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DECAYING STELLAR MAGNETIC FIELDS, MAGNETIC BRAKING: EVIDENCE FROM MAGNETIC OBSERVATIONS IN ORION OB1

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ABSTRACT

I have observed the magnetic fields of 13 Ap and helium-weak stars in the Orion OB1 association. The magnetic fields observed are compared to those of older magnetic stars. It is concluded that the magnetic stars in Orion have magnetic fields stronger (by a factor of 3) than the older stars, in agreement with a fossil origin of the fields. The *e*-folding time of decay is estimated to be of the order of 10^8 years. This short time scale is seen as evidence that internal mass motions are present in upper-main-sequence stars, with potentially important effects on their evolution. Although the periods of variation are uncertain, they suggest that young magnetic stars rotate faster than their older counterparts, implying magnetic braking on the main sequence.

Subject headings: magnetic fields — stars: magnetic

I. INTRODUCTION

Two outstanding unanswered questions in our understanding of stellar formation concern the fates of the magnetic flux and the angular momentum of the protostellar clouds. It is well known (Mestel 1975) that strict magnetic flux freezing and angular momentum conservation lead to predictions that overestimate by several orders of magnitude the observed surface magnetic fields and rotational velocities. Most stars have unobservable surface fields, but a few stars having peculiar surface chemical compositions (Borra and Landstreet 1979, 1980; Wolff and Wolff 1976) stand out by having measurable surface magnetic fields and lower than average rotational velocities. It is puzzling that normal stars and stars having the peculiar compositions typical of magnetic stars (and thus are presumably magnetic) should exist side by side in coeval groups of stars (Garrison 1967; Joncas and Borra 1981). If we understand this, we will gain some insight into the process of star formation.

A knowledge of the secular variations of surface magnetic fields is central to our understanding of stellar magnetism. In particular, it should enable us to settle the fossil versus contemporary dynamo origin of these fields controversy (Mestel 1975). The secular variations can also give precious clues about the internal dynamics of the upper-main-sequence stars (Mestel and Moss 1977; Moss 1977).

It is therefore important to observe the magnetic fields of peculiar stars in young clusters for comparison to the magnetic fields of the older peculiar stars in the solar neighborhood. A comparison of rotational periods will also reveal whether or not angular momentum loss on the main sequence is responsible for the lower rotational velocities of the peculiar stars (Wolff 1981). I report here recent observations of the magnetic fields of 13 helium-weak and Ap stars in the Orion OB1 association.

II. THE OBSERVATIONS

The observations were obtained with the Laval University Pockels cell polarimeter which is similar to the instrument described by Angel and Landstreet (1970). The telescope used is the Las Campanas 2.5 m du Pont telescope. The observational techniques and reduction procedures are the same as in Borra and Landstreet (1980, hereafter referred to as BL). The only differences are that the circular polarization was observed in the wings of Hα (instead of Hβ) with 4 Å HPBW (instead of 5 Å) interference filters. The conversion between circular polarization and average longitudinal field B_e is made, as in BL, by observing the line profiles. It is found that 1% circular polarization corresponds to 14,600 gauss with about a 10% uncertainty. The observations are summarized in Table 1, where, for every star, we have the spectral type (see Joncas and Borra 1981 for the sources of spectral types), number of observations and typical standard deviations, extrema of variations, and root-mean-square magnetic field obtained from:

$$\langle B_e \rangle = \left[\sum \left(B_{e,i}^2 - \sigma_i^2 \right) / n \right]^{1/2}. \qquad (1)$$

The standard deviation is subtracted because we take the squares of signed quantities and would otherwise overestimate $\langle B_e \rangle$. The last column in Table 1 shows the periods of rotation obtained by least-squares fitting

TABLE 1

SUMMARY OF OBSERVATIONS

Star (HD) Spectral Type	n σ (gauss)	Extrema (gauss)	$\langle B_e \rangle \pm \sigma$ (gauss)	Possible Periods (days)
35298	5	+2920	2230 ± 200	1.9
B3 HeW	450	−2810		
35456	6	+1080	615 ± 120	1.7; 2.5; 3.3; 8.2
B6 Ap	300	−300		
35502	6	−95	1490 ± 140	1.7
B5 HeW	340	−2250		
36313	6	+1110	915 ± 180	3.5; 6.2
B9 Ap	440	−1520		
36429	5	+160	425 ± 170	...
B4 HeW	380	−840		
36540	4	+1030	470 ± 220	...
B7 HeW	440	−400		
36526	6	+3480	2130 ± 200	1.6
B9 HeW	490	−980		
36668	6	+1320	900 ± 180	2.1; 2.7; 3.0
B6 Ap	440	−1590		
37140	6	+400	450 ± 210	...
B7 HeW	510	−1050		
37151	4	+345	190 ± 190	...
B8 Ap	380	−530		
37210	4	+400	280 ± 250	...
B9 Ap	500	−760		
37470	4	+150	0.0 ± 230	...
B8 Ap	450	−260		
37642	6	+2700	2110 ± 180	0.8
B9 Ap	440	−2980		
Orion Nebula Cluster				
36981	1	+450	450 ± 440	...
B4 V	440	...		
37062	1	+760	760 ± 690	...
B5 V	690	...		
37150	1	...	489 ± 260	...
B2.5 V	260	−489		

sine curves to the data with trial periods between 1 and 15 days. These periods are uncertain because of the small number of observations and the short time bases. Because I never observed a star more than once per night, the real period could be less than 1 day. In the case of HD 37642, the only period that could fit the observations was less than 1 day.

The 13 stars comprise about half of the complete list of Ap and helium-weak stars in Orion OB1 compiled by Joncas and Borra (1981). No particular selection criterion was used, except that stars that were suspected to be nonmembers in the literature cited in Joncas and Borra (1981) were not observed, and HDE 290665 was considered too faint. The remaining stars were not observed merely because the additional 10 nights needed were not available.

Table 1 shows detections of several stars having magnetic fields stronger than average (compare to BL). Three stars were not detected and three more were detected marginally. When comparing to BL, however, consider that the standard errors in Table 1 are considerably larger. The correction in equation (1) insures that this does not lead to overestimations of $\langle B_e \rangle$, but, obviously, nothing can be done to improve detection of weaker fields.

III. DISCUSSION

I have performed several Kolmogorov-Smirnov one-tailed two-sample tests, comparing the $\langle B_e \rangle$ distribution of the Orion stars to several other $\langle B_e \rangle$ distributions. The results are summarized in Table 2. First, I have tested the hypothesis that the Orion distribution and the $\langle B_e \rangle$ distribution of the stars in the bright northern hemisphere survey in BL are issued from the same parent distribution. This hypothesis can be rejected at the 2% confidence level. This northern hemisphere survey is complete and unbiased. I have repeated the test with the bright southern survey in BL, supplemented by data from Borra and Landstreet (1975), but only for the stars in Table 12 of BL and excluding a few stars in BL that were observed only once. This bright southern sample is

TABLE 2

SUMMARY OF KOLMOGOROV-SMIRNOV TESTS

Distributions Compared	Significance Level
Orion, northern sample	2%
Orion, southern sample	0.1%
Orion, helium-weak	1%
Young sample, older sample ...	0.003%

not as complete and unbiased as the northern sample, but the Kolmogorov-Smirnov test rejected again the hypothesis at the 0.1% level.

One might object that the Orion stars cannot be readily compared to the BL samples because the Orion stars are hotter on the average, a few are helium-weak stars, and they have, on the average, short periods of rotation. The silicon Ap stars do not have significantly higher surface magnetic fields than the cooler Eu-Sr-Cr Ap stars (Preston 1971). The much hotter helium-strong stars (B2 V) have stronger magnetic fields than the Ap stars (Borra and Landstreet 1979), but three of them (having the largest $\langle B_e \rangle$ values) are in Orion itself. The remaining sample (six stars) is too small for meaningful comparison. But, because they are so hot, the helium-strong stars cannot be much older than Orion OB1. Also, the three helium-strong stars in Orion (σ Ori E, HD 37017, HD 37777) have $\langle B_e \rangle$ values (1950 gauss, 1520 gauss, 1050 gauss) in keeping with the distribution of Table 1. There is therefore no indication that magnetic field strength increases much with effective temperature and, in any event, there is overlap in the temperature distributions of the Orion and the BL stars. I have then compared the Orion stars to a sample taken from a survey of magnetism in helium-weak stars (Borra and Landstreet, unpublished), excluding the stars observed only once and stars in the upper Scorpius association, which has the same age as Orion OB1. The hypothesis of a common parent distribution can, again, be rejected (1% level). Finally, BL find no evidence that magnetic fields increase with decreasing rotational periods.

It is possible that the Orion magnetic fields are stronger simply because of intrinsic variations from cluster to cluster. However, consider that the field stars in the various samples of Table 2 originated in many, now disrupted, clusters and associations (e.g., six stars in BL are in the UMa stream). The Orion stars are thus compared to means of different ancient clusters, and Orion would therefore have to be much above average. There is, moreover, some evidence to suggest that the peculiar stars in upper Scorpius also have strong magnetic fields. The helium-weak star 3 Sco has a very strong magnetic field (Landstreet, Borra, and Fontaine 1979), and two of the helium-weak stars in upper Sco observed by Borra and Landstreet (unpublished) also have fairly large $\langle B_e \rangle$ values (HD 142990, $\langle B_e \rangle = 1050$ gauss; HD 144334, $\langle B_e \rangle = 770$ gauss). I have made a last Kolmogorov-Smirnov test, comparing a sample of young stars containing all of the Orion magnetic stars (including the three helium-strong stars) and the upper Sco helium-weak stars from Borra and Landstreet (unpublished) to a sample comprising the other older samples discussed earlier. The hypothesis that they originate from a common parent distribution can be rejected (0.003% confidence level).

IV. CONCLUSION

The most likely conclusion we can draw from this discussion is that the Orion stars have magnetic fields larger than the other samples because they are in a less advanced stage of evolution. This seems, prima facie, to favor a fossil origin of the fields. The Orion and upper Scorpius stars have ages of about $5 \times 10^6 - 10^7$ years and an average $\langle B_e \rangle$ value of about 1000 gauss. The remaining older stars have an average $\langle B_e \rangle$ value of about 300 gauss and have ages that probably span a large range, from at least a few 10^7 years up to the roughly 3×10^8 years of the stars in the Ursa Major stream. The Ursa Major Ap stars (Roman 1949) have also an average $\langle B_e \rangle$ value of 300 gauss (BL). If we assume that surface magnetic fields decay as

$$B(t) = B_0 e^{-t/\tau}, \tag{2}$$

we can readily see that τ will be of the order of 10^8 years, significantly below Cowling's (1945) estimate of 10^{10} years. Cowling's estimate of the ohmic decay time is for a plasma at rest; we can therefore advance the hypothesis that internal mass motions are responsible for the shorter decay time. Rotation-driven circulation currents are the most likely cause of mass motion. The observations thus lead us to a picture in which the decay of surface magnetic fields of a fossil origin is speeded up by rotation-driven circulation, perhaps by a mechanism of the type discussed by Mestel and Moss (1977). However, the theoretical situation is, at this stage, somewhat uncertain as the results are model dependent (Moss 1977; Mestel *et al.* 1981). This picture is also in agreement with the marginal evidence for a correlation between magnetic field strength and periods of rotation found by BL.

It is possible that τ is actually geometry- and rotation-dependent, and that the estimate of $\tau \approx 10^8$ years is merely an average value. Further speculation, at this stage, is unwarranted. The most significant information that τ gives us is that internal mass motions are probably present in all upper-main-sequence stars. This has potentially far-reaching implications because, if these motions can mix interior material in sufficiently short time scales, evolution on and perhaps off the main sequence will be affected, and therefore the dating of young clusters will be in error. Further theoretical work in this subject is highly desirable. One might wonder, in particular, whether the field itself does not, somehow, cause or trigger the mass motions that cause its own decay.

The angle between the magnetic and rotation axes is an important parameter of the internal dynamics of the oblique rotator (Mestel 1975). We do not have enough stars and do not know precisely enough the extrema of magnetic variation for a meaningful statistical analysis as in BL. However, Table 1 shows that most curves reverse polarity and that many opposite extrema are of about equal amplitude. This indicates a number of medium-to-high obliquity cases in these young stars.

The uncertainty in the periods shown by Table 1 precludes a meaningful comparison to the periods of field stars in Preston (1969). However, Table 1 gives the impression of an excess of short-period stars. This would indicate that magnetic Ap stars suffer magnetic braking on the main sequence. We shall await later photometric determination of the periods for further discussion.

The last three stars in Table 1 are in the Orion Nebula cluster. I have only one observation per star; however, these measurements are interesting because these stars are very young ($< 5 \times 10^5$ years). These observations show that strong magnetism is not a common occurrence among very young stars.

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