A STUDY OF THE SPECTRUM AND MAGNETIC VARIABLE STAR HD 125248

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Summary

The relationship between variability in line intensity, radial velocity, magnetic field, and luminosity of HD 125248 is examined. Using the period 9·295 days given by Deutsch for the spectrum changes, the radial velocity measurements made by Morgan in 1931 are analysed. These measurements suggest a radial velocity variation of approximate amplitude 13 km./sec. with zero velocity when the *Eu* II lines have their maximum intensity. Thus the velocity zeros occur when the magnetic field variation discovered by Babcock has its extreme values. Photometric measurements leading to the light curve of the star are described. An harmonic analysis shows the light variation to be symmetrical about the maximum, the first and second harmonics being the principal terms. The elements of the light variation are

$$\text{Light maximum} = \text{JD } 2433\ 103{\cdot}95 + 9{\cdot}295E,$$

the maximum occurring when the *Cr* II lines have their greatest intensity. The light maximum occurs when the magnetic intensity of the polar field is −6500 gauss, and the minimum when the field is +7800 gauss. The amplitude of the light variation at the effective wave-length 4000 A. is consistent with a colour temperature change from maximum to minimum light of about 250 deg. K., corresponding to a gradient change of about 0·01. No change in colour has so far been detected.

1. The spectrum of HD 125248 (BD −18° 3789 Vir) has been analysed by Morgan (1) who discovered large changes in the absorption line intensities. The lines due to ionized europium were found to exhibit periodic variations in intensity out of phase with somewhat similar variations in the lines due to ionized chromium. The neutral chromium line λ 4254 was found to vary with the *Cr* II lines with a range of variation about the same as the strongest *Cr* II lines λλ 4242, 4269 and 4558. The most marked *Eu* II intensity variation was shown by λ 4205. An unidentified line at λ 4296 was found to vary in phase with the *Eu* II lines. Possible changes in the lines of *H* and *Mg* II were also noted.

The line intensity variations were later studied in detail by Deutsch (2) who found the elements of the variation to be

$$Eu\,\text{II maximum} = Cr\,\text{II minimum} = \text{JD } 2430\ 143{\cdot}07 + 9{\cdot}295E.$$

In addition to the above-mentioned changes in the spectrum the lines of *Ca* II K and *Mg* II λ 4481 were found to vary with *Cr* II, and lines of *Si* II and *Fe* II probably with *Cr* II also. Deutsch found an abrupt change in the spectrum near the phases $0^{P}{\cdot}2$ and $0^{P}{\cdot}8$ after *Eu* II maximum, the minimum being flat while the maximum is more rounded. He concludes that the line intensity variation is certainly anharmonic.

Somewhat similar spectrum variability is shown by α^2 Canum Venaticorum (HD 112413) and has been studied comprehensively by Struve and Swings (3). This star shows the same out-of-phase variation between the *Eu* II and *Cr* II lines as in HD 125248, but the range of variability with a period of 5·469 days is much greater, the *Eu* II lines increasing from invisibility to an intensity which places them amongst the most conspicuous lines in the whole spectrum.

2. Morgan found that the line intensity estimates from twelve plates were satisfied by a period of 3·18 days, but the radial velocity measures assembled on this period did not give any certain evidence of periodicity. However, the scatter in the measures appeared to be much larger than it should be if the velocity were constant. We have found that when the phases of Morgan's radial velocity measurements are calculated with the revised period given by Deutsch, there is then definite evidence of variability. Weighting the measures in his 1931 series, according to plate quality, we have made a least squares solution for the radial velocity in the form

$$V = v + a \sin\theta + b \cos\theta,$$

where $\theta = 2\pi \times$ phase, and phase zero $=$ *Eu* II maximum. Twelve equations of condition gave

$$v = -2{\cdot}4 \pm 1{\cdot}2 \text{ (p.e.)}, \qquad a = 12{\cdot}6 \pm 2{\cdot}0, \qquad b = 1{\cdot}6 \pm 1{\cdot}4.$$

We conclude that there is evidence for a sine variation of amplitude about 13 km./sec., the variable component of the velocity being zero when the *Eu* II lines are a maximum.

It is not clear to which lines Morgan's radial velocity measures refer, and consequently the variation suggested is to be regarded as tentative in view of the fact that the velocity measurements of Struve and Swings (3) for α^2 C Ven show a complex state of affairs. The rare earths and some other elements of low ionization potential give a shallow minimum and a sharp maximum with zero velocity roughly in phase with the *Eu* II line intensity maximum; *Cr* II and some other elements give two maxima in the radial velocity per period, whilst *Mg* II, *Si* II, *H* and *Ca* II show no appreciable variation. Babcock (4) has indicated that in HD 125248 there are systematic changes in radial velocity with phase for three groups of elements characterized by the rare earths, iron and chromium, but that the differences between the various elements are small. For the purpose of the discussion in Section 5 we shall make use of our analysis of Morgan's measures which suggest an amplitude of about 13 km./sec. with zero velocity at the *Eu* II maximum.

3. The investigations of Babcock (5) on magnetic effects in stellar spectra have made it possible to measure the intensity of the polar field from a study of the Zeeman effect in the spectrum lines. The displacement δ of the centre of gravity of a normal Zeeman triplet blend when observed with a circular analyser is interpreted in terms of the surface field due to a magnetic dipole at the centre of the star. The Zeeman effect integrated over the visible hemisphere has been calculated by Babcock for the case of a star with limb darkening coefficient $u = 0{\cdot}45$, the magnetic axis and the line of sight being coincident. The integrated displacement, obtained partly by numerical methods, is given as $\delta = 0{\cdot}311 aH_p$, where aH_p is the displacement at the pole. The integrated Zeeman effect for a star viewed at any angle to the magnetic axis has not yet been given. In view of the possibility that the magnetic axis may be inclined to the axis of rotation, as in

the Earth and the Sun, we have given in an appendix to this paper a brief consideration of the case of a star with a linear law of darkening ($1-u+u\cos\theta$) viewed at any angle α to the magnetic axis. The integrated displacement is found to be given by

$$\delta(\alpha, u) = a\frac{M\cos\alpha}{10R^3}\cdot\frac{15+u}{3-u},$$

where R is the radius of the star and M the moment of the magnetic dipole at the centre of the star giving rise to the polar field $H_p = 2M/R^3$. We conclude that a star whose surface field is due to a dipole of magnetic moment M at its centre, when viewed at an angle α to the magnetic axis, gives an integrated Zeeman effect due to a dipole of moment $M\cos\alpha$.

If the axis of rotation of the star makes an angle ρ with the line of sight and an angle β with the magnetic axis the value of α at any phase of the rotation is given simply by

$$\cos\alpha = \cos\rho\cos\beta + \sin\rho\sin\beta\cos\theta,$$

where $\theta = 2\pi \times$ phase. The variation in the displacement has been computed for a variety of conditions in order to demonstrate the order of magnitude of the magnetic variability which the movement of the magnetic axis simulates.

Babcock (**6**) has found that the magnetic field of HD 125248 is not only variable but reverses its polarity. The magnetic variation with period 9·3 days takes place in synchronism with the spectrum variations described in Section 1, showing a maximum polar field strength +7800 gauss in phase with the maximum in the *Eu* II line intensity, and a polar field −6500 gauss when the *Cr* II lines are strong. Zeros in the field occur approximately when the *Eu* II and *Cr* II lines are about the same intensity. Although the effect described in the preceding paragraph and illustrated in Fig. 1 may well be of importance in some cases of magnetic variability, as has already been suggested by Babcock (**4**), the reversal in polarity in HD 125248 and the fact that the spectrum lines show only about half the rotational broadening due to a nine-day rotation, suggest that the magnetic changes in this case are intrinsic variations of the surface field.

4. A photometric study of HD 125248 has been made at the Commonwealth Observatory with a view to detecting changes in the luminosity of the star. The investigation was undertaken following Dr Babcock's discovery of magnetic variability, a phenomenon which seemed to cast some doubt on the proposed relationship between angular momentum and magnetic moment. A preliminary announcement has been made by the writer (**7**) of the discovery of a small but well-defined light variation of range $0^{\mathrm{m}}{\cdot}053$ with a period of 9·3 days. The observations were made with the Oddie Refractor (nine inch), and a 1P21 electron multiplier photometer which has been already described (**8**).

A survey of possible comparison stars for HD 125248 indicated the suitability of HD 124683, a star which combined the convenience of proximity with the virtue of constancy, and in addition was only one subclass different in spectral type from that of the variable. Table I gives the results of the photometric observations. Each comparison made consisted of five readings on HD 125248 taken between two sets of five readings on the comparison star. The magnitude differences HD 125248 minus HD 124683 for the night were averaged and the probable error determined, the mean epoch of the comparisons for each night being reduced to heliocentric Julian Day. A glance at the second and fifth columns in Table I shows the continuity of the observing. The light variation was followed through eight periods in the twenty-six observing nights finally adopted for the determination of the light curve.

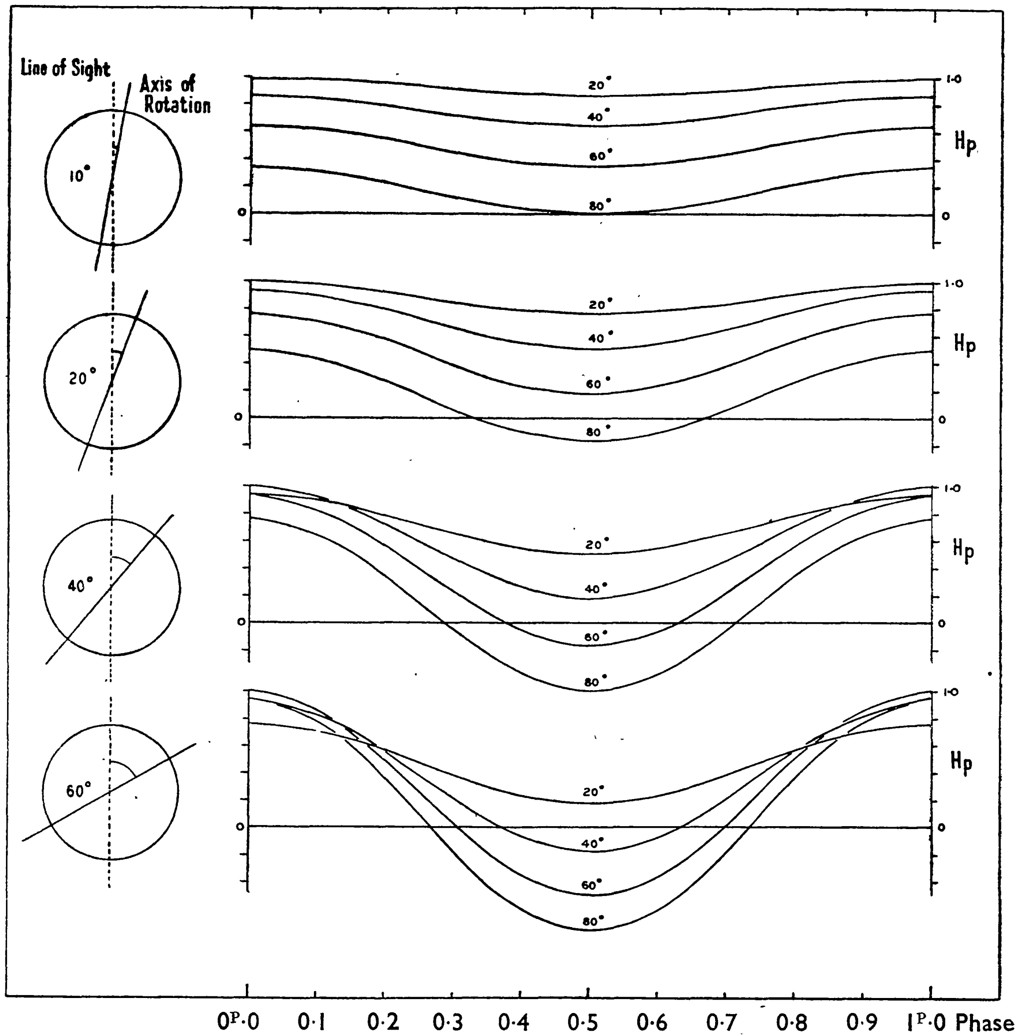

FIG. 1.—*Apparent magnetic variations during the rotation of a star when viewed obliquely to the axis of rotation, the magnetic and rotational axes not being coincident. The four curves shown for each inclination to the line of sight are for co-latitudes* 20°, 40°, 60° *and* 80° *of the magnetic pole.*

The well-defined nature of the variation shown by the preliminary light curve (7) strongly supports the nine-day period as the period of light variability. However, Deutsch has drawn attention to the possibility that a period of the order of the reciprocal of his adopted period is not entirely ruled out by the spectrum measurements, although the use of periods near one day does give an appreciably greater scatter in his assembled observations. But the photometric measurements enable us to reject this possibility because a period of order one day would give a maximum rate of change of brightness of about $0^{m}\cdot01$ per hour, and throughout an observing period extending over two to three hours at the epoch of maximum rate the residuals should readily show an effect. An examination of the behaviour of the residuals throughout each night's observations shows that in no instance do they have a definite trend and furthermore the expected effect is between ten and twenty times the probable error in the mean magnitude

TABLE I

Photometric Observations

Number of comparisons	Mean epoch of comparison JD 2433100·0+	Mean magnitude difference HD 125248 —HD 124683	Number of comparisons	Mean epoch of comparison JD 2433100·0+	Mean magnitude difference HD 125248 —HD 124683
17	6·928	0·355±002$_0$	18	40·910	0·314±000$_6$
15	7·933	·367±001$_0$	22	41·898	·318±000$_8$
14	8·950	·368±002$_2$	18	42·929	·339±001$_0$
11	9·994	·363±001$_6$	19	44·913	·362±001$_1$
10	18·991	·364±000$_8$	30	45·900	·365±000$_8$
17	23·927	·330±000$_8$	13	47·906	·352±001$_0$
9	26·927	·369±000$_8$	19	49·881	·321±000$_9$
12	28·893	·359±000$_6$	18	50·883	·317±000$_6$
10	33·894	·345±001$_8$	9	53·923	·364±002$_2$
17	34·895	·358±001$_1$	15	58·890	·320±000$_8$
21	35·916	·366±001$_0$	15	59·898	·314±000$_9$
20	37·927	·359±000$_8$	10	75·887	·353±002$_0$
12	39·885	0·325±000$_8$	14	76·884	0·332±002$_0$

difference for the night. The twenty-six mean points have therefore been combined into a composite curve on the basis of the period of 9·295 days given by Deutsch for the spectrum variations. The resulting light curve is shown in Fig. 2, the epoch of maximum light being JD 2433 103·95 with an estimated probable error of ±0·15 days. Table II gives the points on the light curve in order of increasing phase, zero phase being at light maximum. The magnitude difference Δm measured from maximum light is converted into light intensity on the basis of maximum light equal to unity.

TABLE II

Light Curve

Phase	Light intensity	Δm	O–C	Phase	Light intensity	Δm	O–C
P		m	m	m		m	m
0·019	1·0000	0·000	0·000	0·513	0·9541	0·051	+0·002
·049	·9972	·003	− ·001	·538	·9514	·054	− ·001
·083	·9963	·004	+ ·002	·618	·9550	·050	− ·001
·149	·9826	·016	+ ·001	·650	·9558	·049	− ·002
·194	·9772	·025	+ ·001	·655	·9594	·045	+ ·001
·222	·9718	·031	− ·001	·684	·9594	·045	− ·001
·320	·9629	·041	+ ·003	·729	·9655	·038	·000
·329	·9603	·044	+ ·001	·739	·9646	·039	− ·003
·376	·9550	·050	− ·001	·847	·9835	·018	·000
·407	·9568	·048	+ ·003	·866	·9900	·011	+ ·003
·428	·9523	·053	− ·001	·911	·9945	·006	+ ·001
·439	·9532	·052	·000	·942	·9936	·007	− ·004
0·472	0·9506	0·055	−0·002	0·976	1·0000	0·000	0·000

A preliminary harmonic analysis of the light variation showed that the coefficients of the sine terms were negligible, only the first three harmonics appearing in the cosine series. Accordingly a least squares solution was made for the coefficients in the equation

$$l = a + b\cos\theta + c\cos 2\theta + d\cos 3\theta,$$

where $\theta = 2\pi \times$ phase. Taking the observations to be of equal weight we find

$$a = 0{\cdot}9722 \pm 0{\cdot}0002 \text{ (p.e.)}, \qquad b = 0{\cdot}0234 \pm 0{\cdot}0003,$$
$$c = 0{\cdot}0039 \pm 0{\cdot}0003, \qquad d = 0{\cdot}0005 \pm 0{\cdot}0003.$$

The mean light per cycle is of course the constant term in the cosine series. The curve drawn amongst the observations is the light variation given by the harmonic analysis. The residuals O–C in Table II are given in magnitude difference.

The elements of the light variation are

$$\text{Light maximum} = \text{JD } 2433103{\cdot}95 + 9{\cdot}295\, E,$$

the light minimum being 0·9522, and the corresponding magnitude difference from the maximum being $0^{\mathrm{m}}{\cdot}053$ in an effective wave-length of 4000 A. approximately.

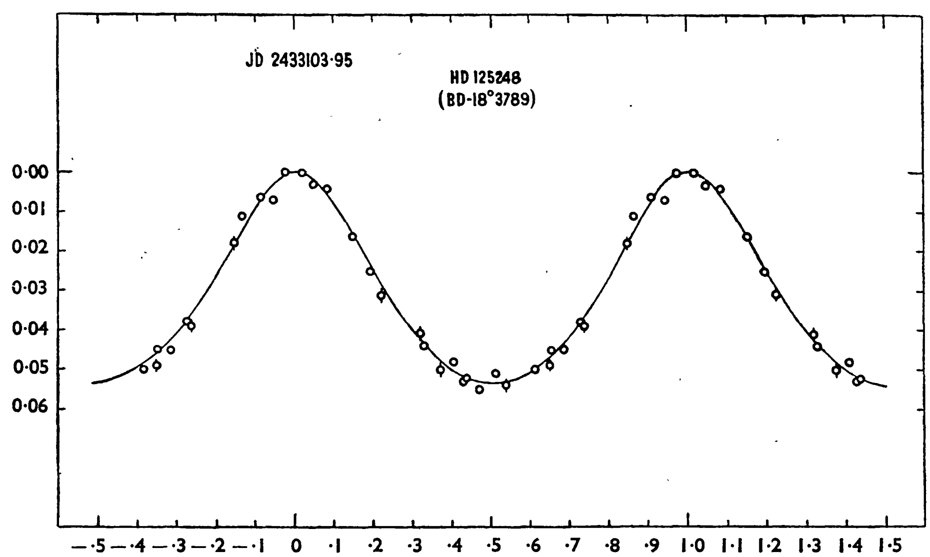

FIG. 2.—*HD* 125248 *light variability.*
Probable error of $0^{\mathrm{m}}{\cdot}001$ *is indicated by the circles. Mean points for which the p.e. exceeded this amount are indicated.*
Ordinates: Magnitude difference.
Abscissae: Phase in period units.

5. We now discuss the relationship between the variation in line intensity, radial velocity, magnetic field and luminosity outlined in the preceding sections. From the elements of Deutsch for the variation in line intensity given in Section 1, and with $E = 318$ periods we find

$$\mathit{Eu}\,\text{II maximum} = \mathit{Cr}\,\text{II minimum} = \text{JD } 2433098{\cdot}88$$

for the extrapolated epoch of zero phase. Comparing this epoch with that of the light maximum in Section 4 we find that the phase of the light maximum with respect to the *Eu* II variation is $0^{\mathrm{P}}{\cdot}55$. Thus the moderately sharp light maximum occurs approximately when the *Cr* II lines have their maximum intensity, and the somewhat shallow light minimum occurs at the *Eu* II maximum. Fig. 3 gives the relationship between the several types of variation. The spectral characteristic given in the figure is that derived by Deutsch from Morgan's 1931 intensity estimates; the radial velocity variation refers to the same epoch but the phase of the light variation has been derived as above, by extrapolating Deutsch's period to the present time. To gain some idea as to the accuracy of the period $9^{d}\cdot295$ we notice that the epoch of maximum in the spectral characteristic which Deutsch derived from Morgan's estimates is located at JD 2426367·90, whereas the later observations in 1944/5 by Deutsch give the epoch of *Eu* II maximum at JD 2430143·07. If 406 periods have elapsed between these two values of epoch we obtain $P = 9^{d}\cdot298$. Now an uncertainty in the period as great as $\pm 0^{d}\cdot003$ would give an error of $\pm 0^{d}\cdot95$ in the present epoch of *Eu* II maximum obtained by extrapolation from JD 2430143·07 to the present time by means of 318 periods. Hence the uncertainty in the location of the phase of the light maximum with respect to the *Eu* II variations would be $\pm 0^{P}\cdot10$.

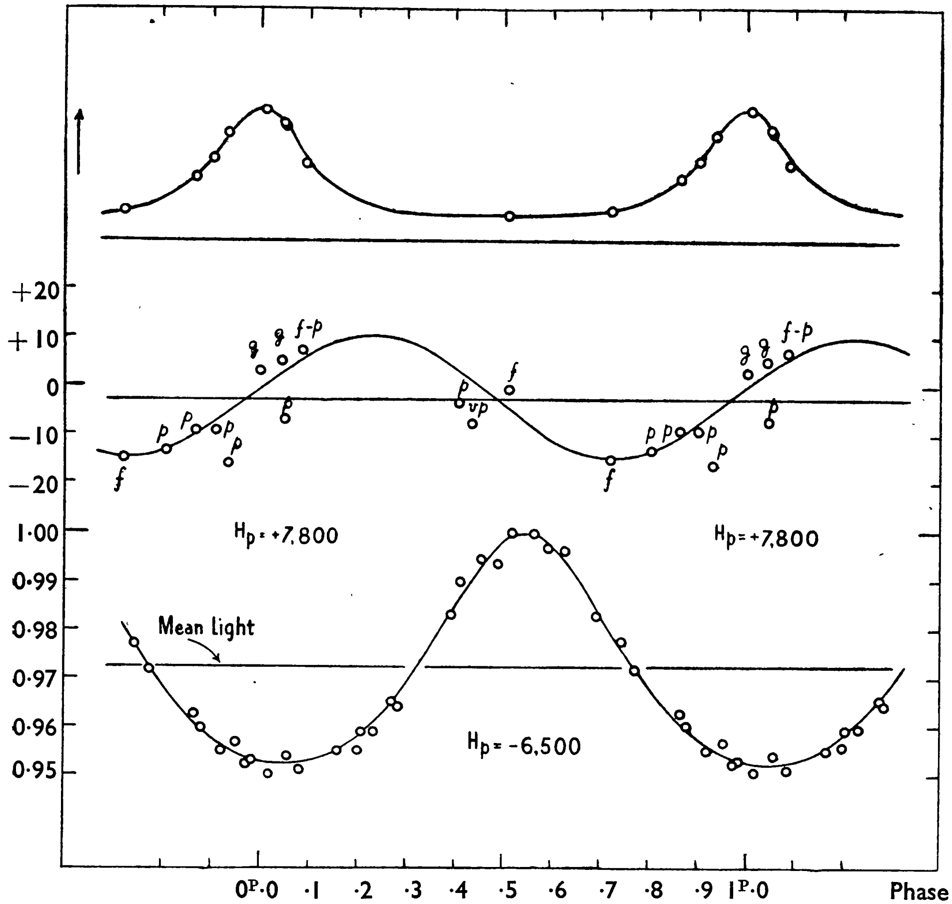

FIG. 3.—*HD* 125248. *Variability in line intensity, magnetic field and luminosity.*
Upper curve: *Special characteristic. Eu II strong.*
Middle curve: *Radial velocity (km./sec.).*
Lower curve: *Light intensity.*

Comparing the light variation with the radial velocity measures discussed in Section 2 we see that the light maxima and minima occur at phases of zero velocity. The magnetic variations described in Section 3 have their extreme values at the radial velocity zeros. Although Babcock (4) has pointed out that the values of H_p quoted have a probable error of about a kilogauss, it is nevertheless interesting to notice that the pulses in luminosity of the star take place during the apparently smaller variation in negative H_p. Thus the magnetic energy of the star during the light maximum seems to be less than during the shallow light minimum when the apparently larger variation in positive H_p gives a larger magnetic energy of the star.

A theory of magnetic variability in stars has been given recently by Schwarzschild (**9**) in an investigation of the magneto-hydrodynamic oscillations which can take place in a non-rotating star composed of homogeneous incompressible matter with infinite conductivity. This idealized star is considered to have a permanent magnetic field on which is superimposed a small variable component h. The modes of oscillation investigated are those in which the vector potential of the solenoidal stream velocity is symmetrical and anti-symmetrical with respect to the equatorial plane. These are called the even mode and the odd mode respectively. In the even mode the oscillatory component of the magnetic field has the character of a reversing quadrupole, and in the odd mode the field behaves like a reversing dipole. In both modes the zeros of stream velocity * occur at the phases of the amplitude maxima of the variable field. Although the theory in its present form is severely simplified it is interesting to note the agreement of the theory with the coincidence of the phases of zero velocity and the magnetic field maxima as found above for HD 125248.

We now examine some consequences of the light variability given in Section 6. We suppose that the luminosity of the star in the wave-length λ is given by $L_\lambda \propto R^2 B_\lambda(T)$, where R is the radius and $B_\lambda(T)$ the Planck Function. Since the photocell admits a fraction f of the intensity of radiation at the effective wave-length λ_e, the photometric measures in Table II give this reduced intensity $l = fL_{\lambda e}$ in terms of the maximum light as unit. If we neglect changes in the radius, thereby supposing that variations in the luminosity are brought about only by changes in T, we find

$$-\log_e l \sim \frac{hc}{k\lambda}\left(\frac{\Delta T}{T^2}\right).$$

With $T = 14{,}000$ deg. K. as the colour temperature for spectral type A0 the change ΔT in colour temperature required to account for the observed variations in luminosity at wave-length 4000 A. amounts to about 250 deg. K., the star being bluest at maximum light.

According to Struve and Swings (**3**) a change in colour temperature of about 2000 deg. K. has been found by Nikonov and Brodskaja (**10**) in α^2 C Ven, the star being bluest when the total light is a minimum. It should be pointed out that a colour temperature change of 2000 deg. K. would give a change of approximately 0·10 in the relative gradient. One should expect that a change in gradient by an amount as large as this would have shown up in the Greenwich gradients (**11**). But such an effect does not appear in the measurements, in fact α^2 C Ven is taken as one of the standard stars. More recently Stebbins and Whitford (**12**) have studied this star and did not find any large change in colour.

On the basis of a colour temperature change in HD 125248 of 250 deg. K., as suggested by the above calculation, a change in relative gradient of about 0·01 from maximum to minimum light might be expected.

6. This investigation benefited from the visit of Professor S. Chapman to the Commonwealth Observatory, and from some correspondence with

* Schwarzschild's stream velocities integrated over the visible hemisphere are taken to be the radial velocities measured.

Dr H. W. Babcock. The writer also acknowledges the benefit of conversations with his colleague Dr S. C. B. Gascoigne.

APPENDIX

Take the magnetic axis in the xz plane and inclined at an angle α to the axis of z, the line of sight. Let P be a point on the visible hemisphere with coordinates (x, y, z), and (X, Y, Z) with respect to the magnetic axes. The components of magnetic intensity at the point P are as follows:—

$$H_X = \frac{3M}{R^5} XZ, \qquad H_Y = \frac{3M}{R^5}, \qquad H_Z = \frac{M}{R^5}(2Z^2 - X^2 - Y^2),$$

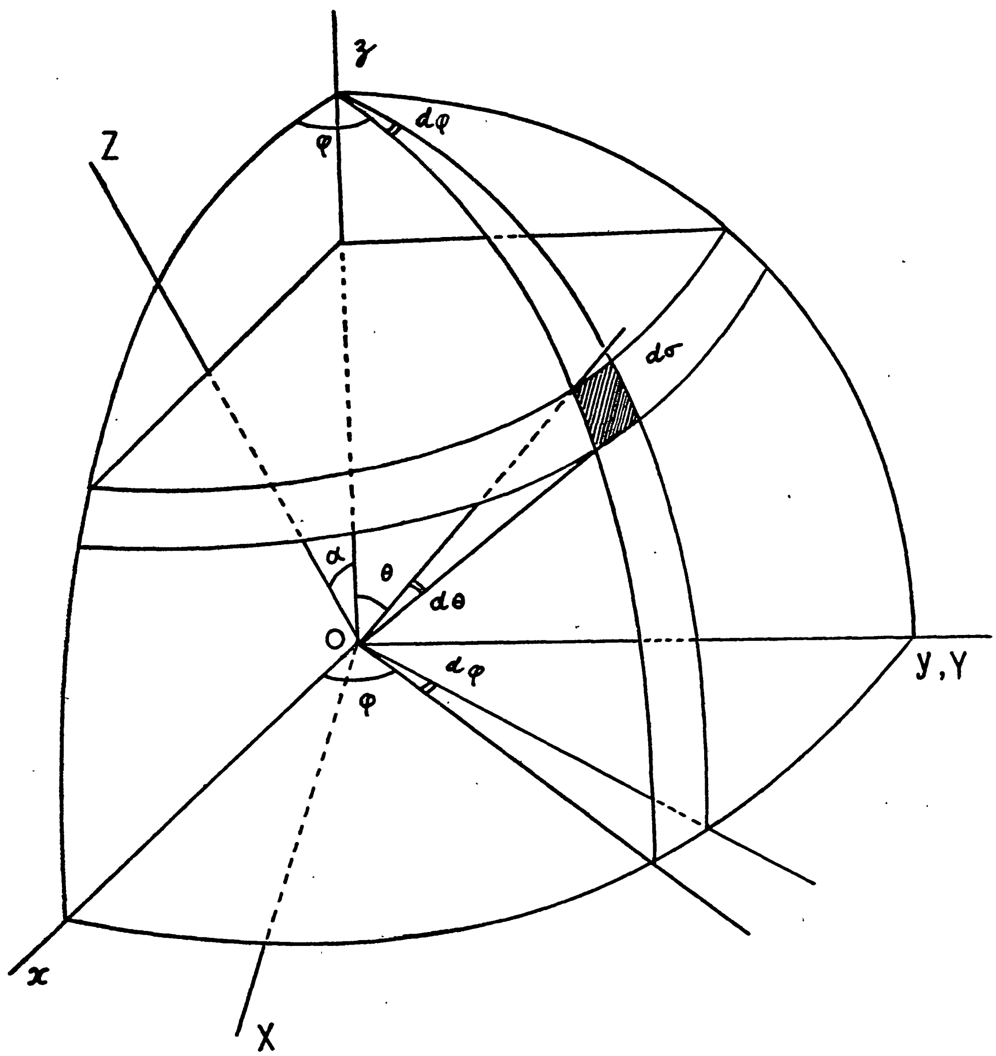

FIG. 4.—*Zeeman effect for an inclined dipole.*
Line of sight: oz.
Magnetic axis: OZ.

where M is the magnetic moment of the dipole at the centre of the star, and R is the radius. The component of magnetic force in the line of sight is

$$H_z = H_Z \cos\alpha - H_X \sin\alpha.$$

Introducing the transformation

$$X = x\cos\alpha - z\sin\alpha, \qquad Y = y, \qquad Z = z\cos\alpha + x\sin\alpha,$$

where $x = R\sin\theta\cos\phi$, $y = R\sin\theta\sin\phi$, $z = R\cos\theta$, we find

$$H_z = \frac{M}{R^3}(-\sin^2\theta\cos\alpha + 2\cos^2\theta\cos\alpha + 3\sin\theta\cos\theta\cos\phi\sin\alpha).$$

The displacement δ is proportional to the line of sight component of the magnetic intensity. To obtain the effect integrated over the visible hemisphere of a star which is darkened towards the limb, H_z has to be weighted by the line-of-sight flow of radiation $I_\lambda(\theta)\,d\sigma\cos\theta\,d\omega$ from the surface element $d\sigma$ at the point P. Since the area on the sphere between planes of co-latitude $\theta, \theta + d\theta$ is $2\pi R^2 \sin\theta\,d\theta$, and the element of lune with angle $d\phi$ intercepts the fraction $d\phi/2\pi$ of this zonal area, we have $d\sigma = R^2 \sin\theta\,d\theta\,d\phi$. Integrating over the visible hemisphere the displacement shown in the total light received from the star is given by

$$\delta(\alpha, \lambda) = a\,\frac{\int_0^{\pi/2}\int_0^{\pi} H_z(\theta,\phi) I_\lambda(\theta)\sin\theta\cos\theta\,d\theta\,d\phi}{\int_0^{\pi/2}\int_0^{\pi} I_\lambda(\theta)\sin\theta\cos\theta\,d\theta\,d\phi}.$$

If we take a linear law of darkening $I_\lambda(\theta) = I_0(1 - u + u\cos\theta)$, where u is the coefficient of darkening for the wave-length in question, we find

$$\delta(\alpha, u) = a\left(\frac{M\cos\alpha}{10R^3}\right)\left(\frac{15+u}{3-u}\right).$$

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Canberra:
1950 *February* 22.

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