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A two-cell photoelectric polarimeter at the Uppsala Observatory used for observations of some magnetic variables and other stars

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ABSTRACT

A photoelectric polarimeter for accurate measurements has been constructed at the Uppsala Observatory. In the first part of this paper a description is given of the instrument and method of observation as well as the accuracy obtained in the observations.

We have chosen to investigate the possible polarization of some bright stars, known to be magnetic variables. A report on these observations is given in the second part of the paper.

Introduction

Polarimetric observations of the light from stars and nebulae are now considered an important complement to other types of astronomical investigations, and polarimeters of different types have been constructed at several observatories. In Uppsala we wanted an instrument which can be used to good advantage in a clima that only seldom offers a perfect sky. Differential measurements with a two-channel polarimeter seems to be the best method to eliminate the influence of small fluctuations in sky conditions during the night.

For similar reasons A. Behr (1956) had constructed a two-channel photoelectric polarimeter at the Göttingen Observatory. When planning our polarimeter we profited from the experiences he had gained with his instrument. The actual design of our equipment in Uppsala differs from Behr's polarimeter in several respects, however, and a description of our instrument therefore seems justified.

The polarimeter

A schematic drawing of the polarimeter, showing the main parts, is given in Fig. 1 and a photograph of the instrument is reproduced in Fig. 2. In our observations the polarimeter has been attached to the visual refractor of the Uppsala Observatory by means of two half-rings R with 12 screws. If later used with another telescope it may easily be attached to a plate or other arrangement fitting into that telescope.

The starlight enters through an aperture A at the focus of the telescope and a free opening at O. If the shutter S is open, the light passes through the lens L (designed to produce an image of the telescope objective on the photocathodes) and the thin plate

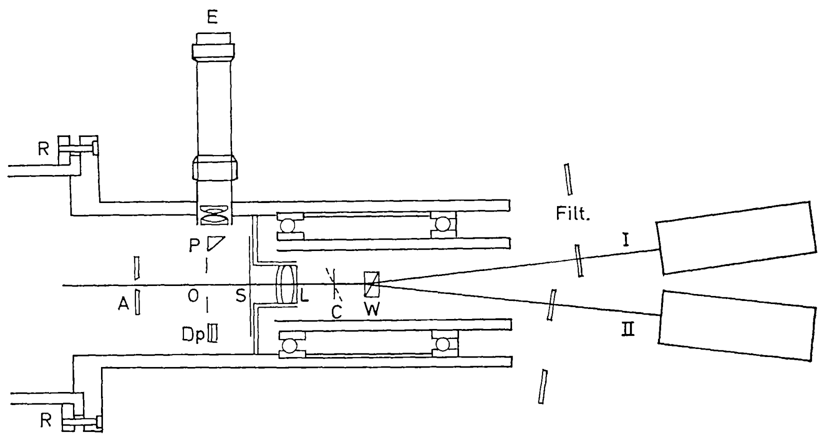


Fig. 1. Sketch of the polarimeter. The outer tube is attached to the telescope. The inner tube can be turned into different position angles. With the inner parts rotate the glass plate, the Wollaston prism, filters and photocells.

of cover glass *C* to the Wollaston prism *W*. There the incoming light beam is split in two plane polarized beams with mutually perpendicular light vibrations. Each beam goes to a photomultiplier. The currents from the two photomultipliers are fed into two (as nearly as possible) identical amplifiers. The resulting voltage difference is indicated on a Brown recorder.

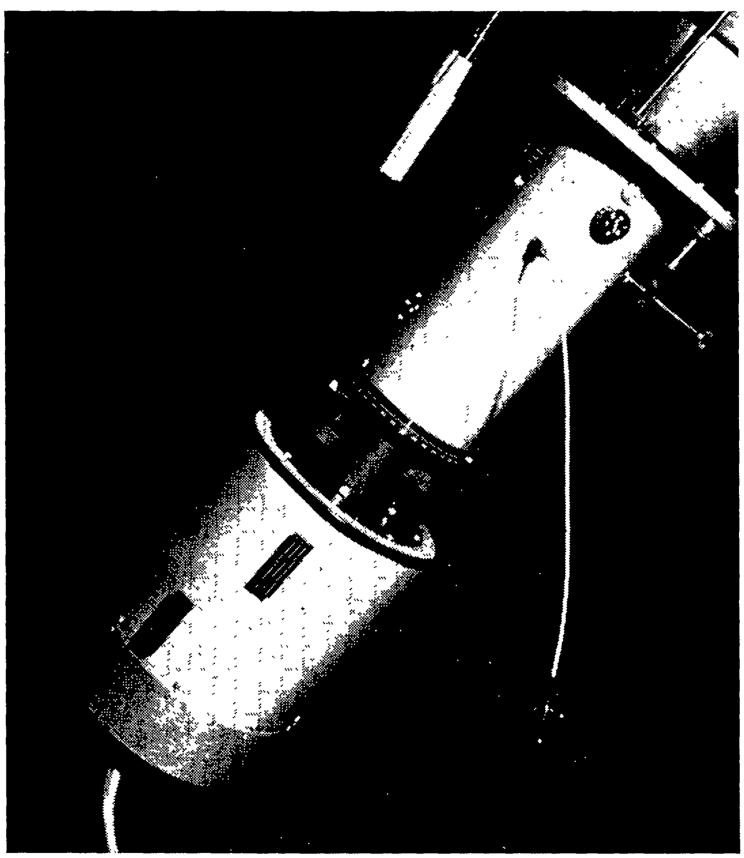


Fig. 2. The two-cell polarimeter attached to the visual refractor of the Uppsala Astronomical Observatory.

If there is no instrumental polarization and if we observe an unpolarized star, the light beams I and II should have the same intensity and the Brown recorder should indicate zero polarization (independent of the position angle of the polarimeter).

If the light from a polarized star passes through the Wollaston prism, the two emerging beams will usually differ in intensity. The intensity ratio of the two beams is a function of the position angle of the Wollaston prism relative to the position angle of the strongest vibration of the polarized light. When the rear end of the polarimeter, including the inner tube with the Wollaston prism, is rotated slowly, the Brown recorder should show a double sine wave for every whole turn (360°). The amplitude of the sine wave depends on the degree of polarization and on the brightness of the star (as well as on amplifier gain etc.). Since no independent measurement of the brightness of the object is obtained with the equipment described here the degree of polarization is calibrated by means of a thin plate of cover glass, *C*, which can be tilted through a certain angle to give a constant degree of polarization. The degree of polarization introduced by this plate is determined empirically by comparisons with a number of well-observed standard stars with known polarization. The zero point of the position angles is calibrated in a similar way.

It is of great interest to study the polarization in different colours. Therefore colour filters are usually inserted in the light path between the Wollaston prism and the photocells. With the present arrangement observations can be made through the Schott filters BG 12, VG 6, or RG 2, or without filters. As ultra-violet light is not transmitted by the telescope lens, no UV filter has been used so far. Other filters may be used later in other investigations, especially when the polarimeter will be used in combination with a reflecting telescope. To make observations with red filters possible a fairly red-sensitive type of cell, EMI 9558 B, has been used.

In place of the free opening *O* a depolarizer *Dp* may be inserted. With the depolarizer in the light path the Brown recorder should show the line of zero polarization. Thus the depolarizer can be used to define the line of zero polarization. The depolarizer and the free opening occupy two positions on a wheel where the third position is held by a prism *P*. The wheel is turned by a knob into one of these three positions. The prism is used to reflect the light beam into an eyepiece *E* to check that the star is centered in the aperture.

Three apertures of different size are used. A large opening is used for finding and centering the star in the field. Then a smaller aperture, 1 or 2 mm in diameter, is used for the measurements. The apertures are mounted on a wheel which can be turned into three different well-defined positions. The apertures now used may easily be exchanged for apertures of other size or form.

The eyepiece mentioned above has also been used during the observations reported here to check the guiding. The light beam is then for a moment interrupted by the prism and the records are disturbed. This causes unnecessary time delay. It is therefore desirable that this eyepiece is used only at the beginning of each series of observations and that another eyepiece is used for the subsequent guiding when necessary. Such an eyepiece has now been built at the observatory. A star in the outer part of the field shall be used for guiding with this eyepiece.

A comparison between the new polarimeter and Behr's instrument

The large ball bearings, connecting the inner, turnable and the outer, fixed parts of the polarimeter were placed at the front end of the Göttingen instrument. We preferred to have the ball bearings in a different place, so that no parts would stick out in front of the outer tube which is attached to the telescope. The new design is also advantageous from other points of view. There is less strain on the bearings when they are placed near the middle of the instrument rather than at the front end. Also the limiting aperture at the focus of the telescope now remains fixed. This will make possible the use of non-circular apertures for special purposes. In Behr's instrument the aperture was rotated with the polarimeter. The same is true for the eyepieces. During the observations we find it preferable that the eyepieces are always situated at the side of the telescope where they can be easily reached.

It should be mentioned, however, that in our instrument the optical parts must be hidden in the closed, cylindrical case, where they are more difficult to reach for adjustments. We have not found it desirable, however, to change anything in the interior of the instrument after it has been completed and tested. It may even be an advantage in some cases that the optical parts are well protected.

The photomultipliers have been placed side by side in our instrument rather than perpendicular to the main axis as in Behr's polarimeter. No reflecting prisms are then needed in the light path. The two cells are also close enough together to be refrigerated in the same cold box if necessary. Refrigeration of the cells is necessary only when the air temperature is fairly high. It has only been used during some observations in September.

Voltage supply and amplifier

The photomultipliers are usually operated at a voltage in the range 1600–1800 volts. The stabilized high voltage supply for the two cells has been built in such a way that a possible small fluctuation in the voltage will affect the two cells simultaneously and in the same way.

Though special care was taken to choose two photomultipliers with as similar characteristics as possible, the tubes always differ somewhat in sensitivity and the difference may change with temperature, applied voltage or colour of the light. In order to compensate for the sensitivity differences two extra resistors have been included in the high voltage supply so as to make possible individual corrections to the voltage of each cell at the beginning of a new series of measurements.

The photocurrents from the two cells are fed into a double amplifier system where each current is amplified separately. The output from the amplifier then gives the difference between the two amplified currents. This difference is indicated on a Brown recorder, as mentioned above.

Method of observation

The equipment is adjusted in such a way that zero polarization is indicated by a line near the middle of the Brown recorder chart. At the beginning of the observations therefore the zeropoint and the relative sensitivity of the two amplifying systems is checked and, if necessary, adjusted. Then the polarimeter shutter is opened and the light from the star to be measured will reach the photocells. The depolarizer is now used to give "zero polarization" so that the right individual corrections to the high voltage on the photocells can be made to bring the Brown recorder pen to the middle of the chart.

Each series of observations consists of deflections with and without depolarizer for 8 settings of the position angle of the instrument (0°, 45°, etc., to 315°). It also includes several measurements with the calibrator in tilted position to indicate the scale of the degree of polarization.

The use of the calibrator C several times during a series of measurements provides a check on the atmospheric transparency, because the deflections due to C should be equally large each time. If they come out significantly different in different parts of a series, this series of observations should be rejected, if a high accuracy is attempted. Corrections may be used for very small systematic differences. The deflection due to C also indicates the scale of the degree of polarization, as mentioned before. The degree of polarization introduced by C may differ somewhat for different colours. Since each series of observations is calibrated by means of C, the results do not depend on changes in weather conditions or any other changes taking place between the different series of observations.

Suggested improvement of method of observations

With the equipment so far available to us the use of C for calibration of the scale of polarization gave the highest possible accuracy. We believe, however, that the accuracy could in many cases be improved considerably, if a more suitable recording system would be used. We hope to get (in the future) a digitized, two-channel integrating system, which would make it possible to record also the brightness of the star in linearly polarized light as seen by the two photomultipliers. Not only will it be possible to increase the readability of the records in this way but it will also be possible in certain cases to relate the intensity variations of a star to possible variations in its degree of polarization. This may be of special importance for observations of variable polarization in the light from certain types of stars, e.g. eclipsing variables, where the variations may be rapid.

Reduction of the polarization measurements

We introduce the following definitions:

Ff = deflection for starlight through the free opening,
Fc = deflection due to additional constant polarization of the starlight introduced by the calibrator plate without depolarizer in the light path,
D = deflection for starlight through the depolarizer,
Dc corresponding to Fc with depolarizer in the light path,
Fs = deflection for sky background without depolarizer,
Fsc = deflection due to additional constant polarization of the sky background.

From the abovementioned deflections, read on the Brown charts, cf. Fig. 3, we deduce the following quantities:

$$f(B) = \frac{Ff - Fs}{Fc - Fsc},$$

$$d(B) = \frac{D}{Dc},$$

$$F(I) = f(B) - d(B),$$

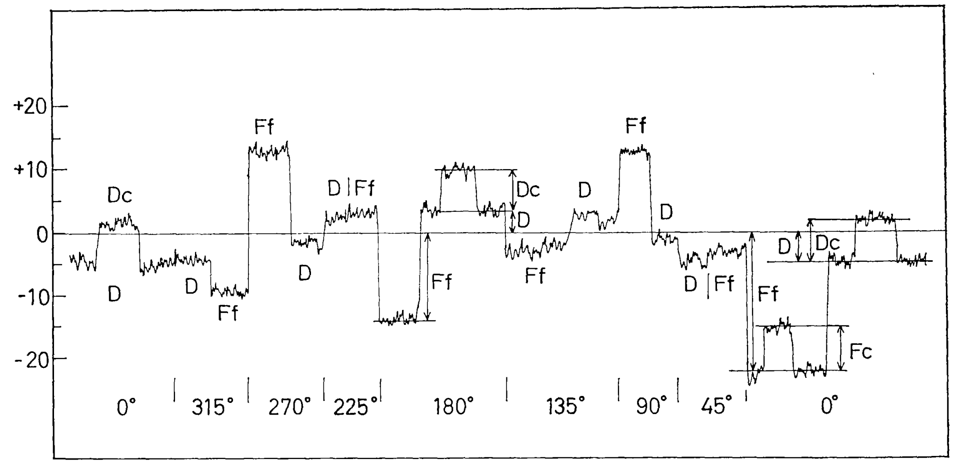


Fig. 3. Brown recorder tracing of polarization measures on HD 21291. Filter VG 6. Nov. 19, 1963. It is shown how the quantities *Ff* and *D* are measured from a straight line in the middle of the record. The final results are not changed, if this line is chosen higher or lower. At the end of the record (*left*) the first measures were repeated as a check on the stability.

where B is the position angle of the analyzer (0°, 45°, etc., to 315°). The parameter I takes the values 1, 2, ... 8, and is related to B through the formula $I = B/45 + 1$.

In order to find the degree of polarization and the position angle of the strongest electric vector, B_0, we solve the equation:

$$A \cos 2(B-B_0)+K=F(I)$$

for A and B_0. Here A is a measure of the degree of polarization (on an arbitrary scale) and K is a correction to the level of zero deflection.

The observed values of quantities mentioned above were fed into the electronic computer IBM 1620, and the following quantities were computed:

$$FM=0.25\ [F(2)-F(4)+F(6)-F(8)],$$

$$FN=0.25\ [F(1)-F(3)+F(5)-F(7)],$$

$$A=(FM^2+FN^2)^{1/2},$$

$$B_0=0.5 \arctan \frac{FM}{FN}.$$

In order to estimate the accuracy of the results, we formed

$$C=-\tfrac{1}{8}\sum_{I=1}^{8}(A \cos 2(B-B_0)-F(I)).$$

For each of the 8 readings in a series of observations the random error v was derived from the formula

$$v=A \cos 2(B-B_0)+C-F(I).$$

Finally the mean error in A, defined as

$$\varepsilon_A = \left(\frac{\sum v^2}{24}\right)^{\frac{1}{2}}$$

was computed.

For each series of observations the IBM machine printed a table containing the observed data and the computed values of A, B_0 and ε_A. In the present work the degree of polarization and the uncertainty in this value are far more important than the accurate value of the position angle. Thus we did not find it worth while to compute in each case the error in B_0. It may be estimated when necessary. (For highly polarized stars it is of the order of $\pm 1°$, part of which may be due to inexact adjustment of the polarimeter when mounted on the telescope.)

In astronomical investigations the degree of polarization is often expressed as a magnitude difference Δm_p, defined as

$$\Delta m_p = 2.5 \log \frac{I_{\max}}{I_{\min}} = 2.5 \log \frac{I(B_0)}{I(B_0 + 90°)},$$

where $I_{\max}$ and $I_{\min}$ stand for intensity of light vibrating in one plane, the total intensity of the starlight observed with the filter in question being $I = I_{\max} + I_{\min} = I(B_0) + I(B_0 + 90°)$. We have $\Delta m_p = X \cdot A$. In order to determine the factor X we observed a number of standard stars, the polarization of which was assumed to be known from previous observations reported in the literature. The stars are listed in Table 2. It may be pointed out that the small uncertainty introduced in our results because of this method of calibration does not influence our results significantly, as will be discussed later.

Since the position angle B_0 corresponds to a certain setting on the scale of our instrument, we also used the standard stars for a reduction of B_0 to the corresponding position angle θ in the equatorial system, counted in the usual way from North over East.

For the three filters we found the following values of the factor X:

Filter	*BG 12*	*VG 6*	*RG 2*
X	0.035	0.032	(0.036)

The small difference between the X values for different filters may not be real, as is seen from the data in Table 2.

Accuracy obtained in the observations

In order to study the performance of the instrument we have observed not only the standard stars and some magnetic variables but also a few other stars, as listed in Table 1. The detailed data for these stars are given in Table 3, after the data for the magnetic variables.

Due to poor weather conditions or other difficulties some series of observations have been given a lower weight than others. The weights are indicated in the tables.

It is of interest to estimate the accuracy that has been obtained with our instrument in the present work before planning other investigations in the future. It is easily seen that the accuracy depends on several conditions which might be divided in the following groups:

Table 1. List of stars observed for polarization.

HD	Star name	1950 coordinates R.A.	Decl.	Sp.	Vis. magn.	Remarks
7 927	ϕ Cas	$1^h16^m.9$	$+57°58'$	F0Ia	$4^m.95$	Standard
21 291	2H Cam	3 25.0	59 47	B9Ia	4.23	Standard
43 384	9 Gem	6 13.9	23 45	B3Iab	6.28	Standard
183 143		19 25.3	18 11	B7Ia	6.93	Standard
198 478	55 Cyg	20 47.2	45 56	B3Ia	4.83	Standard
224 014	ϱ Cas	23 51.9	57 13	F8Iap	4.4	Standard
15 089	ι Cas	2 24.9	67 11	A5p	4.50	Spectr. var.
10 221	43 Cas	1 38.6	68 47	A0(p)	5.59	Magn. var.
18 296	21 Per	2 54.3	31 44	A0p	5.10	Magn. var.
65 339	53 Cam	7 57.4	60 28	A2p	6.00	Magn. var.
71 866		8 27.9	40 24	A0p	6.66	Magn. var.
112 413	α^2 CVn	12 53.7	38 35	B9.5p	2.89	Magn. var.
23 480	Merope	3 43.4	23 48	B6IVnn	4.17	Cluster member
23 512	Hz 371	3 43.6	23 28	A0V	8.09	Cluster member
208 218	NGC 7160–1	21 51.0	62 28	B1	6.69	Cluster member
208 392	NGC 7160–2	21 52.1	62 23	B3	7.04	Cluster member
208 440	NGC 7160–3	21 52.2	62 21	B8	7.90	Cluster member

1. Observing conditions (weather, etc.).
2. Zenith distance of the star.
3. Brightness of the star.
4. Degree of polarization of the starlight.

1. The influence of poor observing conditions on the accuracy of the results is trivial and needs no further discussion. It might only be pointed out that the larger errors in the results from such observations must not be used in the discussion of the accuracy of the instrument. Thus only observations with high weight should be used for this purpose.

2. In the ideal case of perfect equipment (telescope + polarimeter) we should have $d(B) \equiv 0$.

In the actual observations, however, $d(B)$ usually differs from zero, because the deflection obtained with the depolarizer in the light path varies with the position angle B. The cause of such variations has been discussed by Behr (1956). As he points out, the light spots on the photocathodes rotate, when the analyzer is turned around. Further the light spots in their motion will cover slightly different parts of the cathodes, if the axis of rotation of the polarimeter does not coincide exactly with the optical axis of the telescope. Even if the two axes do coincide almost exactly during observations of stars near the zenith, the bending of the telescope tube in observations closer to the horizon will displace the optical axis of the telescope relative to the rotation axis of the polarimeter and thus move the light spots on the cathodes. Because of the variation in sensitivity over the surfaces of the two cathodes, the instrumental effect, denoted by $d(B)$, will be observed. It was evident in our observations that this effect increases with the zenith distance because of the increasing bending of the telescope.

In our method of observation we think that we have to a large extent eliminated

Table 2. Observations of Standard stars.

		Observations in Uppsala					Adopted values			Results	
Filter	HD No.	Obs. Date	A	ε_A	B	Wt	Δm_p	θ	Ref.	X	$B+\theta$
BG 12	183 143	18.IX.63	3.501	±0.098	21°.4	2	$0^m.122$	179°	2	0.0348	20°.4
	198 478	19.IX.63	1.833	0.060	17.4	2	0.058	2	2	0.0316	19.4
	21 291	10.XI.63	2.343	0.116	86.7	1	0.071	115	1	0.0303	21.7
	21 291	19.XI.63	2.020	0.065	84.9	3				0.0351	19.9
	21 291	20.XI.63	1.793	0.053	84.4	2				0.0396	19.4
	21 291	7.XII.63	1.972	0.043	86.8	4				0.0360	21.8
	21 291	18.I.64	1.886	0.033	86.7	3				0.0376	21.7
	21 291	18.I.64	1.821	0.066	87.3	1				0.0390	22.3
	43 384	18.II.64	1.624	0.158	29.1	1	0.053:	172	1	0.0326	21.1
	43 384	16.III.64	1.731	0.059	28.8	3				0.0306	22.8
BG 12		Mean values								0.035	21°
VG 6	224 014	18.IX.63	0.957	0.098	152°.5	1	0.029	55°	3	0.0303	27°.5
	224 014	19.IX.63	1.098	0.050	144.4	3				0.0264	19.4
	7 927	19.IX.63	2.066	0.049	110.6	3	0.072	92	2	0.0348	22.6
	198 478	19.IX.63	1.966	0.092	19.8	1	0.066	2	2	0.0336	21.8
	198 478	20.IX.63	1.974	0.081	18.2	2				0.0334	20.2
	21 291	19.XI.63	2.122	0.040	84.7	3	0.071	115	1	0.0335	19.7
	43 384	16.XII.63	2.024	0.083	30.8	2	0.055	172	1	0.0272	22.2
	21 291	21.XII.63	2.200	0.050	86.6	3	0.071	115	1	0.0323	22.1
	21 291	18.I.64	2.192	0.058	85.0	3				0.0324	20.0
	43 384	6.III.65	1.496	0.144	28.2	1	0.055	172	1	0.0368	20.2
VG 6		Mean values								0.032	21°
RG 2	7 927	19.IX.63	2.259	0.067	111°.6	2	0.057:	92°	2	0.0252	23°.6
	198 478	19.IX.63	1.438	0.023	19.2	3	0.061	2	1	0.0424	21.2
	198 478	20.IX.63	1.633	0.043	17.8	3				0.0374	19.8
RG 2		Mean values								0.036:	21°

References: (1) Gehrels (1960); (2) Martel and Martel (1964); (3) Serkowski (1960).

the influence of this instrumental effect by measuring $f(B)$ and $d(B)$ immediately after each other for each position angle. When the value of $d(B)$ is large we must, however, expect a lower accuracy than for small values of $d(B)$.

3. Most of the stars selected for observation have been bright, mostly around the fifth magnitude for which no sky corrections have been necessary. To test the equipment we have also chosen a few fainter stars down to visual magnitude 8.1. Though for them corrections have been made for the polarization of the sky background, the results are more uncertain. Thus if high accuracy is attempted, stars fainter than about magnitude 7 should not be observed with the present equipment in the city. With a larger telescope and darker sky the limiting magnitude may be greatly increased. We hope to be able to use the polarimeter on the new telescope in Kvistaberg within a few years from now.

4. The present equipment is designed mainly for accurate measurements on objects with a low degree of polarization. Objects with a high degree of polarization can usually be studied with simpler equipment just as well. With our method the accuracy in the observed degree of polarization for highly polarized stars will be set mainly

Table 3. Polarization.

Star and filter	Date	U.T.	Uncorrected P.A.	Uncorrected Pol.	m.e.	Corr. f. instr. pol. Pol.	Corr. f. instr. pol. P.A.	Wt (0–5)
HD 010221	*1963*							
BG 12	Dec. 06	20^h10^m	$41.^{\circ}8$	$0.^{m}0043$	$\pm 0.^{m}0008$	$0.^{m}0011$	$72.^{\circ}3$	4
	Dec. 06	20 45	47.5	0.0051	0.0016	0.0023	70.9	3
HD 015089	*1964*							
VG 6	Jan. 15	20 20	35.7	0.0019	0.0007	0.0008	124.9	4
	Jan. 17	20 50	43.2	0.0044	0.0012	0.0020	52.8	3
	Jan. 18	20 56	38.0	0.0036	0.0011	0.0011	43.1	2
	Jan. 21	19 51	50.6	0.0024	0.0011	0.0014	93.8	4
	Feb. 02	20 53	23.7	0.0040	0.0009	0.0019	5.2	4
	Feb. 05	21 22	17.4	0.0016	0.0008	0.0017	142.4	3
	Feb. 06	21 15	67.7	0.0007	0.0006	0.0025	118.0	4
HD 018296	*1963*							
BG 12	Oct. 24	21 00	22.4	0.0052	0.0013	0.0023	0.5	1
	Nov. 10	23 25	172.0	0.0027	0.0014	0.0046	142.9	3
	Nov. 20	20 49	15.4	0.0042	0.0012	0.0027	163.8	4
	Dec. 07	19 40	15.6	0.0056	0.0015	0.0035	174.0	3
	Dec. 21	19 51	23.1	0.0031	0.0013	0.0016	149.3	1
	1964							
	Jan. 05	17 15	7.5	0.0060	0.0006	0.0049	167.6	5
	Jan. 06	20 40	18.2	0.0016	0.0013	0.0027	134.8	2
	Jan. 08	17 33	8.0	0.0075	0.0011	0.0061	172.7	3
	Jan. 15	18 08	16.2	0.0057	0.0010	0.0035	175.2	3
	Jan. 17	18 53	32.8	0.0042	0.0008	0.0004	10.8	3
	Jan. 18	19 05	18.1	0.0042	0.0009	0.0024	165.6	4
	Feb. 02	18 55	49.5	0.0020	0.0020	0.0024	112.4	0
	Feb. 06	19 10	48.9	0.0055	0.0009	0.0028	70.2	4
	1963							
VG 6	Sep. 09	00 45	28.4	0.0016	0.0020	0.0012	135.2	0
	Oct. 24	23 20	104.5	0.0016	0.0018	0.0040	117.3	0
	Oct. 24	23 56	66.7	0.0016	0.0013	0.0024	106.9	1
	Nov. 10	22 13	15.0	0.0032	0.0007	0.0022	166.4	5
	Dec. 07	18 40	17.3	0.0029	0.0011	0.0018	164.5	4
	Dec. 21	18 54	1.3	0.0046	0.0007	0.0044	163.2	4
	1964							
	Jan. 05	19 00	6.4	0.0049	0.0003	0.0041	168.8	4
	Jan. 06	18 44	149.2	0.0012	0.0012	0.0036	132.0	0
	Jan. 15	19 06	19.6	0.0026	0.0006	0.0015	160.0	4
	Jan. 17	19 53	19.8	0.0024	0.0015	0.0014	156.3	3
	Jan. 18	18 15	126.2	0.0008	0.0016	0.0035	125.1	1
	Feb. 06	18 13	167.5	0.0007	0.0017	0.0029	132.4	0
HD 065339	*1963*							
BG 12	Dec. 17	02 56	46.3	0.0035	0.0021	0.0015	92.3	3
	Dec. 22	00 40	35.3	0.0036	0.0010	0.0003	119.3	4
	1964							
	Jan. 18	00 04	57.4	0.0014	0.0023	0.0031	115.3	0
	Jan. 19	00 03	32.6	0.0013	0.0039	0.0026	126.1	0
	Jan. 21	22 56	59.7	0.0051	0.0019	0.0040	84.3	2
	Feb. 06	23 15	49.9	0.0042	0.0012	0.0021	83.3	3
	Feb. 18	23 08	43.8	0.0076	0.0024	0.0041	52.5	3

Table 3 (*continued*)

Star and filter	Date	U.T.	Uncorrected P.A.	Uncorrected Pol.	m.e.	Corr. f. instr. pol. Pol.	Corr. f. instr. pol. P.A.	Wt (0–5)
	Mar. 14	22^h35^m	$38^{\circ}\!.1$	$0^m\!.0044$	$\pm 0^m\!.0006$	$0^m\!.0007$	$59^{\circ}\!.1$	2
	Mar. 15	19 27	9.7	0.0043	0.0019	0.0035	160.8	2
	Mar. 16	20 55	25.5	0.0032	0.0044	0.0013	150.5	0
	Apr. 01	21 10	42.7	0.0056	0.0019	0.0022	57.6	1
	Apr. 03	21 05	70.8	0.0026	0.0021	0.0039	105.8	2
	Apr. 04	20 58	39.8	0.0044	0.0008	0.0009	64.9	3
	1963							
VG 6	Dec. 17	01 23	23.0	0.0019	0.0010	0.0013	144.7	3
	Dec. 22	00 02	37.7	0.0036	0.0012	0.0009	43.1	4
	1964							
	Jan. 18	00 56	39.8	0.0028	0.0012	0.0004	72.5	3
	Feb. 06	22 20	9.6	0.0019	0.0013	0.0021	146.6	3
	Feb. 19	00 42	35.8	0.0017	0.0017	0.0010	124.8	1
	Apr. 01	19 44	7.1	0.0034	0.0024	0.0030	161.9	1
	Apr. 04	19 55	42.3	0.0028	0.0014	0.0006	78.5	3
	1965							
	Mar. 06	21 35	110.3	0.0205	0.0112	0.0229	111.3	0
	Mar. 06	23 10	141.4	0.0037	0.0029	0.0062	134.1	1
	Mar. 21	20 45	33.9	0.0055	0.0016	0.0028	31.7	3
	Mar. 26	20 25	65.5	0.0016	0.0044	0.0023	106.8	0
	Mar. 30	23 36	29.0	0.0045	0.0027	0.0020	19.1	1
	Apr. 01	23 10	48.0	0.0023	0.0038	0.0011	96.1	0
HD 071866	*1965*							
VG 6	Mar. 26	21 31	59.8	0.0056	0.0028	0.0043	73.2	2
	Mar. 30	21 39	42.6	0.0054	0.0029	0.0029	48.4	1
	Apr. 01	21 26	58.6	0.0030	0.0031	0.0023	87.6	0
	Apr. 01	22 13	31.2	0.0052	0.0021	0.0026	25.8	2
HD 112413	*1964*							
BG 12	Mar. 15	01 07	43.2	0.0040	0.0008	0.0012	82.4	5
	Mar. 19	21 08	35.9	0.0038	0.0008	0.0002	101.2	5
	Mar. 19	22 08	46.9	0.0063	0.0023	0.0032	62.1	3
	Apr. 01	22 25	29.1	0.0039	0.0005	0.0008	167.2	4
	Apr. 03	22 16	39.4	0.0046	0.0004	0.0010	59.9	4
	Apr. 06	22 24	39.5	0.0037	0.0004	0.0006	89.9	4
VG 6	Jan. 18	02 03	28.0	0.0034	0.0006	0.0011	6.7	3
	Mar. 19	22 55	43.5	0.0036	0.0014	0.0012	61.4	3
	Apr. 03	23 34	28.1	0.0025	0.0009	0.0007	157.3	3
	Apr. 06	23 30	37.5	0.0026	0.0006	0.0002	91.2	4
RG 2	Jan. 18	02 48	10.3	0.0054	0.0027	0.0039	173.7	1
	Apr. 04	00 34	28.5	0.0039	0.0018	0.0013	11.7	1
HD 023480	*1963*							
VG 6	Dec. 21	21 30	128.9	0.0063	0.0016	0.0090	127.3	3
	1964							
	Jan. 05	20 36	133.4	0.0051	0.0010	0.0077	130.1	3
HD 023512	*1963*							
VG 6	Dec. 16	21 37	28.3	0.0499	0.0155	0.0473	27.2	0
	1964							
	Jan. 05	21 30	31.7	0.0393	0.0074	0.0367	30.7	0

Table 3 (*continued*)

Star and filter	Date	U.T.	Uncorrected P.A.	Uncorrected Pol.	m.e.	Corr. f. instr. pol. Pol.	Corr. f. instr. pol. P.A.	Wt (0–5)
HD 208218	*1963*							
VG 6	Sep. 20	23^{h}16^m	48°6	0^{m}0304	±0^{m}0050	0^{m}0280	49°1	1
	Nov. 20	17 45	53.3	0.0310	0.0038	0.0288	54.1	1
HD 208392	*1963*							
VG 6	Sep. 20	23 45	43.1	0.0442	0.0023	0.0416	42.9	1
	Nov. 20	18 50	42.4	0.0330	0.0032	0.0304	42.4	1
	Dec. 07	18 35	40.1	0.0381	0.0041	0.0354	39.8	1
HD 208440	*1963*							
VG 6	Sep. 21	01 12	33.1	0.0110	0.0102	0.0083	31.5	0
	Sep. 21	01 36	35.3	0.0172	0.0066	0.0145	34.5	0
	Nov. 20	19 30	50.2	0.0104	0.0060	0.0081	54.1	0
	Dec. 07	18 00	53.4	0.0238	0.0052	0.0217	54.8	0

by the accuracy with which we can read the deflections *Fc* and *Dc*, which tend to be small for such stars. We estimate that the uncertainty in the values of *Fc* and *Dc* will be of the order of 5% of these values. Thus a measured polarization of 0^{m}06 may have an uncertainty of 0^{m}003 in addition to the mean error given in the table and computed from the scatter in the observed values. When the observed polarization is small, the above-mentioned uncertainty becomes insignificant.

The average value of the mean errors computed for the 23 observations given the weight 4 or 5 comes out as 0^{m}0008. This is the accuracy we can expect to obtain with the present equipment under reasonably good observing conditions for stars which are only slightly polarized, as discussed above.

To the uncertainties just mentioned must be added also the uncertainty introduced in the results because of possible effects of instrumental polarization arising in the telescope and therefore not eliminated by means of the measurements with the depolarizer.

Effects of instrumental polarization can be found only after extensive observational data have been analyzed. The observations reported here indicate the presence of a small instrumental polarization of the order of 0^{m}0040 in the blue region and 0^{m}0030 in the yellow region with the position angle of the strongest electric vector about 35°.

It may be pointed out that a constant instrumental polarization does not influence the variations of the polarization which we have tried to study for the magnetically variable stars.

Observations of some magnetic variables

It has been shown by H. W. Babcock (1958) that many peculiar *A* type stars have strong and variable magnetic fields. Many of the stars he has investigated have been studied photometrically by Jarzebowski, Provin, Rakos and others, and periodic variations in brightness and colour have been found. G. Thiessen (1961) also reported variations in polarization for the star HD 71866 of the same period as the variation

Table 4. Photometric observations of HD 18296.

Magnitudes relative to the average magnitudes of HD 18449 and HD 17361.

Date J.D.	Yellow (Δm_G)	Blue (Δm_B)	Date J.D.	Yellow (Δm_G)	Blue (Δm_B)
2438			2439		
670.465	0^m247	-0^m864	041.409	0^m245	-0^m870
672.508	0.218	−0.890	041.481	0.242	−0.874
672.606	0.221	−0.871	041.574	0.235	−0.872
673.464	0.250	−0.854	041.659	0.236	−0.872
690.340	0.250	−0.851	045.452	0.236	−0.871
706.232	0.234	−0.856	045.521	0.241	−0.871
706.373	0.240	−0.862	069.452	0.248	−0.859
706.439	0.243	−0.874	069.524	0.244	−0.862
706.508	0.242	−0.867	069.624	0.243	−0.854
744.209	0.248	−0.866	075.590	0.245	−0.870
822.322	0.216	−0.873	088.338	0.245	−0.839
			116.508	0.225	−0.855

These magnitude differences are on the Uppsala system. They may be transformed to the UBV system by the formulae $\Delta V = \Delta m_G + 0.144$, $\Delta B = \Delta m_B + 0.046$ (Häggkvist and Oja, 1966).

in brightness and magnetic field. His work indicated that polarization measurements on magnetic variables may be of interest.

Some measurements of this kind were made by N. S. Polosukhina (1963) who found very rapid, irregular variations amounting to 1.0 or 1.5 per cent of polarization in the light from the star HD 215441, which is known to have an extremely strong magnetic field (Babcock, 1960). Recently, however, R. R. Zappala and W. A. Hiltner (1966) have reported negative results in their careful search for polarization in the light of HD 215441 as well as HD 71866 and several other stars.

We have tried to study the polarization of light from a number of stars known to have moderately strong magnetic fields. The results of our observations, mainly during the winter 1963–1964, are listed in Table 3. Our data indicate that the polarization of light from these stars always remains quite small. It is indeed difficult to tell whether there is any polarization due to the magnetic properties of the star or whether the variations in the polarization indicated in some cases are significant or not.

As it may be assumed that small variations in the polarization, if real, would be related to variations in the brightness and magnetic field of the same star, we have tried to find such relations. Unfortunately, no simultaneous observations have been made of the different quantities to be related. In the case of irregular variations no relation can thus be studied. In the case of periodic variations a relation may be found, if it exists, provided that the period has not been changing with time.

Special attention was paid to the star 21 Per, HD 18296. K. D. Rakos (1962) has studied this star photometrically and determined the period of brightness fluctuations in blue and yellow light. More recent observations in the ultraviolet made him believe that the period may decrease with time (1964, private communication). Therefore, a series of photometric measurements on this star were started in the fall of 1964 in Uppsala. We are much indebted to Dr. T. Oja, Dr. B. Ljunggren and Mr. L. Häggkvist for including this star in their observational programs. The data

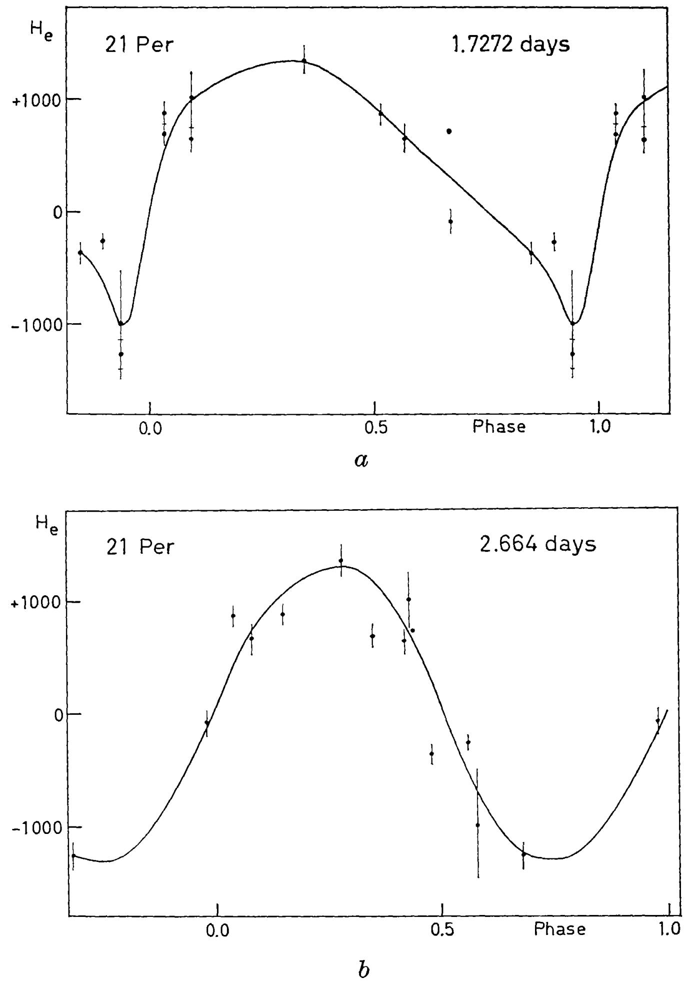
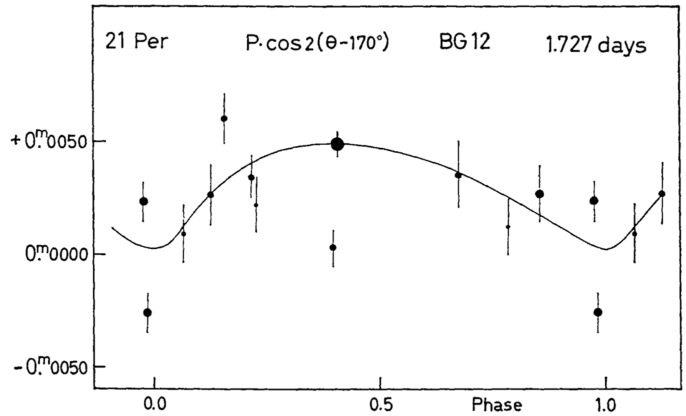


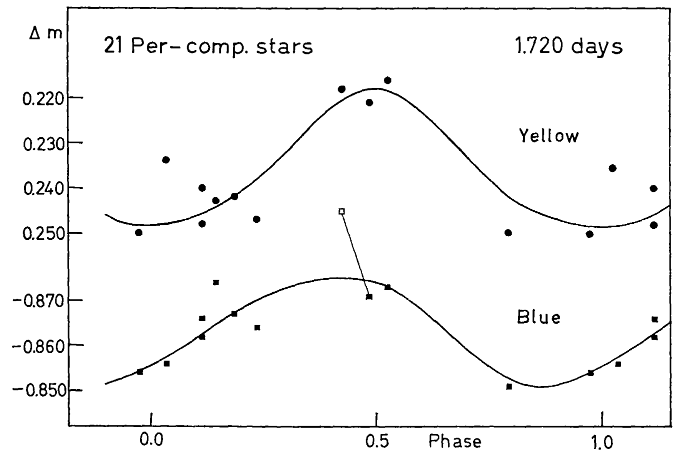
Fig. 4*a* and *b*. Possible periodical variations in the magnetic field of HD 18296, 21 Per. Data from Babcock (1958; and private communication). The period 1.7272 days is not far from the period of brightness variations observed by Rakos (1962). The longer period represents the magnetic data better, although some of the additional observations (Babcock, 1958), for which only the polarity of the field has been published, seem to disagree with both curves.

obtained by them are listed in Table 4. The stars 24 Per and 39 Ari were used as comparison stars. These data indicate that the brightness of 21 Per varied with a period of 1.720 days, slightly less than the period of 1.729 days obtained by Rakos four years earlier. The Uppsala data are, however, based on a much smaller number of observations and are thus less accurate than those obtained by Rakos.

Dr. H. W. Babcock has kindly sent us detailed data about the times of observation of the magnetic field of 21 Per corresponding to the values published in his catalogue of magnetic stars (1958). From those observations, for which the strength of the magnetic field was published, we have derived some possible periods, as shown in Fig. 4. In the catalogue, however, there are several observations reported, for which only the polarity of the magnetic field but not its strength has been given. Some of these observations do not seem to fit into any of the periods considered here. This may be an indication that the field variations are not regular, although a limited number of observations may be represented fairly well by curves like those shown in Fig. 4.



c



d

Fig. 4*c*. The observed polarization vector in position angle 170° is plotted as a function of phase, assuming a period of the same length as in Fig. 4*a*. A small (periodic?) variation in polarization is indicated but is perhaps not significant.

d. Brightness variations according to photoelectric observations in Uppsala from October 1, 1964 to March 2, 1965. With the amplitudes of the variations being only a few times the mean errors of the magnitudes the computed period is uncertain. A thin line connects two measures of the blue magnitude obtained during the same night, one of which has been given a lower weight. Photoelectric data obtained during October–December, 1965, also given in Table 4, were not plotted in the figure. Yellow magnitudes obtained 1965 fit in well with the curve in Fig. 4*d*. Blue magnitudes, on the other hand, seem to disagree.

Our search for suitable periods was much facilitated by the use of an electronic computer. We are much indebted to Mr. Y. Ekedahl, who kindly helped us with a program he had written for investigations of periodic variations.

Finally we have tried to find some relation between the periods indicated in the variations of brightness and magnetic field strength and the small variations probably present in the polarization of light from 21 Per. We did not find the polarization data well represented by any period in the range expected from the photometric observations discussed above. Thus the small variations found in the polarization are either statistically insignificant or they are not related to the other types of variations. In order to give some idea of the amplitudes in the variations compared to the mean error in a single observation, as defined above, we have plotted the polarization vector in the position angle $\theta = 170°$ (approximately the angle of maximum polarization) as a function of phase, assuming the period to be 1.727 days. A small change in period does not change the picture very much in this case where the observations were obtained within a fairly short time (see Table 3).

The observations of HD 112413 indicate practically constant polarization of $0^{m}_{.}0040$ in blue light and $0^{m}_{.}0030$ in yellow light with the position angles in the interval $35° \pm 10°$. This constant polarization may be due to either interstellar polarization or an instrumental effect, arising perhaps in the lenses of the telescope. In order to decide whether this effect is due to the instrument or to interstellar polarization we studied the average polarization observed for several stars. Table 3 shows that position angles around 35° are also common in the results for HD 65339, 15089 and 10221. For these stars the main contribution to the observed polarization may thus consist of instrumental polarization, as it seems less probable that all these stars, in different parts of the sky, would show interstellar polarization of approximately the same amount and direction. Assuming the above-mentioned constant polarization to be an instrumental effect we have subtracted it from the original data. Such reduced data are given to the right of the original data in Table 3. Between the observed and reduced magnitudes are given the mean errors as defined above.

It may be pointed out that the influence of a constant instrumental polarization does not change the conclusions concerning possible variations in the polarization, which we have tried to study.

Except for a few uncertain values of very low weight, to which no attention should be paid, the degree of polarization we observed for the magnetic variables remains very small and seldom exceeds the mean error. Thus we conclude that within the accuracy of the observations there is no polarization of the light from these stars, with the possible exception of HD 18296, discussed above.

Observations of some stars in clusters

Mainly in order to test the equipment for some stars considerably fainter than the magnetic variables included in the main program we observed three stars in the cluster NGC 7160 and the star HD 23512 in the Pleiades cluster. The star Merope, HD 23480, in the same cluster was observed mainly because the small polarization of the light from this star is of interest in the discussions of the polarization of the nebulosity around it (Elvius and Hall, 1966).

The observations of the faint stars are all of low accuracy. Even so, however, it seems possible to draw one interesting conclusion concerning the three stars in NGC 7160.

HD 208440, which is the star 7160-3 in the catalogue by Hoag, Johnson, Iriarte, Mitchell, Hallam, and Sharpless (1961), is definitely less polarized than the stars 7160–1 and 7160–2. This has been confirmed by later observations made with the same equipment but not reported here.

This difference in interstellar polarization is in good agreement with the difference in interstellar reddening indicated by the photometric data of Hoag *et al.* (1961). The difference is, however, unexpected when the very small angular distance (about 2 minutes of arc) between the stars 2 and 3 is considered. The additional amount of interstellar reddening and polarization observed for the stars 1 and 2 may indicate that these two stars are somewhat more distant than the star 3. The stars 1 and 2 have previously been observed by J. S. Hall (1958) who reported for HD 208218 0.025 and for HD 208392 0.029 magnitudes of polarization, for both stars in position angle 44°. The third star has not previously been observed for polarization as far as we know.

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The cold box, including voltage dividers for the photocells, was built at the Uppsala Astronomical Observatory. The high voltage supply and the amplifier were built at the Institute of Electronics at the Uppsala University (Statens Naturvetenskapliga Forskningsråds Elektroniktjänst).

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