Magnetic stars and rotation

Steinitz, R.

Citation

Steinitz, R. (1964). Magnetic stars and rotation. *Bulletin Of The Astronomical Institutes Of The Netherlands*, *17*, 504. Retrieved from https://hdl.handle.net/1887/6237

B.A.N. **17**, no. 7, 504–510; *Communication from the Observatory at Leiden*

MAGNETIC STARS AND ROTATION

R. STEINITZ

Received July 15, 1964

Various proposed models of magnetic stars are examined with a view to the detailed explanation of observational data. It is suggested that most difficulties encountered by the oblique rotator model can be resolved. In particular, the irregularity which has been assigned to some of the magnetic stars is doubtful, for it is shown that β CrB, which has been regarded as a prototype of irregular magnetic stars, is regular with a period of $18^d.5$. It is concluded that the rotator model is the most promising at the moment. The importance of stellar magnetic fields as an indicator of stellar rotation is stressed and some observations in this direction are suggested.

1. Models of magnetic stars

Since Babcock's success in securing Zeeman patterns of starlight, it is known that some stars possess large-scale magnetic fields at their surface. Our discussion will be based mainly on the results presented in Babcock's 'Catalogue of Magnetic Stars' (BABCOCK, 1958b) and 'Magnetic Fields of A-Type Stars' (BABCOCK, 1958a).

According to BABCOCK (1958b), 'By far the most rewarding, from the standpoint of strong magnetic fields, have been the A-type stars', and 'Since the strongest magnetic fields have been found among the sharp-line A-type stars, this group has been intensively observed'. Unfortunately, other spectral types have not yet been so thoroughly investigated. Measuring magnetic fields of other spectral types may be more difficult, for example due to rotational broadening of spectral lines in B stars or blending of lines in later types; yet some sharp-line G or M type supergiants might lend themselves easier for such measurements. Investigations of magnetic fields on such stars could be of interest in connection with evolutionary problems.

Babcock classified magnetic stars into three main groups with the following prototypes:

α variables (α^2CV)-stars with periodic magnetic changes, generally with reversal of polarity;

β variables (βCrB)-stars with irregularly reversing fields;

γ variables (γEqu)-stars with irregularly changing non-reversing fields.

All stellar magnetic fields observed so far are variable in time, but magnetic stars have other interesting properties.

Some of the important ones we mention here:

1) Spectral peculiarities and their variations. Many of the magnetic stars show strong lines of rare-earth elements and metallic lines. Sometimes they are variable in intensity and profile. In particular in the α variables they vary with the magnetic period (e.g. HD 125248).

2) Light variations. The α variables which have been investigated photoelectrically (JARZEBOWSKI, 1960, 1961; RAKOS, 1962; and further references in their papers) show regular light variations of the order of a few hundredths of a magnitude with the magnetic period.

3) Crossover effect (BABCOCK, 1951). A description of this interesting effect with a detailed discussion is given in section 4.

It is useful to introduce at this stage the basic models which have been proposed to explain the observations:

Oblique rotator (STIBBS, 1950; DEUTSCH, 1958): A dipole field inclined to the axis of rotation and an inhomogeneous distribution of some elements at the stellar surface can account for the periodic field reversals and spectral changes if the surface rotates as a solid body and is viewed at an inclination to its rotation axis. In other words, the model is a geometric one.

Oscillator (SCHWARZSCHILD, 1949; COWLING, 1952, 1953; BABCOCK, 1958a): Changes in field intensity are supposed to arise by some hydromagnetic oscillations at the surface of the star.

Solar cycle model (BABCOCK, 1958a): The magnetic cycle is supposed to be an analogue to the solar cycle, magnified to a vast extent. We would then be looking at a rapidly rotating star at a small inclination to the rotation axis.

2. Difficulties in explaining the observational data with these models

We review in this section the arguments which have led to the models and the difficulties encountered when we try to explain the observations in detail. They add up to a startling collection of facts and apparent contradictions, which have brought the theory of magnetic stars into a deadlock for many years. In the next section we shall suggest ways to solve some of these difficulties.

Field reversal and period. Since stellar material is ionized, its conductivity is high, and magnetic fields must be 'frozen' into the stellar gas, to a high degree of approximation. The field can therefore be regarded as being convected by the motions of the fluid. In particular, it seems difficult, if not impossible, to reverse the polarity of a magnetic field in the relatively short time of a few days, corresponding to the periods of α variables. This is the main difficulty encountered by the oscillator. Gravity oscillations of magnetic stars should have much shorter periods, while horizontal surface osicllations (COWLING, 1952, 1953) would produce a period of the correct order, but not the observed polarity reversals. The rotator model does not encounter these problems.

Irregular variations. Irregular magnetic variables cannot be explained by a rigid rotator model; at most one could expect rotation effects to be superposed on the irregular changes. If this argument is accepted, one has to admit irregular oscillator models of some kind. This, of course, does not overcome the difficulty of the (relatively) fast reversal of polarity. A striking example is βCrB.

Light variations. In α variables the periods of light and magnetic variation are equal. If these light variations are due to the influence of the magnetic field on the local structure (i.e. density, pressure and temperature) of the photosphere of a rotator model, one would expect the luminosity to depend on the field intensity but not on its sign. The light period would then be half the magnetic period. Oscillations of the entire star furnish perhaps a more natural connection of the two periods: they both are simply the period of oscillation.

Stellar rotation and statistics of line widths. BABCOCK (1958a) attaches great importance to the fact that the assumption that most magnetic stars are fast rotators seen nearly pole on, is consistent with the two independent facts:

1) The relative sharpness of spectral lines;

2) The observation that most peculiar A-type and metallic line stars lie on the upper fringe of the main sequence (DEUTSCH, 1947; EGGEN, 1963). In Babcock's explanation the latter effect arises from flattening of a rapidly rotating star, which gives the star a greater effective area for small obliquity, and the larger surface gravity at the poles results in a higher effective temperature and greater surface brightness. However, in a rapidly rotating star the surfaces of constant temperature, density and pressure presumably do not coincide. As the observed degree of ionization depends on these variables, it is not obvious exactly how the spectral type of a rapidly rotating star changes with obliquity, without first having constructed a detailed model for such a star. It is therefore not clear how a 'rapid rotator' moves in the H.R. diagram with obliquity. To suppose that the sharp lines are caused by intrinsic slow rotation of all magnetic stars, would seem to be difficult to reconcile with the accepted distribution function of rotational velocities of A stars.

Computed versus observed line widths. One of the strongest arguments often raised against the oblique rotator model (BABCOCK, 1956, 1958a) is the following. If the rotation period equals the magnetic period, the expected line width due to rotational broadening can be evaluated. Line widths thus calculated with reasonable assumptions about obliquity and limb darkening generally are approximately twice the observed widths. If turbulence is present, the situation is worse.

Covariation of field and abundance peculiarities. SWINGS (1944) has shown that there is a covariation of different ionization stages of some elements (e.g. europium) during a magnetic cycle. It is unlikely that such variations are produced by changes in the thermodynamic variables only. This would imply that a mass element which is seen at some instance, is not seen at some later time. This is consistent with the observation that abundances in α variables are correlated with magnetic intensities. One may try to explain the 'appearance' and 'disappearance' of a mass element on one of two extreme assumptions: 1) The star is rotating and is not viewed along the axis of rotation; 2) The star presents to the observer always the same part of its surface, while the optical depth changes with respect to the true depth during the magnetic cycle. The second assumption must probably be rejected, since magnetic lines of force have to be closed, and it is rather difficult to conceive of an appropriate model which will also show reversal of polarity. The solar cycle model is subject to similar objections.

3. Further support of the rotator model

3.1. *Determination of further periods*

Even if an oscillator model for the irregular variables were accepted, it might still be possible to find effects of rotation superposed on the irregular fluctuations, since one would not expect to see all magnetic stars exactly 'pole on'. For that reason the data presented in the Catalogue were examined from that point of view. The results were the following:

βCrb (No. 55 in the Catalogue)

Comparing the time intervals between dates with extreme values of the field, we note that the following groups have time intervals which are all multiples of 130 days: (1952, July 11; 1953, March 27); (1953, June 26; 1954, March 15; 1955, April 9) and (1953, September 29; 1954, June 11; 1955, March 3; 1956, March 24).

A plot of the measurements in a period of 130 days yields seven cycles; thereafter it is easy to derive a period of $18^d.497 \pm 0^d.006$ (figure 1).

I am grateful to Professor P. Th. Oosterhoff for help in deriving the accurate period.

HD 10 783 (No. 6 in the Catalogue)

Babcock states that 'numerous plates have been taken, but the results indicate that the magnetic variations are irregular'. The measurements indicate a negative field on 1949, July 16 and July 20 (four days interval), and a positive field on the days in between. Plates from 1949, August 7 and August 10, yield small values of the field (≈ 0). Negative fields are indicated by plates taken on 1950, November 25 and December 28, with an interval of 33 days; plates on 1954, October 8 and November 14, with an interval of 37 days again indicate a negative field. Thus a period of about four days is suggested. It is noteworthy that the plates on 1954, October 7, 8 and 9, show respectively + 1420, − 1170 and + 1190 gauss, indicating that the minimum is very sharp. Figure 2 shows the measurements in a period of $4^d.134$, but it is clear that with such large time intervals between groups of measurements as presented in the Catalogue, it is difficult to discriminate between various possible periods.

These results are a strong indication of periodicity in some stars, which Babcock has called irregular. Further

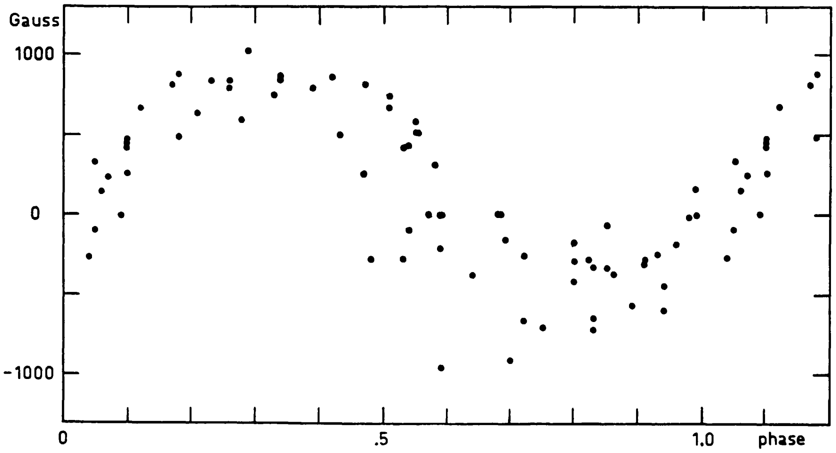

Figure 1. Magnetic field intensities of βCrB as observed by Babcock (1958b), plotted in a period of $18^d.497$.

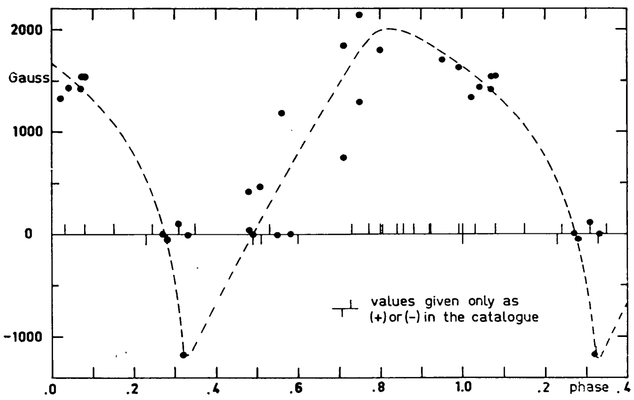

Figure 2. Magnetic field intensities of HD 10 783 as observed by BABCOCK (1958b), plotted in a period of $4^d.134$.

measurements will have to determine whether they really are periodic, but the results suggest that possibly none of the magnetic stars are irregular. It is true that a large dispersion is still present, but this could be ascribed to local activity (similar to sunspots), which has nothing to do with large-scale reversal of polarity. The sharp negative extreme of HD 10783 shows that the magnetic intensity distribution on the surface could be very complex.

If the periodic behaviour of a large number of magnetic stars can be established by more observations, in particular in longer continuous runs, one of the major objections to the rotator model will disappear.

3.2. *Line widths*

We now proceed to suggest an explanation of the apparent contradiction between the computed and obobserved line widths. Babcock cites several cases in which the fields indicated by different elements, or various ionization stages of the same element, are different. An example is HD 188041 (*Ap.J.* **120** 67), plate Pb 1045. The 'mean' field in this example is positive, so are the fields 'seen' by Fe I, Cr I, Cr II and Gd II. A negative field is indicated by Fe II. As Babcock points out, this is *not* a measuring error. Other examples are HD 173650 (No. 65 in the Catalogue), HD 42616 (No. 22) and HD 78316 (No. 34).

From these and similar examples presented in the Catalogue, we may infer that: 1) Fields of different intensity, even to the extreme of opposite polarity can be present at the same instant on the visible hemisphere of the star; 2) The contribution to an absorption line does not necessarily arise from the entire visible part, but can arise from restricted regions. If this is true, the rotational broadening of such a line must be smaller than the width computed on the assumption that the whole visible hemisphere contributes to the line.

3.3. *($\Delta\lambda$,P) Diagram*

In support of the rotator model, DEUTSCH (1956) has noted that stars with longer periods generally have narrower lines. If P is the star's period of rotation in days and $\Delta\lambda$ a typical line width in Å, then one may expect $\Delta\lambda = a/P$, where a depends on the size of the star, on limb darkening and on the angle between line of sight and axis of rotation. For A stars, $a = 3$ to 3.6 is a reasonable assumption. Since DEUTSCH's papers (1956) more data have accumulated, so it is interesting to plot all known periodic stars in the ($\Delta\lambda$,P) plane. This is done in figure 3. The plot also includes stars whose periodicity has been established via spectral changes or luminosity changes, but which could not be measured for Zeeman effect because of large line broadening. Also included are the newly found periodic variables. While turbulence will enlarge $\Delta\lambda$, limb darkening, obliquity and absorption over only part of the surface will diminish $\Delta\lambda$. As can be seen, there is fair agreement with the prediction on a rotator model: all stars, except 41 Tau, fall below the $\Delta\lambda = 3.6/P$ curve.

3.4. *Polarization in HD 71 866*

THIESSEN (1962) found the degree and direction of polarization of HD 71 866 (an α variable) to vary with

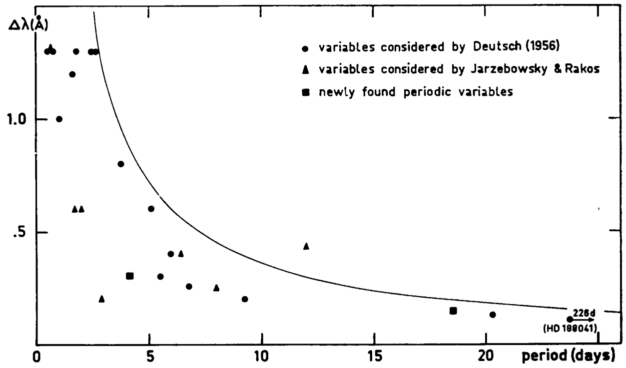

Figure 3. Spectral line widths versus period of peculiar A-type stars with known periods. The smooth curve is given by $\Delta\lambda = 3.6/P$.

half the magnetic period. Figure 4 shows the results given by Thiessen. Variable polarization of a dozen variable stars is also reported by SHAKHOVSKOY (1963). It is clear that such variable polarization is not interstellar, but must be of stellar origin.

A number of mechanisms have been suggested. According to Thiessen the source of polarization is synchrotron radiation. The theory of synchrotron radiation from stars with dipole fields is developed in a recent paper by THORNE (1963). However, WARWICK (1961) maintains that saturation polarization of the absorption lines is sufficient to account for the small polarization which is observed. Moreover, considerable asymmetries in the distribution of electron pressure in the atmosphere could cause polarization of a similar order of magnitude (cf. CHANDRASEKHAR, 1950).

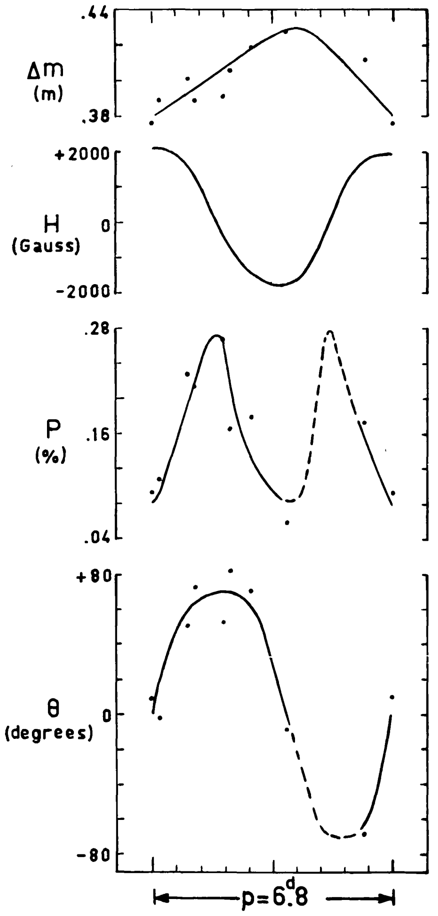

Figure 4. Variable polarization in HD 71 866 (adapted from THIESSEN, 1962).

Leaving aside the detailed mechanisms for explaining the polarization, we can still draw certain conclusions about the most likely model of the star. It is reasonable to assume an asymmetry or anisotropy in the distribution on the visible hemisphere (e.g. a non-symmetric density or magnetic field distribution). With the material on the surface of the star a vector ***P*** can be associated, such that its projection on the sky at any moment determines the degree and direction of the observed polarization. Since the observed direction of polarization changes during the magnetic cycle, ***P*** cannot be parallel to the rotation axis, which is fixed in space. Looking at a rapidly rotating star (as is often assumed, e.g. BABCOCK, 1958), we should expect to see a fast change in the direction of polarization, reflecting the rapid rotation. This is not observed. Slow rotation with a period equal to the magnetic period would offer a more natural explanation. An explanation based on an oscillator model seems to be artificial.

4. Differences between Zeeman components and the 'non-reversing' character of a star

BABCOCK (1951) has noted that sometimes the two circularly polarized components of a line have different intensities and widths. A detailed analysis of these differences and of the examples cited in section 3.2 is of importance in interpreting the observations. We follow now the explanation given by BABCOCK (1951) with a slight generalization.

Suppose we observe on a star two regions which have a relative velocity in the line of sight corresponding to a relative shift of V Å.

Let the two regions have magnetic fields such that the corresponding Zeeman displacements are H_1 and H_2

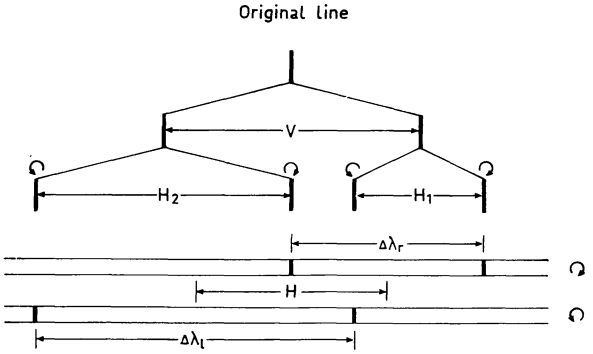

Figure 5. Composition of the circular polarized components by superposition from two magnetic regions.

(figure 5). For simplicity we assume the two regions to contribute equally to the line, and further we represent each Zeeman component by one line only (e.g. its centre of gravity).

The field measured by the relative displacement of left and right circularly polarized components is

$$H = \tfrac{1}{2}(H_1 + H_2),$$

while the 'width' of the left hand component is

$$\Delta\lambda_l = V + \tfrac{1}{2}(H_1 - H_2).$$

For the right hand component we have

$$\Delta\lambda_r = V - \tfrac{1}{2}(H_1 - H_2);$$

the difference in width between the two components, $\Delta\omega$, is given by

$$\Delta\omega = H_1 - H_2.$$

If we assume $|H_1| \approx |H_2|$ (e.g. for conservation of flux), $\Delta\omega$ will be relatively large when the fields are of opposite polarity, so that the difference between the Zeeman components of a line is large when the measured field is small. In a rotator model this would happen at the phase at which the observed field is changing its polarity (hence the term 'crossover effect' used by Babcock). This is indeed observed in α variables. Babcock assumes in his explanation the two fields to be of opposite polarity, but this is not necessary. It is also clear that a star may show the effect without reversal of polarity ever being observed.

We conclude that it is incorrect to say that the observed hemisphere of a 'non-reversing' star must be a unipolar region. Therefore, a classification of fields on stars into 'reversing' and 'non-reversing' seems to be physically insignificant. The case of HD 188 041 already cited proves the point. Reversal or non-reversal is a property which depends on the distribution of field intensity on the surface of a star and on the position of the observer.

Finally it should be pointed out that in any actual case the superposition of Zeeman components from various regions is more complicated than here described, as it depends on limb darkening and other effects.

5. Suggestions for direct determination of stellar rotation

The discussion in the foregoing sections seems to indicate the oblique rotator as the most promising model to explain magnetic stars. If this model turns out to be correct, magnetic stars would gain in importance, as a tool for investigating stellar rotation.

Spectra of many stars have lines which are too broad to be measured for the Zeeman effect, yet variations of polarization could still be detected. This suggests that variable polarization might be used to determine rotational periods of stars. To test this possibility it is necessary: 1) To repeat and verify Thiessen's observations of HD 71 866; 2) To extend these observations to other α variables and to establish whether a relationship similar to the one in HD 71 866 between magnetic field and polarization holds for them. However, it should be kept in mind that Sakhovskoy (1963) offers a different explanation for changes in polarization in pulsating stars, and it may be necessary to use further criteria to distinguish between polarization due to magnetic fields and polarization due to pulsations and shock-waves.

The projection of the axis of rotation of a star on the sky may perhaps be determined by observing the directions between which the plane of polarization oscillates, once a detailed theory for the origin of polarization in magnetic stars has been developed.

Finally, to settle the problem of fast versus slow rotator it may be necessary to observe magnetic stars *continuously* for a few days. Simultaneous magnetic, spectroscopic, photometric and polarization measurements would probably be very useful. The results to be expected amply justify the effort.

Acknowledgements

It is a pleasure to thank Professor H. C. van de Hulst and Professor L. Woltjer for their stimulating discussions and interest in this work. I am indebted to the staff and members of the Sterrewacht at Leiden for their kind hospitality.

References

H. W. Babcock, 1951, *Ap. J.* **114** 1

H. W. Babcock, 1956, *Ap. J.* **124** 489

H. W. Babcock, 1958a, *Ap. J.* **128** 228

H. W. Babcock, 1958b, *Ap. J. Suppl.* **3**

S. Chandrasekhar, 1950, *Radiative Transfer* (Oxford Univ. Press, London)

T. G. Cowling, 1952, *M.N.* **112** 527

T. G. Cowling, 1953, *M.N.* **113** 357

A. J. Deutsch, 1947, *Ap. J.* **105** 283

A. J. Deutsch, 1956, *P.A.S.P.* **68** 92

A. J. DEUTSCH, 1956, *Vistas in Astronomy*, ed. A. Beer (Pergamon Press, Bristol) **2** 1421

A. J. DEUTSCH, 1958, *I.A.U. Symp.* No. 6 209

O. EGGEN, 1963, *A.J.* **68** 697

T. JARZEBOWSKI, 1960, *Acta Astr.* **10** 236

T. JARZEBOWSKI, 1961, *Acta Astr.* **11** 191

R. D. RAKOS, 1962, *Lowell Obs. Bull.* No. 117

M. SCHWARZSCHILD, 1949, *Ann. d'Ap.* **12** 148

N. M. SHAKHOVSKOY, 1963, *Astr. Zhur.* **6** 1055

D. W. N. STIBBS, 1950, *M.N.* **110** 395

P. SWINGS, 1944, *Ap. J.* **100** 132

G. THIESSEN, 1962, *Astr. Abh. Hamburger Sternw.* **5** 273

K. S. THORNE, 1963, *Ap. J. Suppl.* **8**

J. W. WARWICK, 1961, *Ap. J.* **134** 1021