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Photometric and Magnetic Variability of the Late Ap Star HD 3980

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Summary. HD 3980, a late type Ap star has been observed in differential photometry (comparison: HD 4150) in the Strömgren-Crawford system at two epochs (Oct. 1974 and July/August 1978) and additionally with the g_1 and g_2 filters as described by Maitzen (1976). These measurements enable us, together with the data by Vogt and Faúndez (1979) and Seggewiss and Maitzen (1979), to derive precise elements of the light variation: JD (primary min in v) $=2442314^{\mathrm{d}}.48+3^{\mathrm{d}}.9516$ E.

We note a striking similarity with the light curves and the flux distribution found for HD 98088 (Maitzen, 1973): a very outstanding variation of $0^{\mathrm{m}}.13$ occurs only in the Strömgren-v pass band and exhibits two different minima separated in phase by 0.5. Towards longer wavelengths the amplitudes decrease to about zero at Strömgren-y. In addition, like for HD 98088 the published spectral classification (A 9p) does not match the gradient of the continuum flux nor the hydrogen line strength, which both indicate a much earlier type (A 3 V).

With the accurate elements of the photometric variation we can phase the Zeeman spectroscopy obtained by us on La Silla from 1970 to 1972. It turns out that the Zeeman plates show a reversal of magnetic polarity every second day with an amplitude of about 2 kG, and that all but one of the spectra were taken after either the positive or negative crossover. More Zeeman observations are suggested in order to complete the magnetic curve ($=H_{\mathrm{eff}}$) and to establish the possible presence of an unusual strong magnetic field as inferred by Wood (1978).

Key words: Ap stars – photometric variation – magnetic field variation – HD 3980

Introduction

HD 3980 (=HR 183=ξ Phe) is a late type southern Ap star and a common-proper-motion visual binary ($\Delta m=4^{\mathrm{m}}.2$, separation $=13''.4$) with spectral type A 9p according to the catalogue of Berthaud and Floquet (1974). In a 1968 letter to HJW, Bidelman suggested it might be an interesting spectrum variable. Later Bidelman and MacConnell (1973) classified its peculiarity as "Sr–Cr–Eu (F)". The catalogue of Grønbech and Olsen (1976) lists HD 3980 with a note indicating a large amplitude variation in the Strömgren c_1 index: residuals from the mean were −83, 67, and 16 thousands of mag.

Vogt and Faúndez (1979) report 12 absolute Strömgren measurements which show a somewhat lower, but still appreciable amplitude in c_1 ($\sigma=0^{\mathrm{m}}.041$). However, these authors could not reach a conclusion on the periodicity of the light variation.

Maitzen (1976) obtained in his photometric system $\Delta a=0^{\mathrm{m}}.038$ which means a rather strong peculiarity in view of the late type. Moreover, he indicated that the period of HD 3980 as derived from variable m_1-values (Δa was nearly constant) should be close to 4 days.

Seggewiss and Maitzen (1979) investigate the spectral variability of a number of Ap stars (among them HD 3980) which is monitored by simultaneous photometric observations. In the case of HD 3980 on 6 consecutive nights a rather spectacular double wave variation in Strömgren v was detected. Our paper reports differential photometry at two other epochs and discusses all now available photometry in order to derive a final period, but also to describe the flux variation as a function of wavelength of this outstanding cool Ap star.

HD 3980 was also put on the ESO southern magnetic star survey (Wood and Campusano, 1975). By a technique described by Weiss et al. (1978) the variation of the effective magnetic field and its phase relationship to the photometric variation is determined in this paper.

New Photometric Measurements

1. In fall 1974 HMM obtained differential observations with the 60 cm Bochum telescope on La Silla on ten consecutive nights. He used the intermediate band filter system $uvbyg_1g_2$ (Maitzen, 1976), a dry ice cooled EMI 9502 photomultiplier, d.c. amplifier and the Bochum automatic data acquisition system. The only comparison star was HD 4150 (η Phe), the constancy of which was checked by the standard deviations of its $b-y$, m_1 and Δa obtained with the filter system just mentioned. Their values are 3, 4, and 3 thousands of mag, respectively. The means are: $b-y=-2$, $m_1=143$, and $\Delta a=-1$ thousands of mag. Both data indicate that HD 4150 is indeed constant and a normal A 0 IV type star as listed in the BS catalogue.

The angular distance from HD 4150 to HD 3980 is small enough (about 1°) that the maximum differential extinction correction in u never exceeded $0^{\mathrm{m}}.006$.

The internal precision of a filter measurement represented by the mean error of the mean of usually 20–30 one-second integrations was never larger than $0^{\mathrm{m}}.003$. The observing sequence

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* Based in part on observations obtained at the European Southern Observatory, La Silla, Chile

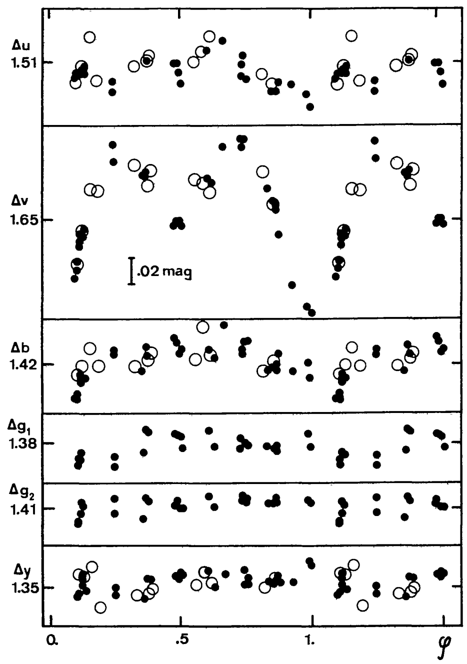

Fig. 1. Light curves using all available data in the sense HD 3980–HD 4150 plotted with the elements given in the text. The data of Vogt and Faúndez (1979) are represented by open circles. Brightness increases to the top

was: comparison star (all filters), Ap star (all filters), comparison star (all filters), the sky measurements being done after each star measurement.

Some loss of accuracy is caused by the relatively nearby companion and the resulting problem of choosing an appropriate diaphragm. Its angular distance is too large as to include the companion in diaphragm of usual size, but sometimes it is too small as to be definitely excluded (in the case of guide errors or bad seeing). This can introduce errors of up to 2%, especially at longer wavelength, where the influence of the red companion is stronger.

2. In summer 1977 HD 3980 did not exhibit short periodic variations during four hours of continuous monitoring in B and V (Weiss, 1978). However, a slope in $(B-V)$ of 0.0039 mag/h was clearly detectable. With the elements presented in this paper, we can now determine the accurate phase of these observations ($\varphi=0.88$). The steep slope in y from our Fig. 1 explains the observed change rate in $(B-V)$.

3. In summer 1978 WWW carried out differential observations with the ESO 50 cm telescope on La Silla on four nights in the Strömgren-Crawford system using a dry ice cooled EMI 6256 photomultiplier, pulse counting and the ESO General Purpose Data Acquisition System (GPDAS). Based on the experience of the first mission, the same comparison star was taken as reference. The observing mode was also the same as in the first run. The results of both missions are given in Table 1.

Period Determination

Periods which are close to 3 or 4 days cause problems not only in the precise determination of the period value but also in the correct derivation of the shape of the light curve. This holds especially in the case of the double wave variations so typical for the oblique rotator behavior of Ap stars. A good example is HD 49976 with a period of 2.9760 days (Maitzen and Albrecht, 1975) and a double wave variation, which required observations over several years in order to establish the full structure of the light curves. The same applies to HD 3980. As already suggested by Maitzen (1976) the 1974-measurements (mission 1) pointed to about 4 days. Plotting these measurements (HD 3980 minus HD 4150) with this period and considering only the filter with the strongest variation, v, we obtained a deep narrow minimum and a rather broad maximum, the difference between both amounting to $0\overset{m}{.}06$. Such an asymmetric light curve is very unusual for a late Ap star, and indicated hidden phases due to the close-to-4-days period. The measurements of our mission in 1978, together with the data by Seggewiss and Maitzen (1979) complete the light curve. They exhibit an amplitude almost twice as large in v, and two different minima. This means that we had observed HD 3980 in the first run only at more or less intermediate phases, avoiding both the maxima and the minima. The same is true for the absolute Strömgren photometry made by Vogt and Faúndez (1979) which was carried out immediately before and after our first mission in 1974. In order to use also their data for our period search we made a zero point adjustment by comparing their mean in v with the mean of our first run.

All four data sets were used for the period search, but only in v, because of the outstanding amplitude of 0.13 mag. Weiss and Kreidl (1979) have recently discussed the performance of several period search methods, among them the "phase dispersion minimization" method according to Stellingwerf (1978). The results of the latter encouraged us to try an application to the v-variation of HD 3980, especially in view of the large amplitude, double wave and a rather restricted number of observations. With this method several "best" periods were obtained. The period $P=3\overset{d}{.}9516$ was finally adopted based on visual inspection of the resulting light curve, giving the smoothest shape. Selecting the primary minimum as most conspicuous and well defined feature of the v curve as zero phase, we can give the following elements:

$$\mathrm{JD(Prim.\ Min.\ v)} = 2442314\overset{d}{.}48 + 3\overset{d}{.}9516\,E\,.$$
$$\text{m.e.} \qquad \pm 0.04 \;\pm 0.0003$$

The quality of the Vogt-Faúndez observations can now be assessed in Fig. 1 where they are denoted by a special symbol. From this we deduce that it is not as good as the differential observations, but still suffices for our purpose because of the large amplitude in v. The error of $0\overset{d}{.}0003$ in period was derived by visual inspection of light curves plotted with close-by period values.

Discussion of the Light Curves

The light curves in $uvbyg_1g_2$ are displayed in Fig. 1. One immediately recognizes that a strong variation takes place only in v. The depth of the primary minimum amounts to $0\overset{m}{.}13$ while the secondary minimum shows about half this value. Both maxima seem to be nearly equal. There is a high degree of symmetry in this light curve, all extrema are separated by nearly 0.25 phase consecutively.

The amplitudes of the other light curves are strongly reduced. The u-curve varies only by about $0\overset{m}{.}04$. Additional precise measurements in this color are required in order to verify a possibly complex structure in the light curve (additional minima?). About the same amplitude is observed in b, but the

Table 1. HD 3980–HD 4150, Journal of Observations obtained at La Silla. Phase ψ was calculated with the elements given in the paper

J.D.	u	v	b	g_1	g_2	y	ψ	Obs.
a) Observations in $uvbyg_1g_2$:								
2442329.d68		1.m626	1.m425	1.m383	1.m406	1.m346	0.85	HMM
2330.72		1.688	1.443	1.397	1.422	1.355	0.11	HMM
2330.73		1.684	1.446	1.392	1.421	1.355	0.11	HMM
2331.74		1.616	1.426	1.387	1.418	1.358	0.37	HMM
2332.71	1.m503	1.619	1.409	1.370	1.401	1.337	0.61	HMM
2333.68	1.534	1.637	1.424	1.385	1.407	1.349	0.86	HMM
2334.74	1.520	1.660	1.435	1.393	1.405	1.340	0.13	HMM
2334.75	1.517	1.663	1.432	1.389	1.408	1.341	0.13	HMM
2335.73		1.617	1.406	1.370	1.402	1.343	0.38	HMM
2335.74	1.510	1,613	1.413	1.372	1.405	1.344	0.38	HMM
2336.72		1.621	1.415	1.383	1.410	1.350	0.63	HMM
2337.69		1.639	1.421	1.383	1.402	1.342	0.87	HMM
2337.69	1.533	1.643	1.425	1.386	1.406	1.344	0.87	HMM
2338.67		1.666	1.428	1.391	1.415	1.343	0.12	HMM
2338.68	1.519	1.670	1.435	1.387	1.415	1.348	0.12	HMM
2443721.64	1.524	1.694	1.446			1.356	0.10	WWW
3721.68	1.520	1.682	1.442			1.355	0.11	WWW
3721.81	1.514	1.657	1.431			1.353	0.14	WWW
3727.86	1.495	1.589	1.390			1.340	0.67	WWW
3728.69	1.526	1.662	1.412			1.347	0.88	WWW
3728.89	1.528	1.701	1.425			1.347	0.93	WWW
3729.70	1.519	1.658	1.431			1.352	0.14	WWW

b) Observations of the β-index of HD 3980 at La Silla

J.D.	β	ψ	Obs
2443716.77	2.875	0.87	WWW
3718.84	2.881	0.39	WWW
3719.70	2.877	0.61	WWW
3720.77	2.861	0.88	WWW

secondary minimum has disappeared. The same applies to the remaining curves, which show a gradual diminishing of the amplitude from about 0.m02 (for g_1, at λ 5020 Å) to practically zero at Strömgren-y.

We have at our disposal only 4 measurements of the β-index, at phases 0.866, 0.389, 0.607, and 0.880, respectively. They scatter around the mean value of 2.m874 with a s.d. of 0.m0087. This means that we cannot infer a variation of β (which is indicative for temperature in the late A type stars) from these measurements. But as they were made outside the phases of the presumed maximum backwarming, we need additional observations at these phases in order to establish the constancy of β. Of course it remains to be shown that any variation of β is not caused by a differential blanketing effect between the narrow and broad Hβ bands filters.

Figure 2 shows the flux distribution with wavelength, where both well known Ap continuum features at 4100 and 5200 Å appear. The latter is constant over the cycle, the former is strongly variable, but always present. The depth ratio of both features is typical for a cool Ap star (i.e. the 4100 feature is much stronger).

At this point we draw the attention to HD 98088, which was studied photometrically by Maitzen (1973), because of the striking similarities with the photometric behavior of HD 3980. The main difference is only the higher degree of peculiarity in HD 3980 expressed by the depth and the amplitude of the λ 4100-feature (λ 5200 has about the same strength in both stars). In HD 98088 Eu II and Sr II vary exactly in antiphase with the light curves in the violet region: Primary and secondary minima of the light variation correspond to primary and secondary maxima in the line variation. A future paper will describe the related situation in HD 3980 (Seggewiss and Maitzen, 1979).

HD 3980 and HD 98088 resemble each other also with respect to the problem of spectral classification of Ap stars: Both are assigned A 9p in the catalogue of Berthaud and Floquet (1974), but this type does not correspond to the visual continuum nor to the hydrogen line strengths. From the β-values we derive a spectral type of about A 3 V, and from Fig. 2 a temperature which corresponds to the same type (considering the spectral type of the comparison star HD 4150). We recall that the visual continuum exhibits only a small backwarming (zero variation at longer wavelength!), so that the energy distribution in the visual is representative for the effective temperature of the star, of course disregarding the depressions at λ 4100 and 5200 Å.

From Maitzen's (1973) discussion we extract the same situation for HD 98088: H_γ and the flux distribution yield also about A 3 V.

Differences of continuum temperature and those related to spectral classification of Ap stars can be explained by a con-

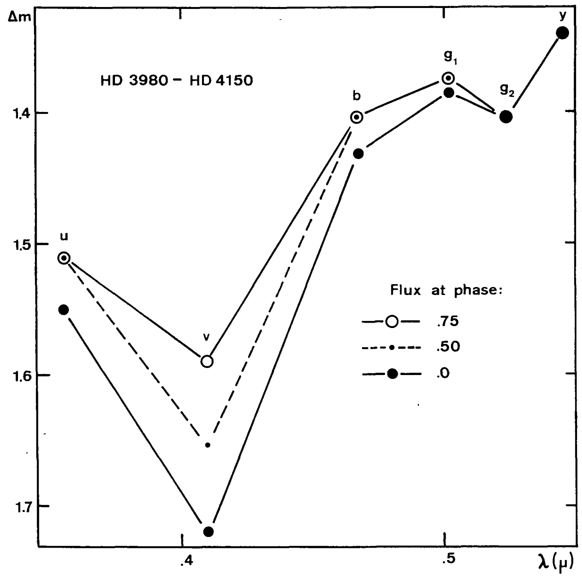

Fig. 2. Differential flux distribution HD 3980–HD 4150 at outstanding phases of the light variation

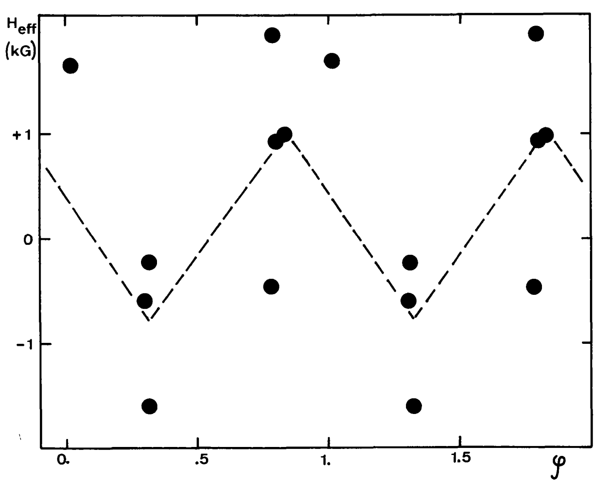

Fig. 3. Effective magnetic field variations plotted with the elements given in the text. Effective fields were obtained by the MSHIFT method (Weiss et al., 1978) using a mean value of $z = 1.3$. The dashed line connects the centers of gravity in the phase intervals 0.78–1.01 and 0.30–0.32

centration of those elements which form the typical F type line spectrum, at the uppermost layers of the stellar atmosphere. This way the lines are enhanced in comparison with a normal star because the temperature of the layers in which they are formed is lower, and second because of the higher abundance of these elements in these layers. Diffusion is most likely to produce such an effect (see e.g. Michaud, 1970; or Shore and Adelman, 1974), although magnetic accretion (Havnes, 1974) could also deposit heavy elements on the top of the atmosphere after a selective capture from the interstellar medium by the rotating magnetosphere.

From this consideration it is probably more meaningful to assign cool Ap stars a spectral type based on the continuum energy distribution rather than on the line spectrum which essentially reflects the peculiarisation process and not primarily the temperature conditions in the atmosphere.

Magnetic Field Measurements

HD 3980 was on the program of a magnetic star survey carried out at the 1.5 m spectrographic telescope at ESO-La Silla. Details can be found in Wood and Campusano (1975). The first plate (Camera II, 12.3 Å mm^{-1}) showed a rich sharp-lined spectrum. However, few plates were obtained because at $V = 5^m.69$ the star required about 6 h exposure with Camera III (3.3 Å mm^{-1}) and no obvious large Zeeman shifts were visible on the first lower dispersion Zeeman plate using a Grant machine. The lines appeared broadened and somewhat complex in structure. Thus the material for the magnetic field measurements is somewhat limited. It is listed in Table 2.

The Zeeman (and Doppler) measurements were carried out with a statistical correlation method called MSHIFT (Weiss et al., 1978). In this approach, Zeeman spectrograms are digitized with the Vienna PDS-1000 microdensitometer system. Zeeman shifts were found by making 51 trial shifts between two 116 Å scans centered on λ 4262 Å in the o- and e-ray component spectrograms. The sum of the squared differences of the approximately 1600 data points in each spectrogram at each trial shift forms the difference curve, the minimum of which defines the best-fit Zeeman offset averaged over the lines in the spectral region of interest. All Zeeman MSHIFT runs were Doppler corrected so that the same stellar wavelength region (and set of lines) were used for each plate.

The Doppler MSHIFT runs used a 23 Å range centered on the same wavelength center λ 4262 Å. The smaller range is necessary because of the Doppler "stretching" or "contraction" of one spectrum with respect to another caused by differences in the observed velocities. To find the minima of the difference curves we used 7-point parabolic fits. Third-order 30 point and fourth-order

Table 2. Effective magnetic fields and radial velocities of HD 3980. For details see Fig. 3

ESO-plate	Å/mm	J.D.	Phase	H_{eff}(G)	RV(km s^{-1})	Obs.
G1557z	12.3	2440930.55	0.78	− 460	12.6	HJW
H463z	3.3	1148.81	0.01	+1670	16.9	HJW
G3354z	12.3	1521.42	0.31	− 210	12.9	WWW
G3361z	12.3	1523.32	0.79	+1960	17.0	WWW
G3365z	12.3	1525.33	0.30	− 570	12.9	WWW
G3370z	12.3	1527,32	0.80	+ 940	14.8	WWW
G3380z	12.3	1529.38	0.32	−1570	14.9	WWW
H955z	3.3	1586.71	0.83	+1000	13.8	HJW

40 point fits were tried but gave poorer correlation with the velocities measured in a conventional way. The five best Camera II plates were measured for velocity using a 13-line list. We have adopted the MSHIFT velocities found from a least-squares regression for these five plates.

The final velocities scatter about a mean of $14\,\mathrm{km\,s^{-1}}$ with a standard deviation of $1.8\,\mathrm{km\,s^{-1}}$. This value is so small that we can assume constancy to within our accuracy.

The Zeeman offsets and the velocities are listed in Table 2. In addition, we have given mean effective magnetic fields calculated from the Zeeman shifts assuming a mean z-value for the spectral region of $z=1.3$. Such a value was found for example in a similar study of Canopus by Rakos et al. (1977).

From the values of H_{eff}, plotted in Fig. 3, we can draw the following conclusions: H_{eff} is variable with a 4-days period: we note a reversal of its polarity every second day in the (rather contiguous) interval JD 2441521–2441586. The amplitude is of the order of 2 kG. From the limited number of measurements and in view of the insufficient phase coverage we cannot deduce precisely the degree of symmetry of the H_{eff} values around zero. In addition, the scatter of the fields in the afore-mentioned interval is rather large: 3 measurements around phase 0.3 yield a mean of -780 G with a s.d. of 700 G, while at phase 0.8 we calculate a scatter of 570 G around 1300 G.

The uncertainty of the calculated phases of the H_{eff}-variation is only 0.015. Thus, if we assume the usual coincidence of the extrema of the magnetic field variation with those of the peculiarity patches (producing the minima in the v-curve, in analogy with HD 98088), we have taken the spectra of HD 3980 shortly after the phases of positive and negative crossover. This may produce the large scatter of the fields obtained by use of the MSHIFT method. As there are indications of an extremely large surface field (Wood, 1978), it is highly desirable to obtain Zeeman plates at the other phases of the variation, especially at phases 0.0 and 0.5.

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