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Relation between Light-variation and Magnetic Variation in Magnetic Alpha Variables

by

T. Jarzębowski

SUMMARY

Light-variations of three magnetic alpha variables HD 71866, HD 153882 and 53 Cam, have been investigated at the Wrocław Observatory. The obtained photometric results, together with previous results concerning α^2 CVn and HD 125248 indicate that there exists a close relationship between light-variation and magnetic variation. The curves of the light-variation and of the magnetic variation for a given star are similar and the extremes coincide. In the case of HD 71866, HD 153882, α^2 CVn and HD 125248 a coincidence of the phase of minimum light and maximum positive magnetic field takes place, while for 53 Cam the phase of minimum light coincides with the phase of maximum negative magnetic field. The possibilities of explanation of this relationship are discussed. It is shown, that this phenomenon can be explained on the basis of the oscillator theory.

Contents

1. Introduction

According to H. W. Babcock's investigations [1], [26] over ninety stars are known in which the presence of a magnetic field has been stated. The magnetic fields of probably all those stars are variable — among them there are seven stars [1]) with periodically varying

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[1]) In a recent paper of Babcock [1] eight periodic magnetic variables are mentioned. A new investigation of Babcock [2] indicates, however, that one of them (HD 32633) is an irregular variable. Therefore that star has not been listed in Table 1.

magnetic fields. These periodic magnetic variables have been classified by Babcock as alpha variables [1] (after the type star α^2 CVn). The stars are listed in the following table.

Table 1.

Magnetic Alpha Variables

Star	HD 71866	HD 153882	α^2C Vn	HD 125248	53 Cam	HD 188041	HD 98088
P	$6^{\mathrm{d}}.799$	$6^{\mathrm{d}}.0075$	$5^{\mathrm{d}}.4694$	$9^{\mathrm{d}}.295$	$8^{\mathrm{d}}.03$	226^{d}	$5^{\mathrm{d}}.905$
$\overline{H}_e$	-1700 $+2000$	-1200 $+1400$	-1300 $+1500$	-1900 $+2200$	-4800 $+3500$	$+300$ $+1200$	-1500 $+1000$

P denotes here the period of magnetic variation, while the values of $\overline{H}_e$ are average extreme values of the effective magnetic-field intensity H_e.

One of the interesting and unsolved problems concerning magnetic stars is the variability of their fields. Two different theories have been put forth to account for the variability of the fields of magnetic alpha variables: the oblique rotator theory and the oscillator theory. Among the observational facts known at present some are in favour of the oblique rotator theory (e. g. the correlation between period and line width [21]), others in favour of the oscillator theory (radial velocity variations, irregularities in magnetic variations). A choice between the two theories requires further investigation and new observational data.

In this paper a new problem referring to the light-variation of magnetic alpha variables is examined and a relationship is found between the light-variation and magnetic variation. This relationship may be explained on the grounds of the oscillator theory and may be treated as a new argument supporting this theory.

The results of photometric and magnetic observations of magnetic variables listed in Table 1 will now be discussed.

Among these seven alpha variables the light-variation of HD 71866, HD 153882 and 53 Cam has been investigated at the Wrocław Observatory. Photometric results of α^2 CVn and HD 125248 are known from former investigations. In the case of the two latter stars listed in Table 1, the light-variations are not yet known (however, HD 98088 differs fundamentally from other alpha variables and one may expect that the relation of light-variation and magnetic variation will not hold in the case of this star).

2. Magnetic Variable HD 71866

According to Babcock's investigation [3] the magnetic field of this star shows reversals of polarity in a period of about $6^{\mathrm{d}}.8$ days. The average extreme values of the effective magnetic-field intensity

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H_e are: — 1700 and + 2000 gauss[1]) (the extreme values of the field obtained from Babcock's measurements are — 2185 and + 2470 gauss). The diagram showing the magnetic variation of this star, reproduced from Babcock's paper [3], is plotted in the upper part of Fig. 1.

HD 71866 is also a spectrum variable. Lines of Eu II undergo moderate variations in intensity in a period of 6·8 days; the spectrum variability is however of comparatively low degree. Radial velocity variations occur, but the measurements show only random fluctuations without definite evidence of periodic variations.

In the Henry Draper Catalogue the spectral type of the star is designated as A0p, its magnitude as $6\overset{m}{.}7$. The coordinates are: $\alpha_{1950} = 8^h 28^m$, $\delta_{1950} = +40^0 24'$. Photometric observations of this star were made by S. Provin in 1953 [5]. This author has reported possible light-variations of small amplitude (on the basis of 6 observational nights) but neither the amplitude nor the period have been determined.

In the present investigation the star has been observed on twenty seven nights from January 13 till April 21, 1959. The observations were carried out by means of a photoelectric photometer with a multiplier 1P21, located in the focus of the 20-cm refractor of the Wrocław Observatory. In the case of this star the measurements were made in the effective wave-length $\lambda_{\text{eff}} = 4200$ [6].

As comparison star HD 71844 has been used, situated only about 10′ from HD 71866. It is fainter than HD 71866 by about $0\overset{m}{.}4$ and has the spectral type A3. The observations were chiefly made near culmination-time; a total of about 320 comparisons were measured (each comparison consisted of four readings of HD 71866 and four readings of the comparison star, together with the corresponding readings of the sky). The magnitude differences for the night were subsequently averaged — from every night one mean value of $\triangle m$ was calculated. The mean error of the measurements (e. g. the mean error of the arithmetical mean for every night) was of the order of $\pm 0\overset{m}{.}003$.

Table 2 contains the results of the observations. The magnitude differences $\triangle m =$ HD 71844 — HD 71866 are the mean values for each night. The number of comparisons from which this mean was taken is denoted by n. The epoch given is the mean epoch of comparison.

The observations indicate that the light of HD 71866 varies periodically with the period $P = 6·8$ days. The mean amplitude of the

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[1]) On the assumption that the magnetic field of the star is a dipole field, the values of the field intensity at the magnetic poles of the star H_p are related with the effective field intensity H_e by the formula [4] (for A-type stars):

$$H_p = 3{\cdot}3 \cdot H_e \cdot \frac{1}{\cos i}$$

In the case of HD 71866 (assuming $\cos i = 1$) the corresponding average values of H_p are: — 5600 and + 6600 gauss.

Table 2.

HD 71866

Date 1959	JD 2436000 +	$\left(\begin{smallmatrix}\text{HD}\\71844\end{smallmatrix}\right)-\left(\begin{smallmatrix}\text{HD}\\71866\end{smallmatrix}\right)$		n	Date 1959	JD 2436000 +	$\left(\begin{smallmatrix}\text{HD}\\71844\end{smallmatrix}\right)-\left(\begin{smallmatrix}\text{HD}\\71866\end{smallmatrix}\right)$		n
Jan. 13	582.61	+0.391	±0.007	4	Mar 22	650.32	+0.401	±0.002	12
Feb. 9	609.42	.396	.006	4	24	652.31	.385	.004	9
14	614.40	.413	.004	10	29	657.29	.402	.006	7
16	616.37	.391	.003	13	30	658.31	.384	.004	14
22	622.41	.409	.002	7	31	659.29	.384	.002	11
28	628.37	.419	.005	10	Apr. 1	560.29	.398	.002	22
Mar. 1	629.38	.412	.004	9	2	661.32	.414	.003	28
2	630.36	.387	.002	9	3	662.30	.409	.003	22
3	631.35	.372	.003	12	10	669.35	.418	.004	12
6	634.35	.409	.007	10	13	672.36	.374	.003	14
9	637.35	.387	.003	12	14	673.36	.385	.002	8
10	638.33	.379	.002	11	15	674.38	.395	.004	5
20	648.33	.409	.004	11	21	680.37	.394	.002	16
21	649.34	.420	.002	12					

light-variation is $0\overset{\mathrm{m}}{.}037$. The value of the amplitude is probably not constant, the difference between the extreme points in the diagram is $0\overset{\mathrm{m}}{.}048$. The magnitude differences $\triangle m$ reduced with this period $P = 6\overset{\mathrm{d}}{.}8$ are plotted in the lower part of Fig. 1.

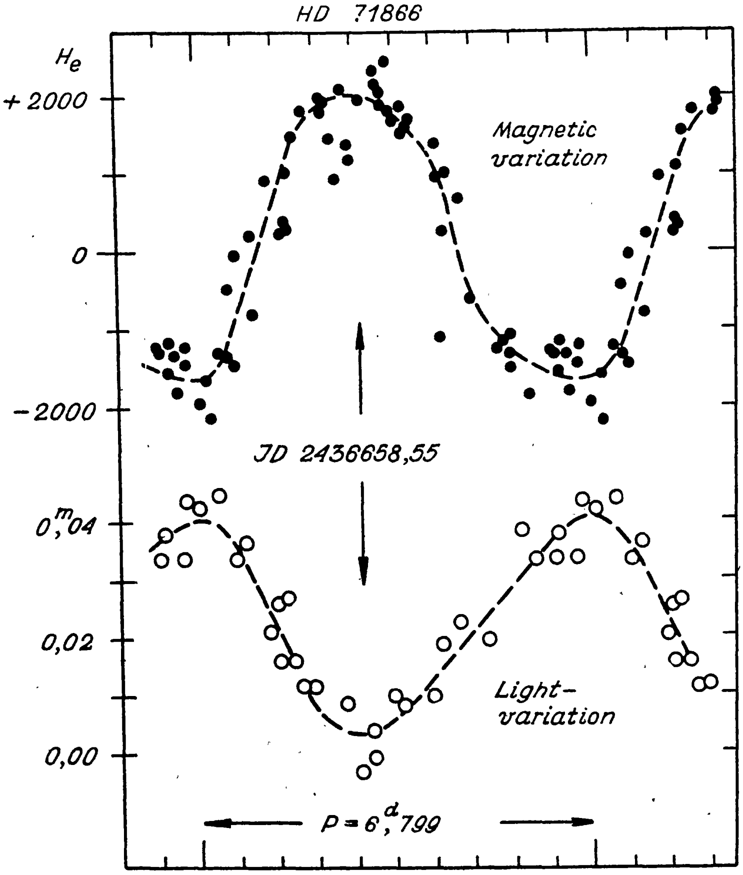

Fig. 1. — The curves of magnetic variation and light-variation in HD 71866.

The curve of the light-variation (Fig. 1) has a distinctly asymmetric form. The interval of time between maximum light and minimum light is $2\overset{\mathrm{d}}{\cdot}8$ and $4\overset{\mathrm{d}}{\cdot}0$ between minimum and maximum. The results of the photometric observations yield the following data:

$$\text{Minimum light} = \text{JD } 24\,36658{\cdot}55 + 6\overset{\mathrm{d}}{\cdot}8\,E$$
$$\text{Maximum light} = \text{JD } 24\,36662{\cdot}55 + 6\overset{\mathrm{d}}{\cdot}8\,E$$

We shall now compare the obtained photometric results with the results of magnetic observations.

According to data obtained by Babcock [3], the magnetic variations in HD 71866 are represented by the elements:

$$\text{Positive crossover} = \text{JD } 24\,32957{\cdot}90 + 6\overset{\mathrm{d}}{\cdot}79916\ E$$

Positive crossover is the time at which the effective field intensity H_e equals zero in passing from negative to positive values. Taking into account the asymmetry of the curve of magnetic variation (Fig. 1), to obtain the epoch of maximum positive or negative magnetic field the corresponding values $1\overset{\mathrm{d}}{\cdot}90$ or $5\overset{\mathrm{d}}{\cdot}80$ are to be added to the epoch of positive crossover. Thus we obtain

$$\text{Maximum positive magnetic field} = \text{JD } 24\,32959{\cdot}80 + 6\overset{\mathrm{d}}{\cdot}79916\ E$$
$$\text{Maximum negative magnetic field} = \text{JD } 24\,32963{\cdot}70 + 6\overset{\mathrm{d}}{\cdot}79916\ E$$

From an extrapolation for the time of our photometric observations (putting $E = 544$) we get the corresponding epochs:

$$\text{Maximum positive magnetic field} = \text{JD } 24\,36658{\cdot}54$$
$$\text{Maximum negative magnetic field} = \text{JD } 24\,36662{\cdot}44$$

Within the limits of observational errors the above epochs agree with the corresponding epochs of minimum and maximum light obtained from our measurements. Thus we can write the essential relations:

$$\text{Minimum light} = \text{Maximum positive magnetic field} =$$
$$= \text{JD } 24\,36658{\cdot}55 + 6\overset{\mathrm{d}}{\cdot}79916\ E$$
$$\text{Maximum light} = \text{Maximum negative magnetic field} =$$
$$= \text{JD } 24\,36662{\cdot}55 + 6\overset{\mathrm{d}}{\cdot}79916\ E$$

Exact coincidence of the epochs of minimum light and maximum positive magnetic field as well as maximum light and maximum negative magnetic field is the first interesting conclusion.

The second important conclusion, confirming the existence of a physical relation between the two phenomena, results when comparing the curves of light-variation and magnetic variation (Fig. 1). Both curves show a distinct resemblance in that they are similarly asymmetric.

3. Magnetic variable HD 153882

The magnetic field of this star reverses between the approximate limits — 1200 and + 1400 gauss within a period of about 6·0 days [7] (the extreme measured values of the effective field intensity are — 1330 and + 2720 gauss [8]). The diagram of the magnetic variation of this star, reproduced from Babcock's paper [1] is plotted in the upper part of Fig. 2.

Among magnetic alpha variables this is the only star whose spectrum shows little or even no variability in relative line intensities. There occur changes in radial velocities and they are probably periodic, their period being that of magnetic variation [7].

According to the HD Catalogue this is a star of magnitude $6\overset{\mathrm{m}}{\cdot}16$ and of spectral type Aop. The coordinates are $\alpha_{1950} = 16^{\mathrm{h}}\ 59^{\mathrm{m}}$, $\delta_{1950} = 15^{0}\,01'$. Photometric observations of this star were made by Provin in 1953 [5]. This author has stated definite variability in blue light, but neither the amplitude nor the period was established.

In this investigation the photometric observations of HD 153882 were made at the Wrocław Observatory on 23 nights from May 25 till July 13, 1959. The measurements were made in two colors, their effective wave length corresponding to $\lambda_{\mathrm{eff}} = 4200$ and $\lambda_{\mathrm{eff}} = 5350$ (for the A-type stars [6]).

Four comparison stars were used: HD 153809 (A0, $7\overset{\mathrm{m}}{\cdot}24$), HD 153376 (G0, $6\overset{\mathrm{m}}{\cdot}96$), HD 154228 (A0, $5\overset{\mathrm{m}}{\cdot}86$) and HD 154160 (K0, $6\overset{\mathrm{m}}{\cdot}52$); in Table 3 these stars are designated by successive Roman numerals I, II, III and IV. The best internal agreement has been attained from the first two comparison stars HD 153809 (I) and HD 153376 (II). Therefore during the last sixteen nights only these comparison stars were used; the two others being suspected of slight variability. A total of over 700 comparisons between HD 153882 and comparison stars were made. After averaging, 60 points on the diagram were obtained; each point on the diagram is a mean value obtained on an average from 12 comparisons.

The observations were made only near culmination (for $|t| < 2^{\mathrm{h}}$) and the values of $\triangle \sec z$ for a given comparison star were practically constant. Taking into account the low declination of the star, the relative values of extinction had to be carefully determined for each night. For this purpose a comparison of the light of a star in the zenith with a constant radioactive light source was made on each night. The value $\triangle \varepsilon = 2{\cdot}5 \log \frac{\Phi}{\Phi_0}$ has been calculated for each night (Φ_0 denotes the average value of the ratio: star in the zenith to the radioactive light source, while Φ — the corresponding current value of this ratio for the night). The value of the corresponding correction resulting from the variation of extinction ($\triangle \varepsilon \cdot \triangle \sec z$) did not exceed $0\overset{\mathrm{m}}{\cdot}008$ the average being $\pm 0\overset{\mathrm{m}}{\cdot}0025$.

The results of the photometric observations of HD 153882 are listed in Table 3. The values of $\triangle m$ have here another significance than in the case of HD 71866. As several comparison stars were used, the magnitude differences had to be reduced to one system. Using formula $\triangle m = m$ (comp. star) — m (HD 153882) + const, such a con-

Table 3.

HD 153882.

Date 1959	comp. star	JD 2436000 +	Δm $\lambda_{eff} = 4200$		Δm $\lambda_{eff} = 5350$		n
May 25	I	714.42	$0^{m},039$	±0.004	—		3
28	I	717.48	,038	.005	—		4
30	I	719.51	,029	.004	—		14
	III	719.54	,022	.006	—		4
June 4	I	724.40	,016	.005	—		13
	III	724,45	,016	,004	—		18
	III	724,50	—		$0^{m}.011$	±0,004	15
	I	724,53	.018	.005	—		8
5	III	725,38	—		0,021	±0.005	10
	III	725,42	,021	.003	—		18
	I	725,46	,029	,004	—		11
	III	725,50	.019	,003	—		12
6	III	726.37	—		0.035	±0,005	16
	III	726,42	.031	,004	—		24
	I	726,50	,026	,006	—		21
	III	726,54	—		0,028	±0.005	10
8	III	728,41	,039	,005	—		13
	I	728,47	,036	.006	—		17
	III	728,51	,041	.006	—		11
14	I	734,51	,038	.007	—		8
17	I	737,41	,000	,004	—		11
20	I	740,42	,030	,005	—		12
	IV	740,48	,035	,003	—		12
	II	740,51	,037	,004	—		7
21	I	741,40	.034	.002	—		12
	II	741.42	.040	.005	—		9
	II	741.45	—		0.031	±0.005	6
22	I	742,39	.021	.004	—		11
	II	742,41	.012	.005	—		6
	II	742,43	—		0.011	±0.006	6
	IV	742,44	,018	,006	—		4
23	I	743.38	,018	,004	—		8
26	I	746.41	,029	.004	—		11
July 2	I	752,43	,025	.002	—		12
	II	752,46	.033	.006	—		10
	II	752,50	—		0,043	±0.003	6
5	I	755.42	.025	.004	—		14
	II	755.44	.020	.003	—		10
	IV	755.47	.023	.005	—		10
	I	755.49	.026	.001	—		6
7	I	757,40	.031	,006	—		16
	II	757,42	.027	.005	—		10
8	II	758.38	—		0.030	±0.005	15
	I	758.40	.037	.003	—		8
	II	758,42	.038	.002	—		12
	I	758,46	.031	,005	—		10
9	II	759,40	,033	,005	—		10
	I	759,43	.027	.003	—		18
	II	759,47	—		0,024	±0.003	10
10	II	760.38	—		0.019	±0,004	21
	I	760.42	.014	.002	—		18
	II	760,47	.020	.006	—		15
11	I	761.41	.016	.003	—		20
	II	761.45	,019	.005	—		12
	II	761.48	—		0.027	±0.005	10
12	II	762.37	—		0.029	±0.005	14
	I	762.41	,025	.003	—		21
	II	762.46	,015	.004	—		12
	II	762.48	—		0.034	±0.005	6
13	I	763.46	,037	,007	—		13

stant value has been adopted for every comparison star in order to obtain $\triangle m = 0$ for the lowest point in the diagram of light-variation. These reduced values of $\triangle m$ are given in Table 3.

The results of photometric observations indicate that the light of HD 153882 varies with the period $P = 6{\cdot}0$ days. The mean amplitude of the light-variation is $0\overset{\rm m}{\cdot}019$. The amplitude is practically the same in yellow and in blue. The period of light-variation equals that of magnetic variation.

In the lower part of Fig. 2 the values of $\triangle m$ are plotted for

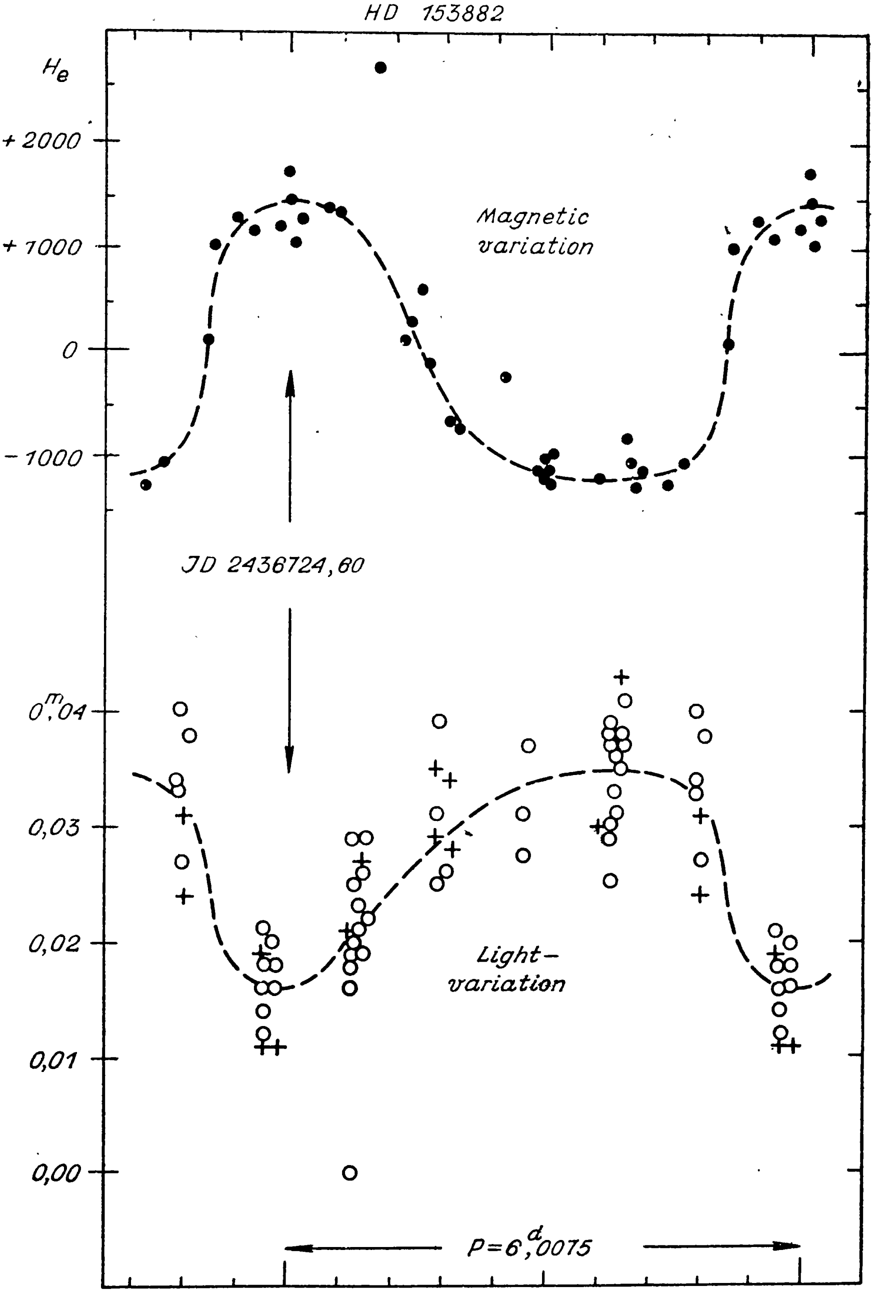

Fig. 2. — Diagrams of the variations of the magnetic field and light in HD 153882.

a period of 6·0 days. Circles in the diagram represent measurements in $\lambda_{\mathrm{eff}} = 4200$, crosses — measurements in $\lambda_{\mathrm{eff}} = 5350$. There are considerable deviations from the mean curve — the difference between the extreme points in the diagram being $0\overset{\mathrm{m}}{.}043$.

The photometric observations yield the following elements of light-variation

$$\text{Mininum light} = \text{JD } 2436724.60 + 6\overset{\mathrm{d}}{.}0\ E$$

A comparison of the light-variation with magnetic variation leads to similar conclusions as in HD 71866, however in the case of HD 153882 the period is known less exactly.

Guro Gjellestad and H. W. Babcock [7] have established as period the value $6\overset{\mathrm{m}}{.}005$. The value of the period has been subsequently corrected by Babcock to $6\overset{\mathrm{m}}{.}009$ [8] and the corresponding elements of magnetic variation are:

$$\text{Positive crossover} = \text{JD } 2432752.73 + 6\overset{\mathrm{d}}{.}009\ E$$

Taking into account the asymmetry of the curve of magnetic variation, we shall obtain the phase of maximum positive magnetic field by adding $0\overset{\mathrm{m}}{.}93$:

$$\text{Maximum positive magnetic field} = \text{JD } 2432753.66$$

Accepting as the value of the period $6\overset{\mathrm{d}}{.}009$ (and putting $E = 661$) we get by extrapolation the epoch JD 2436725·61. This epoch is about one day earlier in comparison with the epoch of minimum light. If, on the other hand, we accept as the period the previous value $6\overset{\mathrm{d}}{.}005$, the corresponding calculated epoch of maximum positive field would be $1\overset{\mathrm{d}}{.}64$ late in comparison with the epoch of minimum light obtained from our measurements. The phase of minimum light coincides exactly with the phase of maximum positive magnetic field when accepting for the period the value $6\overset{\mathrm{d}}{.}0075$ (approximately the mean of both). Thus we could write:

$$\text{Minimum light} = \text{Maximum positive magnetic field} =$$
$$= \text{JD } 2436724.60 + 6\overset{\mathrm{d}}{.}0075\ E$$

A glance at the curves of magnetic variation and of the light-variation (Fig. 2) shows a very distinct resemblance of both curves. The only logical assumption is the supposition that the sharp loop of the minimum of the light curve coincides with a similar loop of the maximum of the curve of magnetic variation (as drawn in Fig. 2). Therefore one may suppose that the slightly changed value of the period ($P = 6\overset{\mathrm{d}}{.}0075$) accepted in the above calculations would be an improved value of the period for this star.

In the case of HD 153882 still another detail is noteworthy. In both diagrams (Fig. 2) anomalous points are present near the same phase. These points are certainly physically real, because the probable error of this anomalous point according to Babcock's measurements is ± 150 gauss [8], while the probable error of the corresponding point according to our photometric measurements is $\pm 0\overset{\mathrm{m}}{\cdot}004$ (Table 3). If the phase relationship of both points were not accidental, it would show near this phase a tendency to an abrupt growth of the magnetic field, involving the corresponding variation of light. Generally speaking, this detail could be interpreted as a confirmation of the rule stated in the case of this star (and the case of three others), that the growth of a positive magnetic field involves a decrease of the light of the star.

4. Magnetic variable α^2 CVn

This is a bright Aop star — an outstanding widely investigated spectrum variable and magnetic variable. The period of the spectrum variation is 5·46939 days [9]. The magnetic field of this star, investigated by H. W. Babcock and S. Burd [10], varies in the same period between the approximate limits — 1300 and + 1500 gauss. The intensity of Eu II lines is at its maximum when the magnetic field has a negative pola-

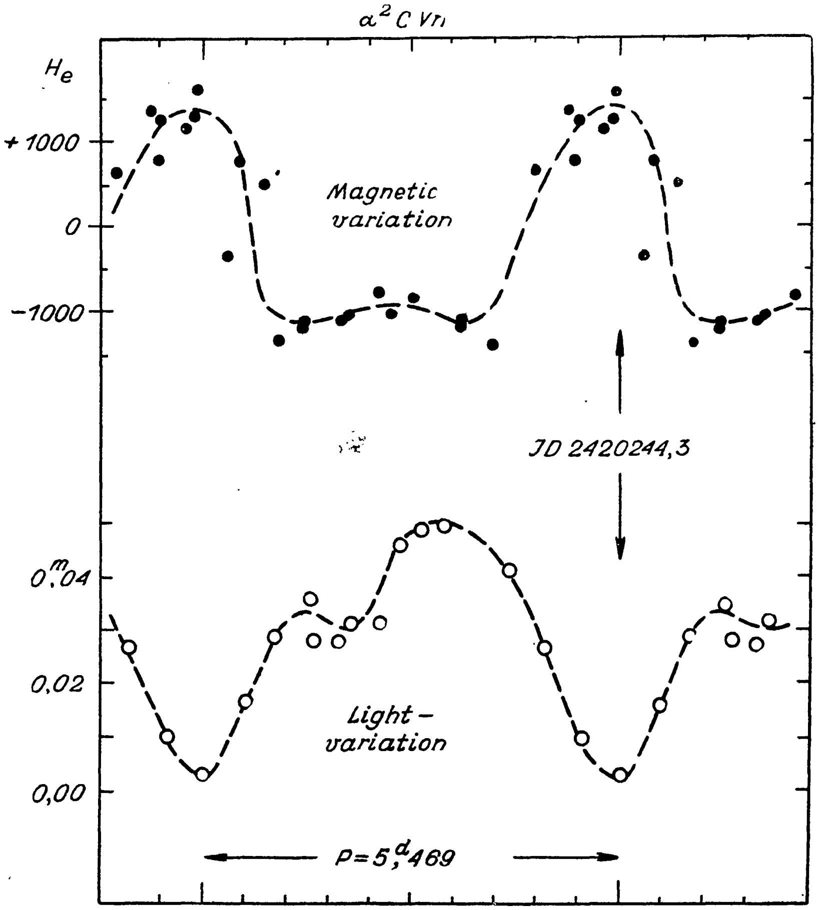

Fig. 3. — The magnetic variation and light-variation in α^2 CVn (According to Babcock's and Guthnick's measurements).

rity, while maximum intensity of Cr I and Cr II occurs at the phase of maximum positive field. Variations of radial velocities are periodic — the zero velocity phase coincides with the extremes of the magnetic field.

Light-variations of this star have been investigated first by P. Guthnick and R. Prager in 1914 [11], afterwards by Guthnick [12], M. Güssow [13], W. Tai [14] and by Provin [5].

According to the results of magnetic and spectrum measurements [10] one obtains: Maximum positive magnetic field = JD 24 19872,46 + $+ 5\overset{\mathrm{d}}{\cdot}46939\, E$. The epoch of maximum light, according to Guthnick's investigation [1]) is: JD 24 20242·04. Taking into account the shape of the light curve (Fig. 3) and extrapolating ($E = 61$) one obtains (with an accuracy to $0\overset{\mathrm{d}}{\cdot}1$) the relation [2]):

$$\text{Minimum light} = \text{Maximum positive magnetic field} =$$
$$= \text{JD } 2420244{\cdot}3 + 5\overset{\mathrm{d}}{\cdot}46939\, E$$

The curve of the light-variation, drawn according to Guthnick's results [12] and the curve of magnetic variation reproduced from Babcock's paper [1] are plotted in Fig. 3. Both curves show a distinct resemblance.

5. Magnetic variable HD 125248

The variable magnetic field of this Aop star varies between the approximate limits — 1900 and + 2200 gauss in a period of 9·295 days. Lines of Eu II and of Cr I and Cr II undergo extraordinary changes in the same period in opposite phases. Eu II lines are at maximum and Cr I and Cr II at minimum when the magnetic field has positive polarity — thus inversely than in the case of α^2 CVn. Radial velocity variations are periodic and the zero velocity phase coincides with the extremes of the field.

The light-variation of this star has been investigated by D. Stibbs in 1950 [15]. Stibbs has stated that in the case of this star minimum light occurs at the time of maximum positive magnetic field. The calculations show, that the phase coincidence is very strong (with an accuracy of up to $0\overset{\mathrm{d}}{\cdot}05$). The corresponding relation for this star is:

$$\text{Maximum light} = \text{Maximum negative magnetic field} =$$
$$= \text{JD } 2433103{\cdot}95 + 9\overset{\mathrm{d}}{\cdot}2954\, E$$

The curve of the light-variation drawn according to the results of Stibbs [15] is plotted in Fig. 4 together with the corresponding curve of magnetic variation reproduced from Babcock's paper [1].

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[1]) In Guthnick's paper [12] the value of the period $5\overset{\mathrm{d}}{\cdot}553$ is given. The value used here ($5\overset{\mathrm{d}}{\cdot}46939$) was established by Goldena Farnsworth [9] on the basis of investigations made during the years 1913 — 1932.

[2]) This phase relationship was mentioned by Provin in 1953 [5].

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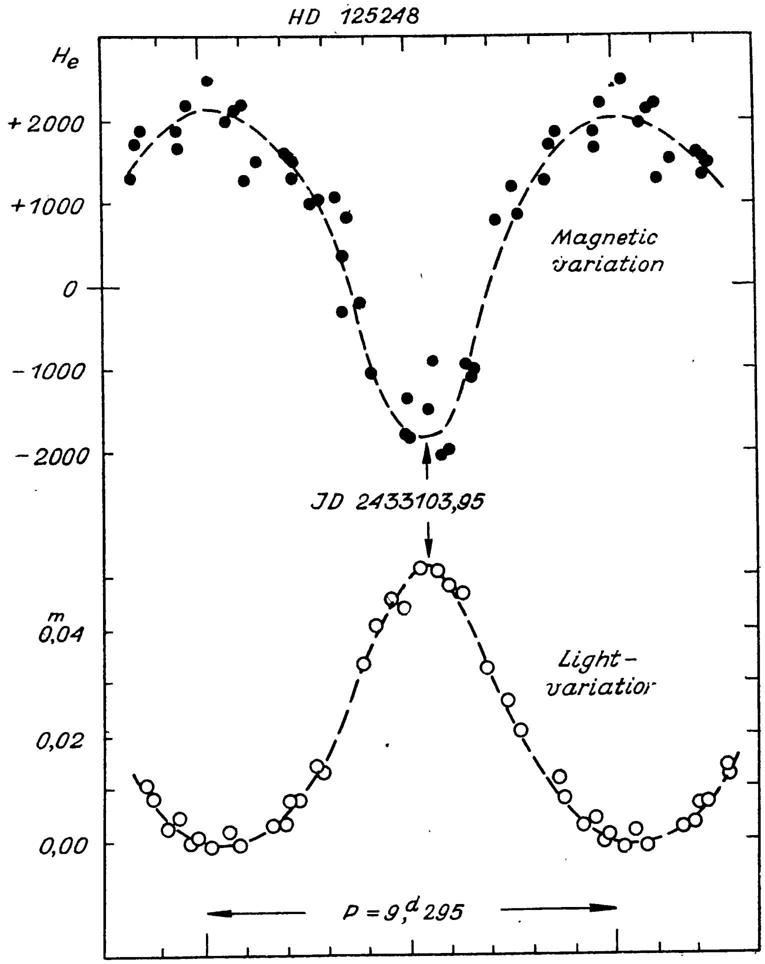

Fig. 4. — The curves of magnetic variation and light-variation in HD 125248 (the curve of light-variation according to the results of Stibbs).

The similarity of both curves is very striking; as yet this was not taken into consideration.

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In four of the above discussed magnetic alpha variables — HD 71866, HD 153882, α^2 C Vn and HD 125248 — the phase of minimum light coincides with the phase of maximum positive field. Another relationship takes place in the case of the fifth star listed in Table 1: 53 Cam.

6. Magnetic variable 53 Cam

Among magnetic stars listed in Babcock's catalogue [8], [1] this is the star showing the strongest magnetic field 1). The extreme measured values of the effective field intensity H_e are —5120 and

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1) Another magnetic variable star — HD 215441 — recently investigated by Babcock [26] which is probably also a periodic variable, shows a stronger magnetic field than 53 Cam.

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+ 3700 gauss (the corresponding values of H_p are — 16900 and + 12200 gauss). The period of magnetic variation and spectrum variation is 8·0 days. The spectrum of this star resembles that of HD 71866.

53 Cam (HD 65339) according to the HD Catalogue has the spectral type A2p and the magnitudes $m_{pv} = 6\overset{m}{.}00$, $m_{pg} = 6\overset{m}{.}06$; the coordinates $\alpha_{1950} = 7^h 57^m$, $\delta_{1950} = 60^0 28'$. No results of photometric investigations of this star have been published till now.

The photometric observations of 53 Cam were made at the Wrocław Observatory during 32 nights from January 13 till May 9, 1959. The measurements were made in the effective wave length $\lambda_{eff} = 4200$. HD 65301 was used as comparison star; the spectral type of this star is F2 and for $\lambda_{eff} = 4200$ it has nearly the same magnitude

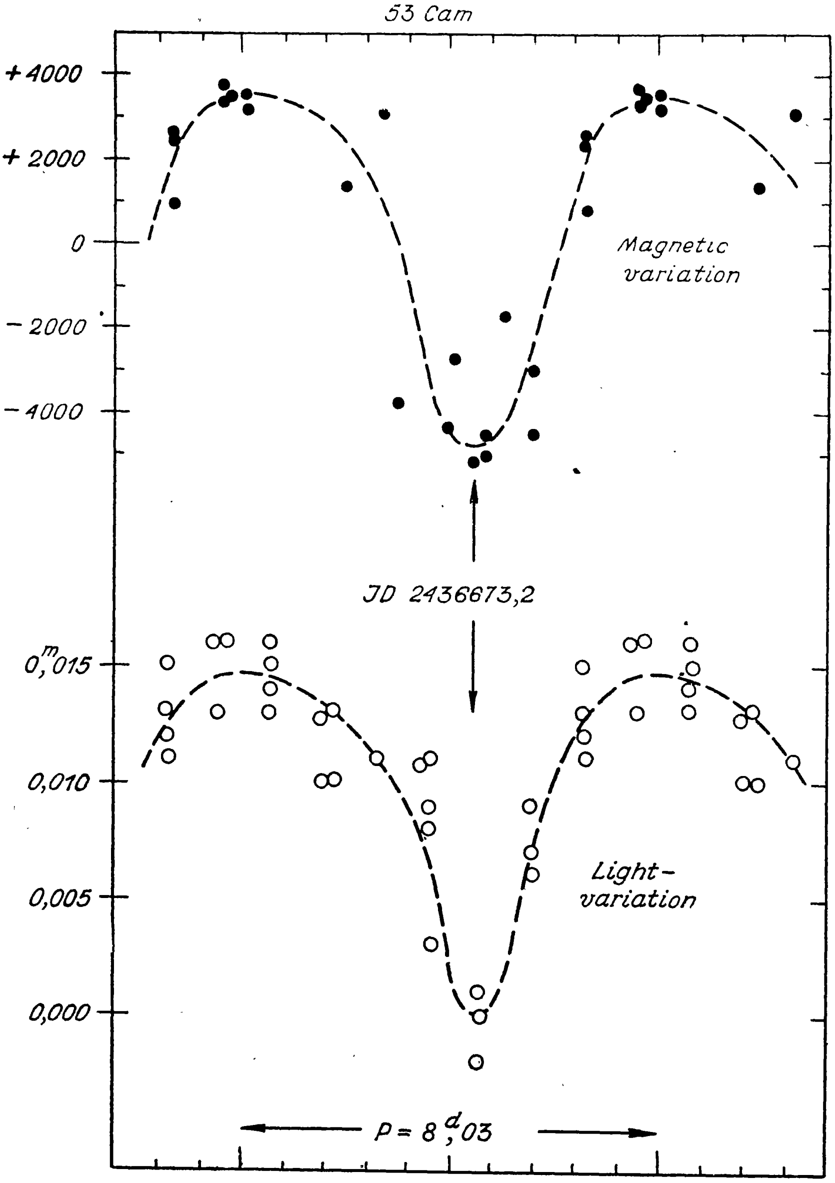

Fig. 5. — Variations in light and field of 53 Cam.

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as 53 Cam. A total of 460 comparisons were made between HD 65301 and 53 Cam.

The results of the first eleven nights have apparently pointed out that the light of the star is not variable and that the obtained magnitude differences Δm are constant within the limits of error. Further careful investigations have shown however that the light of 53 Cam varies periodically within a period of 8·0 days, but the range of the variation in light is small. The curve of the light-variation (Fig. 5) has short abrupt minima and relatively broad and flat maxima. (During the first 11 nights there were no observations near the phase of minimum light — this fact caused the apparent constancy in light).

The magnitude differences $\Delta m = \mathrm{HD}\ 65301 - 53\ \mathrm{Cam}$ obtained in successive 27 nights [1]) are listed in Table 4 and are plotted for the period of 8·0 days in the lower part of Fig. 5. Every point in the diagram represents the mean value of an average of 16 comparisons. The mean error of each point is $\pm 0^{\mathrm{m}}.0027$. The mean amplitude of the light-variation is $0^{\mathrm{m}}.015$. The difference between the extreme points in the diagram of the light-variation amounts to only 0·018. The photometric observations yield the following elements of light-variation

$$\text{Minimum light} = \text{JD } 24\ 36673.2 + 8^{\mathrm{d}}.0\ E.$$

We shall now discuss the question of a comparison of light-variation with magnetic variation.

Table 4.

53 Cam

Date 1959	JD 2436000 +	(HD 65301) - 53 Cam		n	Date 1959	JD 2436000 +	(HD 65301) - 53 Cam		n
Mar. 1	629.35	+0.006	±0.003	11	Apr. 13	672.33	+0,001	±0.000	10
2	630.33	0.000	.002	8	14	673.33	-0,012	.002	20
3	631.33	+0.001	.004	11	15	674.33	-0.003	.002	20
9	637.31	+0.003	.002	10	16	675.32	+0.003	.002	17
10	638.35	+0.003	.005	6	21	680.34	-0.002	.001	36
20	648.29	+0.001	.001	10	22	681.33	-0.010	.006	8
21	649.31	-0.009	.002	12	24	683.33	+0.002	.002	29
22	650.29	-0.001	.001	12	25	684.32	+0,006	.004	16
24	652.28	+0.004	.003	12	26	685.35	+0.005	.003	26
31	659.31	+0.005	.003	12	29	688.34	-0.001	.002	23
Apr. 1	660.34	+0.006	.005	12	May 5	694.37	0.000	.004	18
3	662.34	+0.003	.002	12	7	696.37	-0.007	.004	22
8	667.36	+0.001	.002	6	9	698.38	-0.004	.003	26
10	669.33	+0.004	.004	12					

The elements of magnetic variation, according to data given in Babcock's paper [1] are: Positive crossover $= \mathrm{JD}\ 24\,35857.0 + 7^{\mathrm{d}}.9863\ E$. Taking into account that the phase of maximum positive field occurs

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[1]) The results of the first five nights are omitted because they showed the greatest probable error.

$1\overset{\mathrm{d}}{\cdot}8$ later, we get from extrapolation the epoch JD 24 36673·4 coinciding approximately with the epoch of minimum light.

The above agreement is however only fortuitous. H. W. Babcock derived recently some improved elements from the magnetic variation [16]: Positive crossover = JD $24\,35855{\cdot}65 + 8\overset{\mathrm{d}}{\cdot}0269\ E$. Adding $6\overset{\mathrm{d}}{\cdot}35$ (according to the diagram of magnetic variation) we get by extrapolation ($E = 101$) the epoch of maximum negative magnetic field JD 24 36672·7. This epoch agrees with an accuracy of up to $0\overset{\mathrm{d}}{\cdot}5$ with the epoch of minimum light obtained from our measurements. Thus for 53 Cam we can write the probable relation

$$\text{Minimum light} = \text{Maximum negative magnetic field} =$$
$$= \text{JD } 24\,36673{\cdot}2 + 8\overset{\mathrm{d}}{\cdot}03\ E$$

In Figure 5 the curve of light-variation and the curve of magnetic variation are plotted together. A glance at both curves shows their similarity, but in this case the phase relationship is different than in the four preceding cases. A sharp minimum of the curve of light-variation corresponds to similar minimum (maximum negative field) in the curve of magnetic variation and both curves have similarly broad asymmetric maxima. The conspicuous similarity of both curves in this comparison confirms the different phase relationship in the case of this star.

7. Magnetic variables HD 188041 and HD 98088

No photometric investigations of these two stars have been made till now.

HD 188041 ($5\overset{\mathrm{m}}{\cdot}6$, A5p or F0p)

This is the only known long-period magnetic variable. The period of magnetic variations of this star is 226 days. The approximate limits of H_e are $+300$ and $+1200$ gauss (the extreme measured values of H_e are -230 and $+1470$ gauss). Radial velocity variations of this star show a random dispersion without definite evidence of periodic variations.

This star shows many similarities to the other magnetic alpha variables and it is to be expected that the relation between the magnetic variations and light-variations will appear also in the case of this star.

According to the elements of magnetic variation [17] (Minimum $H_e = \text{JD } 24\,32323 + 226^{\mathrm{d}}\ E$) maximum field will take place e. g. on September 4, 1960, while the next minimum field suitable for observations ($\alpha \approx 20^{\mathrm{h}}$) — on August 9, 1961. Consequently, if the discussed relationship holds in the case of this star, minimum light can be expected in September 1960 and maximum light in August 1961 (or maximum light in September 1960 and minimum light in August 1961, if the phase relationship were such as in 53 Cam).

Photometric investigations on this star, rather difficult to realize at the Wrocław Observatory ($\delta = -3^{0}$) would be very desirable because light-variations are to be expected and the knowledge of the phase relationship in the case of this star would be very important.

HD 98088 ($6^{m}.0$, gFop)

This star is a spectroscopic binary with a period of orbital revolution of 5·905 days. In the same period the magnetic field of this star varies within the limits of — 1500 and + 1000 gauss. The curve of the magnetic variation is a sinusoid. As mentioned by Babcock [8] the variability of the magnetic field of this star may be due to a purely geometrical effect (the period of axial rotation equals the period of orbital revolution — the side of the star carrying the positive magnetic field persistently faces the invisible companion).

In the case of this star periodic variations in luminosity can probably be expected too (e. g. there occur periodic variations of Sr. II). However, the cause involving here such light-variations would be probably different than in other alpha variables. Thus the discussed relationship between light-variation and magnetic variation, confirmed in the case of five alpha variables and possible in HD 188041, will probably not appear in the case of HD 98088.

8. Recapitulation of observational results

All magnetic alpha variables investigated till now show periodic variations in luminosity (in the classification of variable stars they are variables of the α Canum Venaticorum type). A comparison of photometric and magnetic observations of these five stars allows to formulate the following general conclusions.

1. **The period of light-variation equals the period of magnetic variation** (and of an eventual spectrum variation).

2. **The curve of light-variation and that of magnetic variation of each star show a distinct resemblance.**

It should be noted that the mentioned curves of different stars are different.

The next conclusion refers to the phase relationship. In the case of four stars: HD 71866, HD 153882, α^2 CVn and HD 125248, the phase of minimum light coincides with the phase of maximum positive magnetic field, while in 53 Cam the phase of minimum light coincides approximately with the phase of maximum negative field. These results may be generally formulated as follows.

3. **The extremes of the magnetic field coincide with the extremes of luminosity variations.**

These three conclusions indicate the existence of a relationship between variations in luminosity and magnetic field.

The discussed relationship between light-variation and magnetic variation can be generally formulated: **In magnetic variable stars every change of the magnetic field is related vith a variation in luminosity of small amplitude.** This conclusion is based on observational data of periodic magnetic variables. One might suppose, however, that this relationship would also hold for irregular variables if the causes of variation of the field in these stars were similar, or if the light-variations were involved directly by magnetic variations An immediate solution of this question could be obtained from simultaneous photometric and magnetic observations. Certain conclusions could however be drawn from photometric investigations of irregular magnetic variables.

The irregular magnetic variable HD 32633 (cp. note on page 31.) has been investigated on 13 nights at the Wrocław Observatory. This star has a strong rapidly reversing magnetic field — the extreme measured values of H_e are -4000 and $+$ $+2200$ gauss. The photometric results of this star indicate irregular variations in luminosity ($\pm 0\overset{\mathrm{m}}{\cdot}02$ in four nights) while in one night the variation of $0\overset{\mathrm{m}}{\cdot}05$ was noted during an interval of one hour. Photometric observations of this star will be continued. The present preliminary results confirm the supposition that the discussed relationship can also hold in the case of irregular variables.

A certain contradiction of this supposition could perhaps be found in Provin's photometric observations of HD 133029, the magnetic field of which varies irregularly within limits of $+1150$ and $+3270$ gauss [8]. The results of 10 nights show no indication of light-variation; this was interpreted by Provin that there is no relation between light-variation and magnetic variation [5]. Similarly, no variations in luminosity were found in the case of HD 42616 and 45 Leo [5], in which Babcock discovered subsequently the presence of weak magnetic fields [8]; on the other hand, light-variations were stated in the magnetic star $\varkappa$ Psc [5]. These photometric results require however confirmation.

Another problem presents the fact, that among the magnetic stars there are several stars in which periodic light-variations have been stated, while the variations of the magnetic field are irregular. In the first place HD 224801 is to be mentioned. This star shows periodic variations in luminosity with a period of 3,7 days and an amplitude of $0\overset{\mathrm{m}}{\cdot}04$. Magnetic measurements of this star, quite difficult because of the width and shallowness of the lines, show that the variations are either irregular or occur in a period of 1 day [5], [8], [18]. Similarly light-variations in a period of 20·3 days and an amplitude of $0\overset{\mathrm{m}}{\cdot}04$ (and periodic spectrum variations) were stated in 73 Dra, the magnetic field of which varies irregularly within limits -700 and $+200$ gauss [8], [19]. Finally, among the magnetic stars there are three well-known variable stars: R Gem, VV Cep and RR Lyr. In the case of these three stars the cause of light-variation is probably not directly related with variations of the field. One can suppose that the mentioned first two stars HD 224801 and 73 Dra would present a similar case.

9. Tests for an interpretation of the relationship between light-variation and magnetic variation

To account for the ralationship between light-variation and magnetic variation, two different possibilities might be considered.

1. Observed variations in luminosity are caused directly by the presence of a variable magnetic field of the star.

2. There is a common independent cause involving the light-variations as well as the magnetic variations of a star.

In considering the first possibility, the variability of the magnetic field of a star would be a separate problem. Assuming thus the existence of a variable magnetic field in a star, the possibility of light-variations involved by this variable field is to be considered. To account for this, one could suppose for instance that the presence of a magnetic field of a given polarity vould involve an increase of electron density (or other charged particles) in this region of the star. In that case a corresponding variation of the flux of radiation in this region may be expected. This supposition meets, however, with two serious difficulties. Firstly, from a physical point of view there is no obvious reason why electrons or any other particles should be associated with one polarity. Secondly, a certain discrepancy with observational data arises. Namely, as discussed before, the phase relationship in 53 Cam is the reverse than in the first four stars. Thus, if the observed variations in luminosity were caused directly by the presence of the field, positive polarity would involve a decrease of light in these four stars and, inconsistent with this, an increase of light in 53 Cam. These reasons would lead rather to a rejection of this possibility.

According to the second supposition, a mechanism causing variations of the magnetic field must also cause variations in luminosity. Thus the theory accounting for magnetic variations of a star must also account for light-variations.

Two different possible ways of accounting for the variability of stellar magnetic fields have been considered: the **oblique rotator theory** and the **oscillator theory.**

The oblique rotator theory assumes that the magnetic axis of the star is inclined to the axis of rotation, which in turn is inclined to the line of sight. The rotation of the star will thus produce apparent variations of the field. This theory is described in detail in [20] and [21].

The oscillator theory assumes that the star performs periodic oscillations and the movement of the material of the star involves corresponding variations in the magnetic field (the electrical conductivity being taken as infinite). This theory has been considered by M. Schwarzschild [22] and by T. Cowling [23]. A model of such oscillations, according to Cowling's suggestion, is shown in Fig. 6. Among the known observational facts periodic radial velocity variations (stated with certitude in α^2 CVn and HD 125248) strongly support this theory. Essential is here the detail that the phase of zero velocity coincides with the extremes of the field, as it results from that theory.

We shall now consider which of these two theories could also account for the observed light-variations.

In considering the **oblique rotator theory,** two possibilities are to be taken into consideration.

The first and the simplest supposition would be that the flux of radiation emitted by various parts of the surface of a star is different. Assuming for instance, that a star is brighter near the negative pole (and that the magnetic axis is inclined to the axis of rotation, which in turn is inclined to the line of sight), the rotation of the star would involve periodic variations in luminosity and the phase of minimum light would coincide with the phase of maximum positive magnetic field.

There is, however, no reason to base this supposition on the grounds of physical laws. It would be more credible to assume that the brightness would increase or decrease at both magnetic poles, but in that case the period of light-variation would amount to one half of the period of magnetic variation. Similar artificial suppositions (referring for instance to the differences of concentration of Eu II near both magnetic poles) have been made to account for spectrum variability on the grounds of the oblique rotator theory [21].

This supposition would be also difficult to reconcile with observations. Firstly, in this case it might be expected that the curves of light-variations will have the shape of a sinusoid, which has not been observed. Secondly it would be difficult to explain the inverse phase relationship in 53 Cam; there would arise the necessity of assuming that in 53 Cam the positive magnetic pole is brighter, while in the four other stars — the negative pole. A similar discrepancy also arises in the interpretation of the spectrum variability on grounds of the oblique rotator theory (assuming e. g. that in α^2 CVn the concentration of Eu II is greater near the negative pole, while in HD 125248 — near the positive pole).

The second possibility to be considered in the oblique rotator theory is the possible ellipticity of the surface of the star. As has been pointed out by S. Chandrasekhar and E. Fermi [24] and by V. Ferraro [25], the magnetic field tends to produce a flattening of the magnetic poles of the star. In that case a difference of directions of the magnetic axis, of the axis of rotation and of the line of sight involves observed variations in luminosity. This possibility is however excluded on two grounds. Firstly, in this case the period of light-variation would amount to one half of the period of magnetic variation. Secondly as shown by Ferraro [25], for a typical magnetic star the resulting ellipticity is of the order of 10^{-8}; thus the expected variations in luminosity would be unmeasurable.

* * *

In considering the **oscillator theory** the observed variations in luminosity and the relationship between magnetic variation and light-variation may find a simpler explanation.

Let us consider a mechanism of horizontal oscillations, similar to that proposed by Cowling [23]. Two extreme phases of such oscillations are shown in Fig. 6 (assuming that the direction of the axis of rotation, of the magnetic axis and of the line of sight is the same). The left figure corresponds to the phase of oscillation in which the material is the most displaced towards the poles. Hence this is the zero velocity phase when the greatest concentration of material is near the poles. For an observer viewing from above this is the phase of maximum positive magnetic field, while for an observer viewing from beneath it corresponds to the phase of maximum negative field. The figure on the right corresponds to the opposite phase when the material is displaced away from the poles.

It is self-evident that the oscillations here discussed could involve variations of the brightness of the star. This would result from periodic variations of the surface of the star, from simultaneous variations of temperature, or from eventual variations of the coefficient of absorption.

Consider for instance the first mentioned possibility. When the material is moving toward the poles, a decrease of the surface is to be expected and a simultaneous decrease of luminosity takes place;

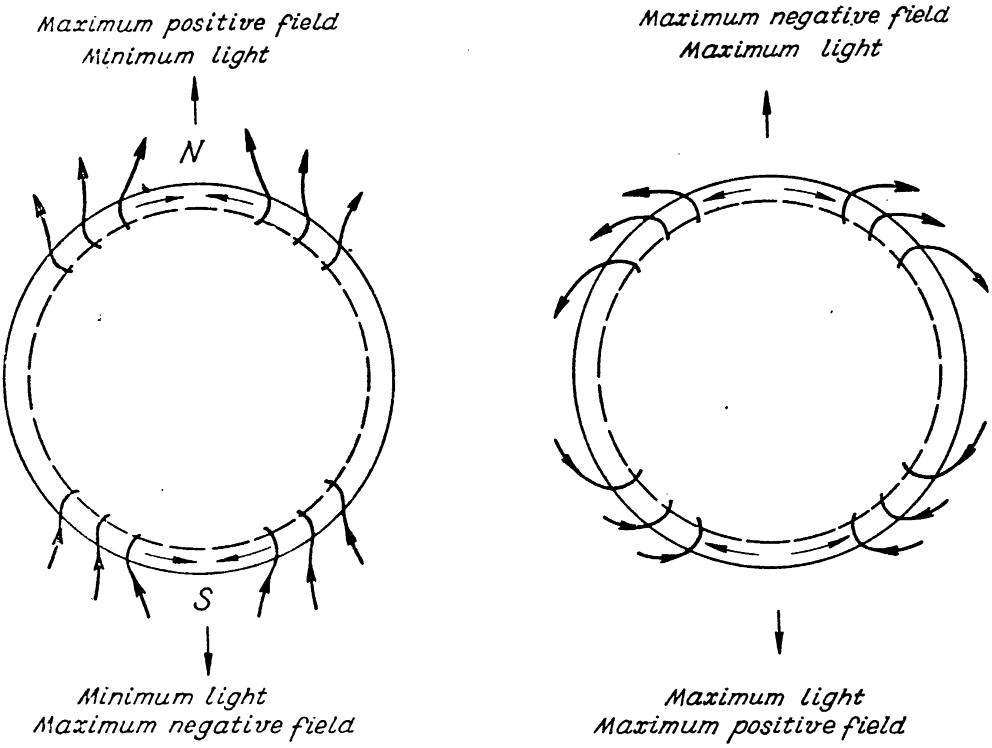

Fig. 6. — A model of horizontal osclations of a magnetic star

in the opposite phase, when the material moves away from the poles, an inverse case will take place. As shown in Fig. 6, for an observer viewing from above the phase of minimum light would thus coincide with the phase of maximum positive field (as in the case of HD 71866, α^2 CVn, HD 153882 and HD 125248), while for an observer viewing from beneath the phase of minimum light coincides with the phase of maximum negative field (as in the case of 53 Cam).

A more detailed discussion confirms the above mentioned possibility. According to the model of nonradial oscillations calculated and discussed by Z. Kopal [27], the extremes of the variations of the radius $\frac{\delta r}{R}$ take place at the surface of the star. Thus the observed variations in luminosity could result from periodic variations of the surface of the star and from eventual synchroneous variations of the temperature. According to the known formula $\triangle m = -2{\cdot}17 \frac{\delta r}{R}$ one obtains that the observed variations in luminosity ($\triangle m \approx 0^{m}{\cdot}02$) could result from the variation of the radius of the order $\delta r \approx 0{\cdot}01\ R$. This value is relatively small, thus rather real. A simple calculation shows that in the case of a magnetic star ($P = 6^{d}$, $R = 2 R_{\odot}$) such variation of the radius would result at velocities of the order of 0·05 km/sek., which are unmeasurable. This could account for the fact that periodic velocity variations were not stated in all periodic magnetic variables.

As shown by Cowling [23] the model of oscillations discussed here requires modification, because it can not account for the reversal of the field and provides only small fluctuations in the observed magnetic field of the star. If however, as suggested by Cowling [23], the observed reversal of the field would result from oscillations causing transportation of patches of different polarity from the invisible to the visible hemisphere, the explanation of the relationship between light-variation and magnetic variation would be analogous.

The discussed mechanism of oscillations can also hold for irregular magnetic variables. If the variations of magnetic fields of these stars were caused by some irregular oscillations causing displacements of the lines of force with the moving material, simultaneous variations in luminosity may occur. Thus one may expect that irregular magnetic variables would also show irregular variations in luminosity — as stated in the case of HD 32633.

In agreement with the oscillator theory is also the fact, that there is no apparent correlation between the amplitudes of magnetic variations and light-variations in different alpha variables. This is obvious because on the one hand the amplitude of variations in luminosity depends mostly upon the structure of the atmosphere of the star and upon the character of oscillations, which would probably be different in different stars. On the other hand, the range of magnetic variation, besides the character of oscillation, will depend particularly upon the value of the original field, evidently differing in different stars. If, for instance, the observed reversal of the field were produced by transporting patches of different polarity from one hemisphere to the other, the range of magnetic variation would depend mostly upon the original field and would be practically unrelated with the range of variation in luminosity.

To summarize, we can say that the oscillator theory might account for the relationship between the light-variation and magnetic variation in magnetic alpha variables. This may be interpreted as a new argument supporting this theory.

In conclusion I would like to thank Dr. H. W. Babcock for suggesting the problem of investigation, for the communication of recent data of his researches and for his helpful remarks. I also wish to thank Dr. P. Bidelman for his critical remarks concerning the observational results. Thanks are also due to Prof. A. Opolski and Dr. J. Kubikowski for many helpful and valuable discussions.

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Wrocław Observatory, September, 1959.

T. Jarzębowski

Note added in proof:

The photometric observations of magnetic variables have been continued during 1960 in two colors. The new results confirm those of 1959, described in this paper. The following remarks may be added:

In the case of HD 71866 the amplitude in blue (4200) is $0\overset{\mathrm{m}}{.}035$, while in yellow (5350) it is much smaller — $0\overset{\mathrm{m}}{.}015$. The phase of maximum temperature coincides with the phase of maximum negative field.

In 53 Cam the amplitude in yellow and blue is of the same order ($0\overset{\mathrm{m}}{.}015$), but there exists a phase shift of the order of $0{\cdot}2\,P$ between light curves for these two colors. The extremes of the field do not coincide exactly with the extremes of luminosity (of neither of the curves), but coincide with the extremes of the color index. The phase of maximum temperature coincides with the phase of maximum positive field.

These new results will be published in one of our next papers.

Wrocław Observatory, June 1, 1960.

T. Jarzębowski