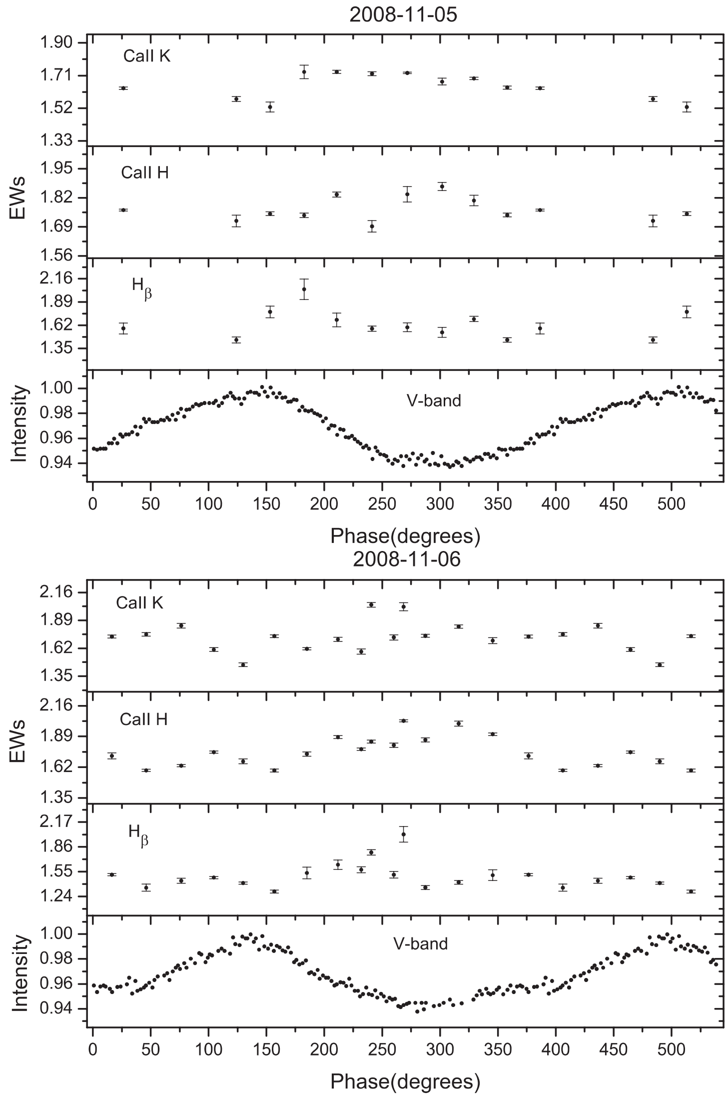

Fig. 10 EWs of Ca IIHK and H_β lines versus rotational phase, and for comparison, the light curve is also shown at the bottom.

4 SPECTRAL ANALYSIS

Our new spectra of AP149, containing Ca IIHK, H_8, H_δ, H_γ and H_β lines, are analyzed with the spectral subtraction technique (subtracting a synthesized spectrum constructed from the reference star), which was described in detail by Barden (1985) and Montes et al. (1995b). The pure chromospheric emissions can be derived by using this technique. Such a technique has been used widely in studying stellar chromospheric properties (Gunn & Doyle 1997; Gunn et al. 1997; Lázaro & Arévalo 1997; Montes et al. 1997; Frasca et al. 2000; Montes et al. 2000; Gu et al. 2002; Zhang & Gu 2008; etc.). In the case of AP149, the synthesized spectrum is constructed using the program STARMOD (Barden 1985), and HR 3309 (G5V) is used as the reference star.

In the course of the analysis, the $v \sin i$ value is set to 102 km s^{-1} (Barnes et al. 2001), and remains fixed in the computation. By rotationally broadening and shifting along radial-velocity, the synthesized spectrum from the reference star HR 3309 is constructed, and consequently the subtracted spectra of AP149 are calculated. An example of the synthesized and subtracted spectra in the Ca IIHK, H_8, H_δ, H_γ and H_β line regions is displayed in Figure 9, where the upper solid lines represent the subtracted spectra, while the lower solid lines and dotted lines indicate the observed and synthesized spectra, respectively. Note that the subtracted spectra are vertically offset for better display.

The spectral type and luminosity class of the inactive star used as the reference star are hopefully the same as the active star's ones for the spectral subtraction technique; however, the inactive stars of a similar spectral type and luminosity class are commonly used as reference stars to construct the synthesized stellar spectra, when the ideal inactive stars are unavailable. For example, Herbig (1985) determined chromospheric H_α emission EWs for 40 F8-G3 dwarfs by subtracting the same reference star β CVn (G0V); Thatcher & Robinson (1993) derived emission of chromospheric Ca IIHK lines for a sample of late-G to early-K stars using only one quiet star of spectral type G6V (61 Vir) as the reference star. Herbig (1985) noted that the spectral type mismatch between the active and inactive stars appeared as a convexity or concavity of the subtracted spectra due to the effective temperature dependence of the wings of the active lines. We estimate the internal error caused by this spectral mismatch by sampling the noise of residual intensities in the subtracted spectra on either side of the chromospheric line H_β (in the regions outside this line). We have obtained the mean standard deviation $\sigma = 0.019$ for all spectra of these two days, i.e., an error of about 2%. Such an error is roughly equivalent to the precision corresponding to the S/N of the H_β line region (in the range 56–81, see Table 1).

The equivalent widths (EWs) of the Ca IIHK and H_β excess emission lines are measured by means of the IRAF/SPLOT procedure in the subtracted spectra additively offset to have a continuum of unity. The EWs of H_8, H_γ and H_δ lines are not measured due to their weak excess emissions (see Fig. 9). For the Ca IIHK lines, the EWs are measured by using a Gaussian function to fit the line profile, while for the H_β line, several Gaussian profiles are used. Additionally, we also evaluate the EWs of these lines by integrating over the emission profile. Consequently, we take the mean values from these two methods as the final EWs for each line, and the relative errors are estimated by using the difference between the results of the two methods. Figure 10 shows the EWs of these lines versus rotational phase, and for comparison, the light curve in the V band is also plotted at the bottom.

5 DISCUSSION AND CONCLUSIONS

5.1 Starspot Evolution

Barnes et al. (2001) showed that there were high latitude spots on the photosphere of AP149, together with spots at low to intermediate latitudes ($35 \pm 15^\circ$), and found that the filling factor of the spots between latitudes 50° and 90° was 0.052. However, our new results indicate that the two spots appear below a latitude of 30°, and no spot appears at high latitude. Perhaps high latitude spots as well as polar spots exist; for a star like AP149 with very low inclination (30°), such spots cause no rotational modulation in the brightness. Hence, we cannot exclude the existence of spots at high latitude or around the pole only based on the light curve modeling.

From the V-band observation on 2008 Nov. 5, we find that one spot is concentrated at a longitude of 10°, while the other one is at longitude 265°. For the dataset on 2008 Nov. 6, the two corresponding spots move to longitudes 20° and 255°. The longitude separation between the two spots varies quickly on a time scale of one day (shifted by about 20°), furthermore, they are moving oppositely with respect to longitude. The possible explanation about such a quick and bizarre motion is the coupling between the meridian circulation and the stellar differential rotation. In other words, one spot is moving towards the pole, while the other one moves towards the equator, therefore, the two spots are moving oppositely with respect to longitude due to the star's differential rotation. Such behaviors in latitude shifts have been found on EK Dra (Järvinen et al. 2007) and HR 1099 (Berdyugina & Henry 2007), especially for the case of EK Dra, where the mean spot position around one active longitude moved towards the equator by about 25° within a year, while the other one at the opposite longitude shifted towards the pole by about 15°. Berdyugina & Henry (2007) pointed out that such a behavior "suggests a precession of the global magnetic field with respect to the stellar rotational axis."

For the dataset taken on 1991 Oct. 18–23, we find that there are also two low latitude spots, and the first spot is at a longitude of 95°, while the other one at 350°. Comparing this result with the above results in 2008, we can see that the active longitude of each spot evidently shifts, indicating an evolution of active regions along longitude on a long time scale. In addition, for the V-band observations of AP149 made in Oct. 1992 (Prosser et al. 1993), its light curve shows an essentially symmetric shape (fig. 14 in their paper), which suggests that there is only one spot in the photosphere, or that there are one main spot and a much smaller one. However, we can see that there are two spots from the above result in Oct. 1991 (see Fig. 8). Therefore, it is evident that the active regions change on a time scale of one year.

To summarize, AP149's active regions in the photosphere evolve not only on a short time scale (one day) but also on a long time scale (one year to 17 yr).

5.2 Chromospheric Activity

The Ca II HK emission lines are associated with the non-radiative heating in a stellar chromosphere, and they are important probes of electron density and temperature, and hence are widely used as the optical indicators of chromospheric activity (Robinson et al. 1990; Thatcher & Robinson 1993). The filled-in absorptions in the cores of the H_α and H_β lines are also used as chromospheric activity indicators (Thatcher & Robinson 1993; Montes et al. 1995a). Our new spectra including Ca II HK and H_β lines allow us to simultaneously analyze the features of these chromospheric activity indicators.

From Figure 10, we find that the EWs of the Ca II HK lines approach their maximum when the star becomes faintest (the light curve in intensity units has a minimum), and vice versa during the two observing nights. This behavior suggests that the spot regions are correlated to the active regions in the chromosphere, which is similar to other active stars, for instance, EK Dra (Järvinen et al. 2007).

We can see that the variation of the H_β line is bizarre; its excess emission is not rotationally modulated during both nights. As discussed above, a mismatch in spectral type could affect the absolute flux of the chromospheric emission lines. However, the subtracted spectra of AP149 are obtained using the same reference star HR 3309. Equivalently, there is the same zero point in the chromospheric emission measurements. Such a mismatch in spectral type could not result in additional rotational modulation. Thus, perhaps such a variation of the H_β line is due to the existence of a prominence in the emission, which has been studied and discussed in detail by Barnes et al. (2001).

To conclude, AP149 is a very active star. Our photometric results show evidence of the rapid evolution of spot regions in the photosphere on a time scale of one day, furthermore, it is evident that the spotted regions vary on a time scale of one year by comparing the observation in Oct. 1991 with the one in Oct. 1992, and the spot distribution along longitude is evidently different from Oct. 1991 to Nov. 2008. Our simultaneous spectroscopic observations imply that the spot regions are spatially correlated to the active regions in the chromosphere. The H_β line is probably contaminated by prominence emission, because there is no evidence of rotational modulation apparent for it.

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