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HD 72968 (3 Hya)—Another Low Amplitude Photometric Double Wave Ap Star*

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Summary. Extensive photoelectric intermediate band photometry of the low amplitude light variations of HD 72968 at ESO—La Silla yields evidence for a double wave variation in all filters with only slightly different maxima. Thus, the real period, in terms of the Oblique Rotator Theory the rotational period, is twice as large as the previously published (a situation which could be present in a number of other Ap stars) and fits the low amplitude reversing magnetic field curve far better than the old half period. The elements are: JD (Max(H_{eff})) = 2432897$^{\mathrm{d}}$68 + 11$^{\mathrm{d}}$305 E. The new elements correspond to an inclination between the line of sight and the rotational axis rendering a rather equator-on aspect. It is suggested that the controversial peculiarity degrees of this star derived from different peculiarity parameters can be understood in terms of a progressed main sequence age.

Key words: Ap stars — light variability — double wave light curves — HD 72968

Introduction

HD 72968 (3 Hya) belongs to the group of magnetic stars for which Babcock (1958) obtained a sufficiently large number of Zeeman spectrograms over a period of 8 years allowing a good phase coverage for the detection of a periodic variation. Nevertheless, his observations are spaced so widely from each other that the normal one week periods are very difficult to establish in the case of HD 72968. Other magnetic field measurements with Zeeman plates were carried out by van den Heuvel (1971), but they are not numerous enough in view of their large errors to get any reliable period. In fact, the errors are so large in comparison with the low field values that van den Heuvel called this star only possibly magnetic. Hensberge and de Loore (1974), however, confirmed the existence of its magnetic field by a curve-of-growth determination of the magnetic line intensification and obtained 2800 ± 600 G for the mean surface field on two consecutive nights derived from two 3 A/mm-plates. Unpublished Sr and La line variations detected by Havnes which were mentioned in the same paper were compatible with a 5.99 days period while the only photometric study (in uvby) was done by Wolff and Wolff (1971) yielding a very low amplitude variation with a single wave and considerable scatter in all filters. Their period of 5.57 days fitted to some degree also the magnetic data of Babcock, although two points strongly deviated from a hand drawn mean curve by about 10 times the error quoted by Babcock. The unsatisfactory large scatter of the photometric data resembles the situation with HD 203006 for which Morrison and Wolff (1971) had found a small amplitude light variation with enhanced scatter in the maximum phase later explained by Maitzen et al. (1974) as the effect of a non-recognized double wave light variation (= use of only half the rotational period). This situation prompted the authors to carry out more observations in uvby for HD 72968 in order to improve the precision of the period so that one could effectively check the existing magnetic field data for taking the decision whether a period near that determined by the Wolffs or the double period is the true one. This can be easily obtained because when taking only half the rotational period for the reduction of the magnetic variation positive and negative field maxima would be placed in the same phase region.

Moreover, the high value of Maitzen's (1976) photometric peculiarity parameter Δa for this star (= 0$^{\mathrm{m}}$050) is indicative that a larger period than the hitherto known cannot be ruled out a priori.

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* Based on observations obtained at the European Southern Observatory—La Silla (Chile)

Table 1. Journal of observations

J.D. 2 440 000+	y	b	v	u
618.01	−0.852	−0.856	−0.812	−0.674
619.00	854	870	820	682
619.98	851	868	817	678
620.97	842	862	816	678
621.94	842	859	814	668
625.94	850	868	818	680
626.96	848	860	807	672
628.99	849	864	821	677
629.95	852	866	819	678
630.90	862	870	821	680
634.94	843	852	808	669
635.94	856	868	818	678
636.94	856	875	812	674
637.94	849	865	816	669
638.98	854	856	814	660
641.92	862	868	819	676
648.87	858	866	810	672
649.82	857	868	812	669
660.79	842	859	814	674
661.79	844	859	818	665
671.79	849	864	808	671
672.80	848	852	812	668
673.79	845	858	810	663
684.80	842	858	808	662
685.78	849	870	820	678
686.80	856	873	820	676
689.77	844	860	810	661
690.78	841	860	812	663
695.81	854	858	810	656
696.79	854	866	816	670
928.84	841	862	829	668
929.80	862	861	810	666
932.81	849	855	801	654
940.83	851	879	814	672
941.83	868	876	817	676
942.81	859	868	814	680
943.80	842	855	816	676
945.80	845	853	800	688
946.80	848	863	824	685
949.77	842	864	814	661
950.83	839	847	806	670
951.74	852	865	824	679
953.77	855	862	812	673
954.73	842	866	826	686
964.76	845	863	818	670
968.74	853	867	813	678
969.73	869	880	814	683
970.79	855	874	822	681
971.73	842	860	809	662
972.71	833	851	799	655
973.74	859	864	811	668
977.68	854	865	819	663
978.70	842	853	818	662
1728.74	858	877	823	682
1729.69	851	862	819	672
1730.69	840	856	806	659
1731.62	849	860	815	675
1732.63	852	867	817	676
1733.66	857	876	819	678
1735.64	839	848	804	654
1736.64	848	860	815	665
1737.64	857	869	817	677
2752.81	848	863	819	665
2753.79	853	866	818	674
2754.79	853	868	823	791
2755.80	861	879	827	688
2756.78	851	863	822	685
2757.77	849	865	820	679
2758.83	846	855	804	662
2759.81	847	863	815	673
2766.83	853	868	820	688
2767.76	860	875	816	678
2768.73	850	866	802	656
2769.72	839	859	803	656
2770.75	846	862	812	667
2772.78	852	865	818	675
2773.74	847	854	813	673
2774.71	847	854	813	673
2775.76	842	851	802	660
2776.76	847	863	817	674
2779.73	862	861	813	683
	$H_\beta B$	g_1	g_2	
1728.74	−0.963	−0.946	−0.881	
1729.69	953	934	877	
1730.69	942	930	872	
1731.62	951	937	873	
1732.63	959	945	884	
1733.66	961	943	884	
1735.64	936	926	871	
1736.64	944	930	875	
1737.64	953	939	879	

The Observational Data

The differential photoelectric observations were carried out in 3 runs at La Silla, Chile and span together with the Wolff's data an interval of almost 6 years. This is large enough to improve the period for checking it with Babcock's magnetic data and to determine the phase relation between photometric and magnetic variations.

The journal of observations is given in Table 1 and includes the numerical uvby-values presented only graphically by Wolff and Wolff (1971) in their Δm vs. phase diagram. Table 2 gives information about the details of the observing runs.

It will not likely improve the overall quality even of differential measurements if one uses in different runs different telescopes with different auxiliary equipment, different comparison stars and observing modes. Unfortunately, this was the case in our undertaking.

The data sets of the individual runs were averaged and then matched to the data of the Wolffs who used HD 73431 as primary comparison star. In our first run the precision of the individual measurement suffered from the use of a dying photomultiplier which can be easily recognized from the scatter of the corresponding data

Table 2. Photoelectric observing runs on HD 72968

Time	n	Observer	Institut.	Telescope	Auxil.	Comp. st.	syst.
Feb. 70–Apr. 70	30	Wolff and Wolff (1971)				HD 73431	uvby
Dec. 70–Jan. 71	23	R. Albrecht	Univ. Bochum/ Univ. Wien	60-cm Cass., Bochum-station La Silla	*dc*-ampl. EMI 9502 dry ice strip-chart	HD 73400	uvby
Feb. 73	9	H. M. Maitzen	ESO/ Univ. Bochum	1-m ESO-La Silla	pulse count. EMI 6256 comput-erized data acquis. dry ice	HD 73997	uvby + $H_\beta B$, g_1, g_2
Dec. 75	19	A. Heck	ESO/ Univ. Liège	50-cm ESO-La Silla	pulse count. EMI 6256 comput. data acq. Peltier cooling	HD 73997 HD 70574	uvby

points in Figure 2. In our third run two comparison stars were used, but the observing mode C_1-Ap-C_2 applied for the sake of time saving lacks the symmetry normally required for getting the highest accuracy. In the reduction one of the comparison stars was matched to the other just by calculating the average of both comparison star data of the whole run applying extinction corrections. This, of course, introduces a new error source, just in view of the fact that all comparison stars used for the different runs lack the criterion of a good comparison star, i.e. small angular distance to the program star. These facts altogether indicate that the precision in the light curves cannot be as high as in similar investigations.

At the end of Table 1 measurements in 3 additional filters obtained in our second run are listed, i.e. H_β-Broad, g_1 (5020 Å) and g_2 (5240 Å). Transmission curves for the latter two are given in Maitzen (1976).

Period Determination

We used the traditional Lafler Kinman method which serves best when

a) the shape of the light curve is not known a priori
b) low amplitudes occur and
c) a good phase coverage (= usually a large body of data) is available.

As points b) and c) are met in our case we can hope to establish the final shape of the light curve, single (like the Wolffs curve) or double wave. If the conditions b) and c) are fulfilled, the recently published modification of the Lafler Kinman method by Hensberge et al. (1977) need not be applied because in this case the double wave has not the disadvantage against the single variation as it has for large variations and a limited number of points when looking for the lowest value of the Lafler Kinman parameter.

Our second run established the first indication for the period search because it comprises a night after night sequence of 8 measurements (except one night) in 7 filters. They corroborate the result obtained by the Wolffs that the period has something to do with about 5.5 days.

Now taking our three runs together with the Wolff's data we checked by Lafler Kinman the interval 5 to 6 days with increments of 0.0001 times the foregoing period. By far the best result was obtained for 5.6525 days whereas no significant minimum of the Lafler Kinman parameter was found for the Wolff's period (5.57 days) and its neighborhood.

We checked also the correlated periods (0.850 and 1.215 days) and its surroundings, the first one without any result, while the second one was only a bit worse than the five days period. Our first result, hence, was 5.6525 ± 0.0010 days. This precision suffices for a test with the magnetic data of Babcock. In Figure 1a this data is plotted with this period (as no precise J.D.s are given in the Babcock catalog midnight observations were assumed which do not introduce any considerable phase error).

It was really surprising that the relatively ordered picture exhibited for the 5.57 days period in the Wolff's paper completely disappeared. As maxima and minima

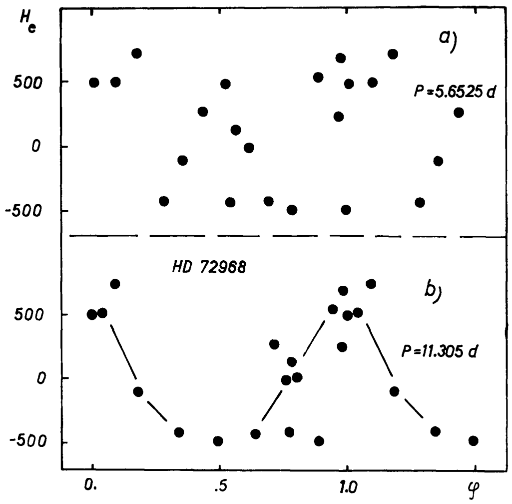

Fig. 1a. Babcock's (1958) longitudinal magnetic field measurements in Gauss plotted with $P = 5.6525$ days and epoch J.D. 2432897.68,
b. the same with $P = 11.305$ days

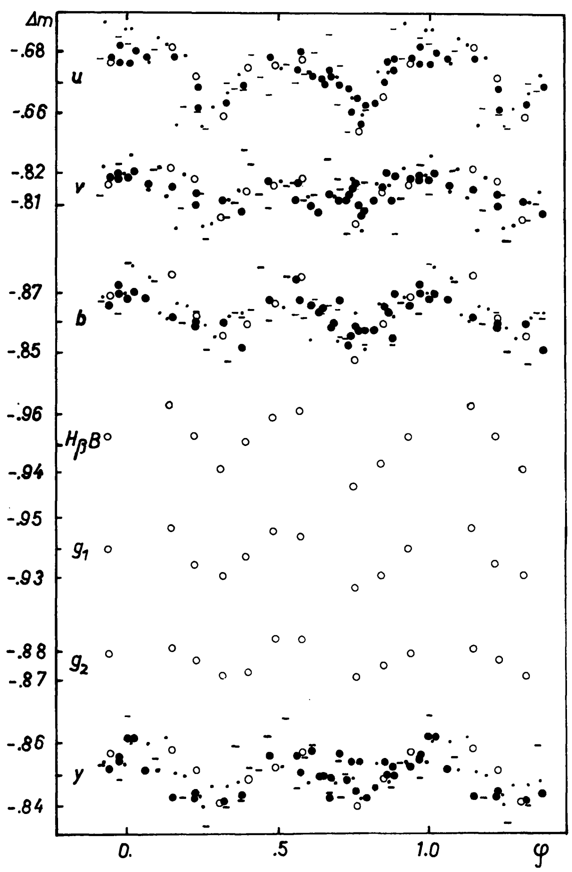

Fig. 2. Seven color light curve of HD 72968. Different symbols indicate different observing runs: filled circles—Wolff and Wolff (1971), horizontal bars—our first run, open circles—our second run, points—our third run; details for the observing runs in Table 2. Phases were calculated with $P = 11.305$ days and epoch J.D. 2432897.68. In uvby the magnitude differences refer to HD 73431 as comparison star, in the other colors to HD 73997

of the magnetic field appear at the same phase this suggests that we obviously reduced the data with only half the rotational period. Hence, in Figure 1b the exact double value of this period was taken and immediately a clear $H_{\rm eff}$-variation results with a mean scatter around a hand drawn smooth curve clearly smaller than using 5.57 days. Only one point deviates from the mean curve by more than 2σ. It is just the value obtained from a plate for which Babcock derived also a strongly deviating radial velocity. As all the other radial velocities including those published by van den Heuvel (1971) indicates an almost perfect constancy we feel that it is more reasonable that this plate suffered from some special effect and that its value for discussing the behavior of this star should be regarded as very doubtful than to give it such a preference that it makes this star a spectroscopic binary.

We did not include van den Heuvel's 5 Zeeman measurements because his probable error indications are about 6–8 times larger than those of Babcock. While it is conceivable that Babcock's errors are somewhat low (ratio of external to internal error $\sim$ 2.5–3) we think that, e.g. van den Heuvel's plate ECZ 7457 with 1179 $\pm$ 505 G demonstrates by its extraordinary deviation from the other measurements that it (and the other measurements) cannot be considered to be useful for period checking, because the errors are too large (= of the order of the amplitude of the variation).

We arrive at the following final result for the period of HD 72968:

$$\begin{aligned} \text{JD(Max}\,(H_{\rm eff})) &= 2432897.68 + 11.305\,\text{E} \\ \text{m.e.} &= \quad \pm 0.23 \quad \pm 0.002 \end{aligned}$$

The precision permits to phase light and magnetic variations together. The light curves in 7 filters are presented in Figure 2. Both maxima and minima are nearly equal. Looking especially at the curves in *u* and *v*, however, a slight difference between the primary maximum (coinciding in phase with magnetic maximum) and the secondary maximum (corresponding to the magnetic minimum) can be noted. This phase relationship is by no means unusual among Ap stars.

Finally we must mention that the eleven days' period was confirmed also by the Lafler Kinman method for the light variation in uvby. This is plausible because when using only half the rotational period one increases the scatter around the phase of the differing maxima.

Discussion

We consider the consequences of the new period for the angle *i* between the line of sight and the rotational axis of HD 72968. By using the bolometric radius formula

$$\log(R/R_0) = 0.2(42.31 - M_{\rm bol} - 10\log T_{\rm eff}) \tag{1}$$

and inserting the radius into the Oblique Rotator relation (see e.g. Stift, 1974)

$$\sin i = v \sin i \cdot P/(50.613R) \tag{2}$$

one can in principle very easily determine i, if besides the rotational period P the projected equatorial velocity $v \sin i$ is known. $v \sin i$ values have been published for HD 72968 by Preston (1971) (= 16 km s^{-1}) and by Hensberge and de Loore (1974) (= 11 km s^{-1} as upper limit based on magnetically unaffected null-lines). Stift (1973) calculated 10.6 km s^{-1} from Babcock's line width index. From formula (2) and the sin i not to exceed 1 we obtain lower limits for the radius: with Preston's value 3.6 and with 11 km s^{-1} 2.5 solar radii. The first value is doubtfully high and strengthens Stift's (1976) finding that Preston's $v \sin i$ values are about 20–30% too high. This supports a value of about 11 km s^{-1} for the best available figure.

Stift (1973) using about this value and taking values for $M_{\rm bol}$ and $T_{\rm eff}$ corresponding to the published $B - V = -0.025$ calculated a bolometric radius $3.2R_0$ and $i = 21°$ with the old half period, whence a rather pole-on aspect to the observer resulted.

With the new period i would increase to 46°. But this should not be considered as final i value, since another weak point in formula (2) is the radius obtained from the bolometric formula (1), depending on the choice of the bolometric magnitude and effective temperature, and both again from $B - V$. $B - V$ does not directly reflect overall characteristics like $M_{\rm bol}$ and $T_{\rm eff}$ in Ap stars because the special atmospheric structure in these stars alters the overall flux distribution considerably. First of all UV studies (see Leckrone, 1976) have shown a large UV flux deficit in comparison to the visual region, which can be explained by UV line blocking and redistribution of the blocked flux into the visual spectral region. Consequently, the quantities $B - V$, M_v (hence $M_{\rm bol}$) and $T_{\rm eff}$ representing the deeper, backwarmed layers of the stellar atmosphere are too blue, too bright, too high, respectively, for the correct determination of a bolometric radius.

In addition the backwarmed visible flux is affected by enhanced line blocking and backwarming, as was shown in the work by Wolff (1967). She determined the blanketing, hence the net effect on the visual flux measuring the line blocking coefficient from spectrographic plates. This net effect on the $B - V$ colors is about zero for the hot Ap stars, but increases to the cooler objects and reddens them to 0.10 magnitudes.

This means that for cooler Ap stars the UV backwarming (which is moreover weaker than for the hot stars) is counterbalanced by visual blanketing, yielding more or less "true" $B - V$ colors. But this is not the case for the hotter stars where increased UV backwarming meets decreased visual blanketing. The observed $B - V$ colors hence mimic a hotter star and consequently a star with a larger radius than corresponds to reality. Our Ap object belongs to the hotter group, and we can estimate that therefore the radius calculated by Stift is too large by about 10–20%. Very probably the radius of HD 72968 will lie between 2.7 and 3 solar radii, whence we calculate for the inclination $55° < i < 65°$. With the new value of the period and our radius estimate we arrived at a rather equator-on aspect of HD 72968.

This is important for a discussion of the relationship between the main features of this star. In Figure 3 the spectral energy distribution in the sense HD 72968 minus HD 73997 is plotted for maximum and minimum light phase. One can infer that both stars match quite well with respect to their visual flux distribution (HD 72968 has spectral type Ao), taking into account that Strömgren-y samples still much of the λ5200-depression which causes the b-y color to be too blue. This depression is obviously very pronounced, and Maitzen (1976) found the above mentioned high photometric depression value. This finding and the relatively long period fit very well together and assign this star a strong Ap peculiarity. On the other hand the low amplitude photometric variations and the small reversing longitudinal field would suggest only a mild Ap character of HD 72968. It is up to theory to reconcile this superficially controversial picture. According to the magnetic accretion theory (Havnes, 1974) older Ap stars should show a statistically larger rotational deceleration caused by the transfer of momentum through the rotating magnetosphere to the interstellar surrounding. Older stars have larger radii than those on the zero age main sequence. Wolff (1975) and Stiff (1976) have shown that the existing material gives good reason to assume a correlation between periods and radii for magnetic stars supporting the concept of a deceleration process during the main sequence lifetime of the Ap stars. HD 72968 does fit very well into the period-radius relation shown in Figure 2 of Stift (1976) with the new period and the reduced radius, but also

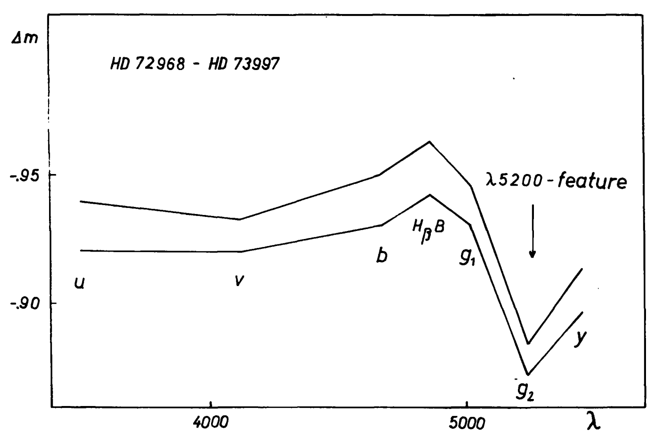

Fig. 3. Differential spectral energy distribution as exhibited by the seven color photometry. The upper curve corresponds to the primary maximum, the lower to the minima of the light curves

gives a good contribution to the Δa vs. log (period) diagram in Maitzen's (1976) paper. This means that probably HD 72968 is a rather old Ap star. Unfortunately we have not at our disposal any other information on the age of this star. Again we must stress the importance of open cluster Ap investigations.

That a mechanism for which the presence of a magnetic field is a necessary condition produces the observed overabundances and the peculiar flux distribution is generally accepted. But HD 72968 like many other Ap stars is an example that strong peculiarity need not be accompanied (caused?) by a strong magnetic field. This obvious non-correlation can only be explained either by a remarkable main sequence lifetime decay of the magnetic field by instabilities (Wright, 1974) or by the fact that the strength of the magnetic field is determining only the peculiarization *rate* and must action over a corresponding time to build up the observed peculiarity. Both interpretations would point to a relatively old star in our case meeting the statement made above.

Finally the low amplitude light variation (which we have shown not to be caused by a pole-on aspect) can also be interpreted in terms of a progressed main sequence age of HD 72968 if we consider the horizontal diffusion effect (Havnes, 1975). Havnes showed that abundance gradients tend to start an expansion and a dilution of the Ap polar spots which will distribute the peculiarities more uniformly, but never completely homogeneously over the whole surface. Again this process needs a certain time and slows down as the gradient of the composition is reduced. It is conceivable that HD 72968 shows the action of this mechanism in a progressed stage, where both polar patches have already spread out over a large part of the surface producing relatively small photometric variations (because the UV backwarming does not vary very much over the surface), but a still rather high absolute degree of peculiarity shown by the deep λ5200-feature.

With these qualitative considerations, hence, it seems to be possible to fit the observed controversial characteristics into a consistent picture for our star. The outstanding character of HD 72968 calls for two desiderata for confirming the above hypothesis:

1) a detailed spectroscopic investigation of HD 72968
2) photometric observations of low amplitude Ap-stars checking them for double wave variations and depth of the λ5200-feature as a rather absolute peculiarity parameter, preferentially in open clusters.

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