DOI 10.1007/s10511-016-9438-5
Astrophysics, Vol. 59, No. 3, September, 2016

MAGNETIC STARS AFTER THE HAYASHI PHASE. II.

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The properties of magnetic stars derived from observational data are analyzed. The degree of "magnetic" braking of parent protostars, which depends the magnetic field and mass, is studied. The conditions under which magnetic and "normal" nonmagnetic stars are separated, which appear to depend only on the rotational velocity of the protostars, are examined. The reasons for differences in the average magnitudes of the magnetic field in massive and low-mass magnetic stars are analyzed. The magnetic field structures of magnetic stars and their stability over time (rigidity of rotation) are examined.

Keywords: *Magnetic CP-stars: evolution: properties of magnetic fields*

1. Introduction

This article is a continuation of Ref. 1. It is devoted to a study of a possible scenario for the origin and evolution of magnetic stars based on an analysis of observational data.

As data accumulate, it becomes possible to refine previous results and discover new ones. Thus, for example, the predominant orientation of the magnetic fields in magnetic CP-stars along the equator of rotation was discovered and first studied by Preston [2]. Landstreet [3] made a more complete study of this property. Data on the preferred orientation of magnetic lines of force along the equator of rotation made it possible for a Potsdam group of

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Original article submitted February 1, 2016; accepted for publication June 22, 2016. Translated from Astrofizika, Vol. 59, No. 3, pp. 359-377 (August 2016).

astrophysicists to try using an α^2-type magnetic dynamo theory [4-6] to explain the origin of the magnetic field. The numerous difficulties with the dynamo theory led later to the better justified relict theory proposed by Cowling, Spitzer, and Mestel [7-9]. In Preston's first studies of the structure of magnetic fields in stars, it was assumed that they correspond to a theoretical magnetic dipole located at the star's center. Landstreet showed, however, that in many cases the magnetic field structure corresponds to a model of a magnetic dipole that has been shifted from the star's center along its axis. Data on the predominant orientation of magnetic fields led to the idea of a slow meridional circulation that bends the lines of force toward the plane of the equator of rotation [10] over the star's lifetime. Further studies showed that there are a number of stars in which the dipole may be shifted perpendicular to the axis, as well as long it, and that some magnetic field structures may correspond to two or even three magnetic dipoles inside the star [11]. Cases of this sort have been observed in the oldest as well as the youngest objects, for which the slow meridional circulation would not have yet succeeded in reorienting the magnetic field lines. There are other difficulties with the meridional circulation hypothesis. The method for modelling magnetic structures developed by the author and the Potsdam group [12,13] has made it possible to study the predominant orientation of magnetic structures in magnetic stars in more detail. It has become possible to approach an understanding of the internal structures of these magnetic fields. Besides the reasons for the predominant orientation of the magnetic fields in CP-stars, here we examine some other important properties acquired by stars during their early evolution.

2. Mechanism for the selective magnetic braking of protostars

In order to understand the reason for the observed preferential distribution of magnetic stars with respect to the angle α, we now consider the most probable mechanism for braking of protostellar clouds. It has been shown [14] that if stars are formed by collapse or fragmentation of nonmagnetic interstellar clouds, a process can develop in which angular momentum is transferred from the collapsing volume of matter to surrounding material. The calculations show [14] that magnetic braking in the case where the magnetic field is oriented $\mathbf{J} \perp \mathbf{B}$ can change the angular momentum of the interstellar cloud by several orders of magnitude over a time of less than 10^6 years. With that configuration, the magnetic braking is much more efficient that when $\mathbf{J} \parallel \mathbf{B}$. This means that clouds in which the magnetic field is parallel to the plane of rotation are slowed down more rapidly. This selective braking with respect to the angle a leads to an excess of magnetic stars with $\alpha = 0^o \div 20^o$. At the same time, this mechanism is the cause of two features of magnetic stars: slow rotation and predominant orientation of the magnetic lines of force. A small fraction of stars with a favorable orientation of the lines of force obviously leads to a 10% fraction of magnetic stars.

3. Among the massive (He-r+He-w) CP-stars the fraction of objects with $\alpha = 0^o \div 20^o$ predominates

Up to the present, models of the magnetic fields and their parameters have been obtained for 115 stars. The values of the average surface magnetic field *Bs* and the angle of inclination α of the dipoles to the plane of the equator of rotation obtained by the modelling method are listed in Table 1. Also given there are the distance Δ*a* of the monopoles from the centers of the stars in units of their radii. The data in the table were taken from Refs. 14-25.

TABLE 1. Data on Magnetic Field Structures

	HD	Type	*Bs*	α1	α2	α3	$\Delta a1$	$\Delta a2$	$\Delta a3$	log*t*	$M_\odot$
1	2	3	4	5	6	7	8	9	10	11	12
1	2453	SrCrEu	**3737**	10			0			8.88	2.18
2	3360	He-r	**294**	3			0:			7.36	4.73
3	3980	SrCrEu	**1863**	0			0:			8.39	1.93
4	4778	SrCrEu	**2600**	9			0			8.43	2.23
5	5737	He-w	**3190**	1.5			0			7.93	4.95
6	8441	SrCrEu	**470**	0			**0:**			8.63	2.33
7	9996	SrCrEu	**4831**	78			0:			8.40	2.14
8	10783	Si+	**2244**	25	0		0.07	0.50		8.48	3.09
9	11503	Si+	**1000:**	15			0:			8.44	2.68
10	12098	Si+	**1690**	44			0			8.93	2.31
11	12288	SrCrEu	**7879**	24			0.08			8.66	2.46
12	12447	Si+	**782**	0			0.20			8.57	2.04
13	12767	Si	**159**	0			0:			8.10	3.83
14	14437	SrCrEu	**7665**	2			0.15			8.36	2.92
15	15144	SrCrEu	**1055**	81			0			8.62	1.71
16	18296	SrCrEu	**890:**	2			0:			8.24	3.40
17	19832	Si	**495:**	0			0:			8.06	2.94
18	21699	He-w	**6150**	5			0.40			7.85	4.65
19	22470	He-w	**2350**	0			0			8.01	3.50
20	24155	Si	**1790**	14			0:			7.19	3.18
21	24712	SrCrEu	**2600**	52			0:			9.01	1.56
22	25267	Si	**4879**	7			0.37			8.24	3.53
23	25823	Si	**914**	55			0:			8.15	3.39
24	27309	Si+	**1350:**	50			0:			7.53	2.98
25	28843	He-w	**580**	8			0:			7.44	3.58
26	32633	Si+	**12000**	25	0		0.60	0.60		8.78	2.70
27	33629	SrCrEu	**4760**	25	0					8.16	3.96
28	34452	Si	**1000:**	21			0:			7.82	3.61
29	34736	Si	**814**	2			0			8.10	3.88
30	35298	He-w	**2886**	2			0			7.00	3.73
31	35456	He-w	**1643**	81			0:			7.90	3.57

TABLE 1. (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
32	35502	He-w	**6500**	10	10		0.10	0.10		7.40	4.00
33	36485	He-r	**5890**	5	5		0.30	0.23		7.34	6.48
34	36629	He-w	**457**	6			0:			7.00	4.80
35	37017	He-r	**2144**	12			0.05			7.50	7.97
36	37022	O	**361**	30			0:			4.8	35?
37	37058	He-w	**2665**	5			0			7.30	6.65
38	37479	He-r	**4312**	15			0.10			7.32	10.09
39	37776	He-r	**3760**	1	4	15	0.5	0.5	0.5	7.00	8.77
40	40312	Si	**650**	5			0.20			8.33	3.41
41	45583	Si	**4990**	35	10		0.10	0.10		8.08	3.47
42	49333	He-w	**1332**	0			0			7.28	4.48
43	49606	He-w	**141**	21			-0.2			7.95	4.44
44	49976	SrCrEu	**1359**	0.0			0.10	0.30		8.42	2.29
45	50773	SrCrEu	**441**	0	2.5		0.15	0.40		-	-
46	51418	SrCrEu	**1126**	1			0			8.60	
47	54118	Si	**5400**	1			0			8.40	2.69
48	55719	SrCrEu	**6501**	5			0.23			8.72	2.10
49	58260	He-r	**3063**	65			0			-	-
50	59435	SrCrEu	**3234**	40			0.10			8.78	2.09
51	62140	SrCrEu	**1566**	0			0.045			8.73	1.63
52	64740	He-r	**850**	16			0.20			7.08	8.58
53	65339	SrCrEu	**13700**	77			0.45			8.87	1.80
54	70331	Si	**12312**	2			0.3			7.90	3.00
55	71866	SrCrEu	**3470**	2			0.05			8.77	2.05
56	72968	SrCrEu	**1637**	3			0			8.60	2.00
57	74521	SrCrEu	**889**	73			0			8.40	2.38
58	75049	SrCrEu	**28160**	18			0.10			8.23	1.56
59	78316	He-w	**541**	3			0			-	-
60	79158	He-w	**1762**	2			0.10			8.13	3.67
61	81009	SrCrEu	**8301**	69			0.1			8.90	2.05
62	83368	SrCrEu	**8400**	?			0:			8.95	1.75
63	89822	Si+	**306**	15			0			8.49	2.07
64	90044	Si+	**2153**	2			0:			8.48	2.39
65	92664	Si	**1140**	50			0			7.87	4.07
66	96446	He-r	**955**	6			0			7.17	11.12
67	96707	SrCrEu	**841**	48			0			8.87	2.25
68	98088	SrCrEu	**1105**	40			0			8.87	2.18

TABLE 1. (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
69	101412	O	**535**	13			0.13			-	-
70	107612	SrCrEu	**439**	10			0			8.72	2.18
71	108662	SrCrEu	**1040**	66			0:			8.40	2.39
72	112185	SrCrEu	**330**	8			0			8.60	2.48
73	112413	SrCrEu	**2600**	8			0.10			8.30	2.85
74	115708	SrCrEu	**3850:**	3			0:			8.96	1.74
75	116458	He-w	**4676**	78			0.07			8.48	2.30
76	118022	SrCrEu	**1270**	25			0.1			8.65	1.94
77	119213	SrCrEu	**1237**	35			0			8.73	2.07
78	119419	Si	**17300**	73			0.05			8.30	2.44
79	122532	Si	**1064**	4			**0**			8.26	2.82
80	124224	Si	**2200**	3			0.30			8.04	3.03
81	125248	SrCrEu	**7300**	0			0			8.40	2.00
82	125823	He-r	**390:**	10			0:			7.48	5.83
83	126515	SrCrEu	**12322**	4			0.24			8.36	2.30
84	133029	Si+	**6157**	35			-0.3			8.36	2.40
85	133652	Si	**2200**	50			0			7.78	3.16
86	133880	Si	**5300**	16			0.20			8.16	2.93
87	137509	Si+	**2967**	20	17		0.10	0.10		7.98	3.43
88	137909	SrCrEu	**5620**	6	5		0.18	0.18		8.93	1.98
89	142301	He-w	**6425**	3	3		0.4	0.4		7.10	4.36
90	147010	Si+	**12000**	65			0.45			9.00	3.41
91	148112	SrCrEu	**276**	50			0:			8.70	2.13
92	148199	Si	**1350**	8			0			8.37	2.72
93	318107	Si+	**13307**	5			0.11			8.00	2.88
94	149438	O9	**828**	5	5	5	0.4	0.4	0.4	5.76?	-
95	151965	Si	**9565**	83:			0			7.73	4.07
96	152107	SrCrEu	**4100**	7	4		0.5	0.5		8.72	1.89
97	166473	SrCrEu	**7649**	15			0.28			9.00	2.06
98	169842	SrCrEu	**2000:**	25:			0			8.81	2.11
99	170397	Si	**1160**	5			0:			8.13	2.20
100	178892	SrCrEu	**8928**	35			0.15	0.0		8.88	1.93
101	182255	He-w	**<100**	0:	0		0.20	0.20		7.90	3.86
102	184927	He-r	**3265**	13			0			7.15	6.18
103	187474	Si+	**5317**	66			0.10			8.50	2.55
104	188041	SrCrEu	**3663**	83			0.07			8.78	2.07
105	191612	O	**600**	22			0			6.0	-

TABLE 1. (Conclusion)

1	2	3	4	5	6	7	8	9	10	11	12
106	192678	SrCrEu	**4668**	20			0:			8.63	2.44
107	196178	Si	**1847**	40			-0.15			8.02	4.02
108	200311	Si+	**8568**	4			0.08			7.95	3.77
109	201601	SrCrEu	**3846**	5			0:			8.97	1.65
110	215441	Si	**34000**	80			0.03			7.00	5.19
111	220825	SrCrEu	**678**	11			0:			8.69	1.94
112	223640	Si	**1026**	38	0		0.40	1.0		8.05	3.09
113	343872	Si	**3717**	26	0		0.10	0.50		-	-
114	200775	Ae/Be	**3950**	0			0:			-	3.36
115	V381Ori	Ae/Be	**2010**	0			0:			-	1.91

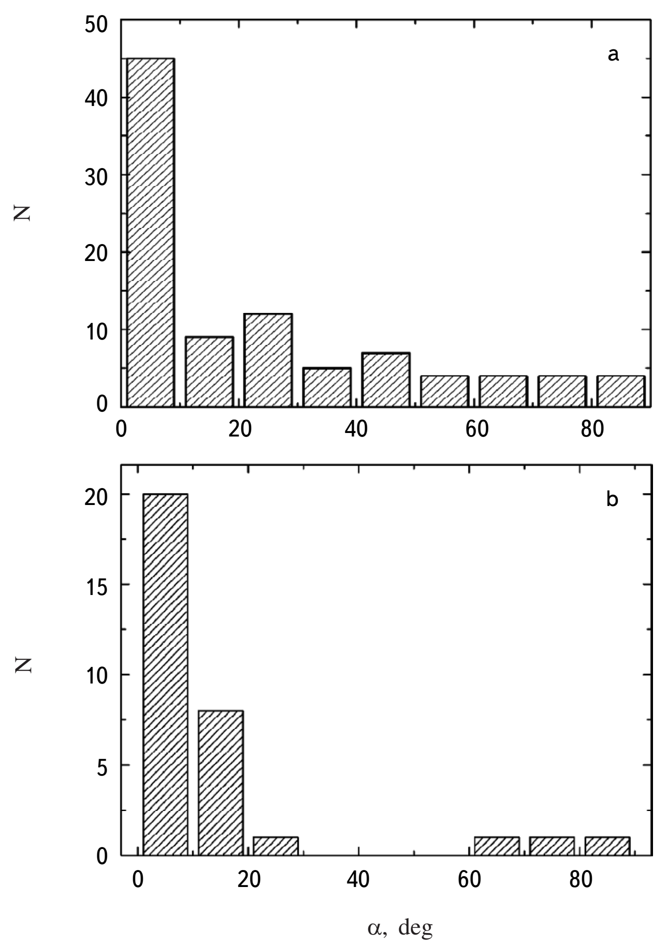

Fig. 1. Distribution of the stars with respect to the angle α: (a) (Si+SrCrEu)-stars; (b) (He-r+He-w)-stars.

The subsequent columns of Table 1 list the ages of the stars estimated using the parameters given in Refs. 20 and 21 and the evolutionary tracks from Ref. 22. The values of α and Δa are enumerated in columns designated 1, 2, and 3. The first column shows data for the "strongest" dipole, the second, for the average, and the third, for the weak dipole (according to the magnetic field strength). If we examine the distribution of the number of stars with different angles given in Ref. 23, then it appears that it is outwardly the same as the distributions of Preston and Landstreet. However, Figs. 1, a and b, show that the distributions constructed separately for low-mass stars of the (Si+SrCrEu)-type and massive stars of the (He-r+He-w)-type are substantially different. Usually we assume that if the angle α between the axis of the dipole and the plane of the equator of rotation lies between 0 and 20°, then the dipole is in the plane of the equator of rotation. It can be seen from Figs. 1, a and b, that among the massive magnetic stars, objects with dipoles lying in the plane of the equator of rotation predominate and there are almost no stars with $\alpha > 20^{\circ}$. Among the stars of the (Si+SrCrEu)-group, the ratio of the number of objects with small and large angles α is 1.35. For stars in the (He-r+He-w)-group this ratio is 7. This property shows up especially clearly in Figs. 2, a and b, where the distribution of a for magnetic stars with different masses is plotted. It is quite clear that massive

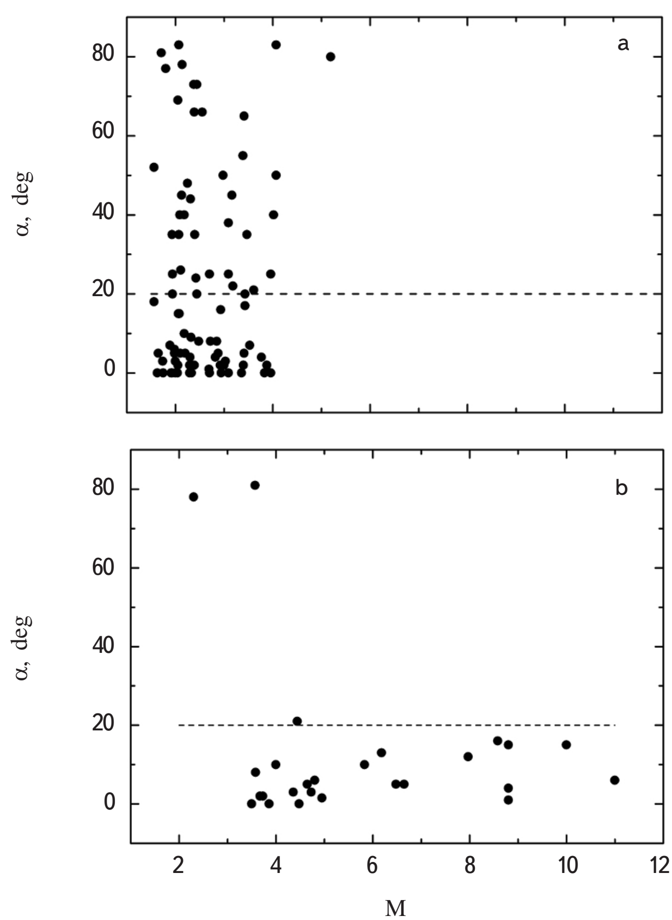

Fig. 2. The distribution of the angle α for stars with different masses.

CP-stars mostly have α < 20°. How can this difference be explained? It might be assumed initially that it is harder to brake massive stars than less massive stars. It is also known that massive protostars have a weaker magnetic field, as will be seen later in section 6 (as well as in Ref. 1). These two factors lead to a relatively weaker braking of massive protostars. Only those protostars which adhere to the orientation condition α = 0° (which leads to an excess of stars with α = 0-20°) more strictly will undergo efficient braking. Probably for the same reason, the relative number of massive magnetic stars is much lower than the number of low-mass stars.

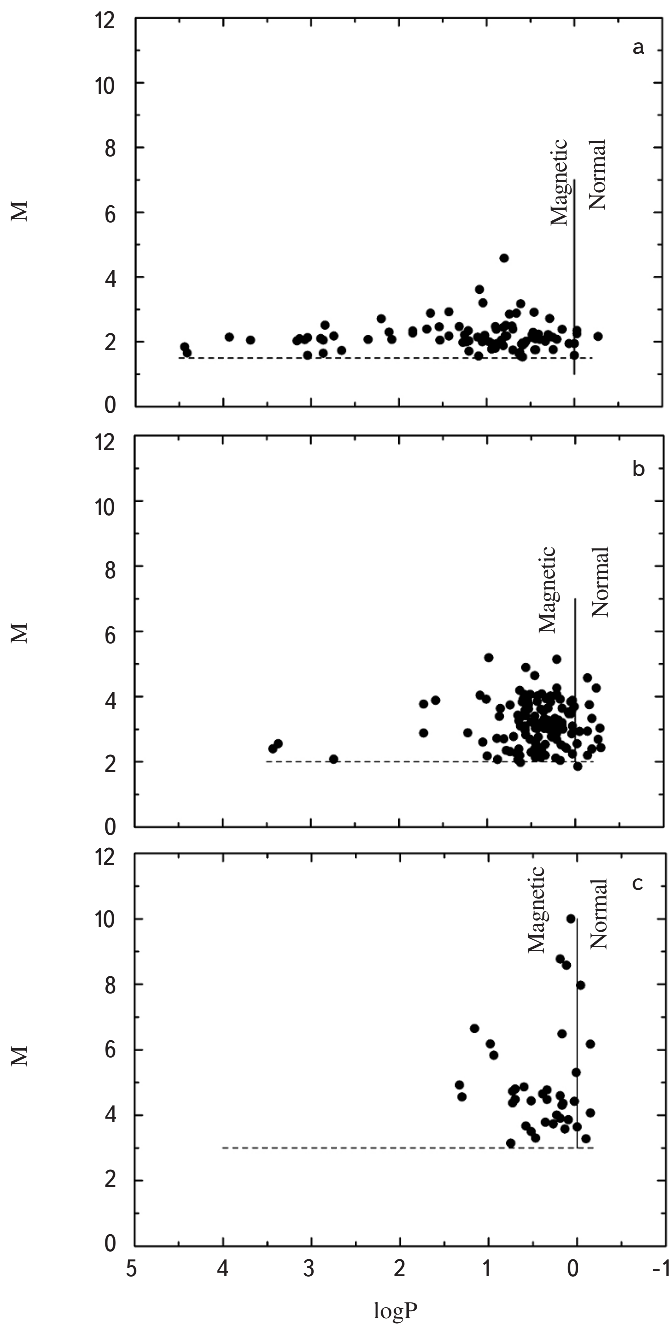

Fig. 3. Distribution of stars with different masses with respect to logP: (a) (He-r+He-w)-stars, (b) Si-stars, (c) SrCrEu-stars,.

4. Low-mass (SrCrEu+Si) stars have maximal rotation periods

We now consider the following property of magnetic stars with different masses: Fig 3 shows mass-rotation period, *M*(logP), plots for (a) low-mass (SrCrEu)-stars, (b) (Si)-type objects with medium mass, and (c) massive (He-r+He-w)-stars. The figure shows that, on the average, (He-r+He-w)-stars, (Si)-, and (SrCrEu)-stars have masses in the respective ranges $M = 3 \div 6 M_{\odot}$, $2 \div 4 M_{\odot}$, and $1.5 \div 3 M_{\odot}$. The large differences between the distributions for these three groups of stars are evident. The helium stars have a range of rotation periods $\Delta \log P = 0 \div 1.5$, the silicon stars have a medium range of masses and have rotation periods in the range $\Delta \log P = 0 \div 3.5$, and the SrCrEu-stars lie in the range $\Delta \log P = 0 \div 4.5$ and have the smallest range of masses. It may be assumed fairly confidently that the maximum rotation period is inversely proportional to the mass of the stars. The longest periods, up to 70 years, are observed in the low-mass SrCrEu-stars. The maximum period for the Si-stars is *P*(*max*) = 7 years and the massive He-stars have *P*(*max*) = 20 days. It is natural to assume that this is related to the facts that (1) it is easier to slow down a less massive parent protostar and (2) the average surface magnetic field is higher in less massive stars than in the massive stars with a helium anomaly (see section 6 and Ref. 1); therefore, they are braked more strongly. In addition, the low-mass stars evolve for longer and the slowing-down process is longer in them. This conclusion is the same as in section 3. The reason for the range of masses in these three groups of stars requires special study.

5. The boundary between normal and magnetic stars

It is clear from Fig. 3 that magnetic stars of all masses are adjacent to normal stars with almost the same value of $\log P(c) \approx 0$. This may mean that a single condition is necessary for differential rotation in the protostar [1,23]: an excess above some critical rotation velocity V_c (with differential rotation the inner regions rotate more rapidly). Most likely, as differential rotation develops, the magnetic lines of force are bent and create an invisible toroidal magnetic field. “Normal” stars formed “without a field” have *logP < 0*. Evidently, the log*P(c)* boundary can be overcome only by those heavy protostars (see section 2) for which the braking conditions are most favorable, i.e., which have the smallest angles α. Thus, in Fig. 2 we can see a predominance of massive stars with small α. Since the heavy stars are slowed down relatively weakly because of their high mass and low magnetic field, the *logP(c)* boundary is surpassed only by a small fraction of the stars and these all have relatively short rotation periods. At present, there are insufficient data on He-r and He-w stars for reliable statistics. Thus, the massive protostars which are slowed down the most are converted into magnetic stars within a narrow range of $\log P = 0 \div 1$, while the low-mass protostars are slowed down more strongly to form stars with $\log P = 0 \div 4.5$.

6. Massive magnetic (He-r+He-w)-stars have lower fields

This question has been discussed previously [1]. The dependence of the magnitude of the average magnetic field on the temperature (mass) of a star shown in Fig. 4 is one of the most interesting and clearest properties of

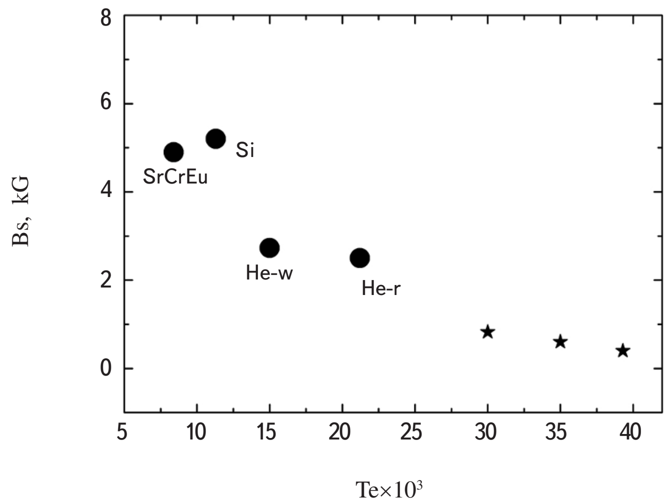

Fig. 4. Average magnitudes of the magnetic field *Bs* for stars with different average temperatures (masses).

magnetic stars. At the same time, we can refer to our earlier paper [24] in which it was shown that the fraction of magnetic stars with a weak field becomes larger as their mass increases. In this figure, the O-stars HD37022, 101412, and 149438, which have still weaker fields, are indicated by stars. There are various reasons for this variation. The first may be related to the different average ages of the stars. The average age of SrCrEu-stars is 20-30 times that of He-r-stars, so that there is less relaxation of the field in the latter after the ZAMS and the dipole magnetic field has also increased less. The second reason may be that the more massive stars were formed from a larger volume of protostellar material in which the number of differently oriented magnetized volumes was relatively larger. Thus, the total field vector is smaller. We now compare Figs. 3 and 4. The maximally braked stars have *logP(max) = 1.5* (3 and 4.5) for the massive and less massive stars, respectively. These groups of stars have *Bs* = 2.5 (5.1 and 4.9) G. Thus, it can be seen that when the magnetic field is stronger, the stars have been braked more strongly. This dependence is entirely to be expected and raises no questions. However, in section 4, based on Figs. 3, a, b, and c, we suggested that a different limiting value of *logP* may appear if the slowing down of low masses is easier. Thus, the two effects operate in the same direction. Which will predominate is unknown, but most likely it will be the magnetic field. Since we adhere to the hypothesis of angular momentum loss by protostellar clouds involving the magnetic field, it is necessary that the weak field in massive protostars should already be in the period before the Hayashi phase. This means that if the assumption of a lower degree of relaxation in stars with a helium anomaly is true, then it is so to a small extent.

7. Magnetic field distributions in protostars with different angular momentum

We shall try to study this distribution using data on magnetic stars in the Main sequence assuming that this dependence has been preserved throughout their previous evolution. For a long time, various authors have tried to find a relationship between the rotation velocity (or rotation period) of magnetic stars and the magnitude of the magnetic field under the assumption that such a dependence must exist, even in the case where angular momentum is lost under the influence of the magnetic field and in the case where the magnetic field was generated by a dynamo mechanism. It was found [26,27] that there are no signs of the braking of magnetic stars in the Main sequence; if this has happened it was only in earlier stages of evolution [28]. Hints of an anticorrelation between the magnetic field and the rotation speed have been noted [29,30]. The $\langle Be \rangle(\log P)$ dependence, which we studied in 1986 [31] using the mean square magnitudes of the magnetic field $\langle Be \rangle$, has a maximum at $\log P \approx 0.7$. There the right hand side was obtained on the basis of a large number of stars and agrees reliably with the assumption of an anticorrelation. The left part is less reliable and corresponds to a direct correlation. As observational data have accumulated, it turns out [32] that there is no doubt about the reality of this maximum. The early papers did not reach a definite conclusion about the nature of this dependence. No definite signs of the working of a dynamo or of a braking mechanism were found. The number of advocates of the dynamo mechanism is becoming ever smaller.

This problem has been re-examined [2,4]. The dependence *Bs*(log*P*) was not studied, but the character of the distribution of the stars in *Bs*, log*P* coordinates was examined. Figure 5 shows this distribution constructed from the data of Refs. 3 and 14. The dashed curve denotes the region occupied by the low-mass SrCrEu-type stars and the

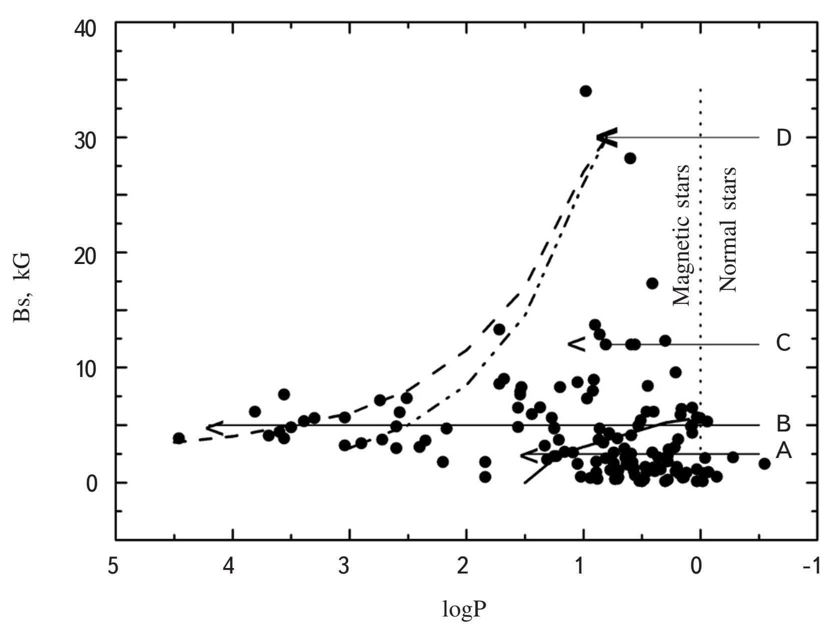

Fig. 5. Distribution of magnetic field (*Bs*) with respect to rotation period (log*P*).

dot-dash curve, medium mass Si-type stars; these curves are similar. The smooth curve bounds the region of massive He-stars. It differs substantially from the other curves. As we saw above, the degree of slowing-down of the protostellar cloud is inversely proportional to the mass and proportional to the magnitude of the field. In massive protostars, these two factors are weak (arrow A). In low-mass protostars, the two factors act strongly. Compared to the massive protostars, the degree of slowing-down in these is greater (arrow B). In both cases we observe signs of an effective slowing-down mechanism that depends on the magnetic field and mass. In the former case, the maximum efficiency occurs at $Bs \approx 2.5$ kG and in the latter, at $Bs \approx 5$ kG.

The asymmetry in the *Bs(logP)* curves toward larger *Bs* for low-mass protostellar clouds in the region $\log P = 0 \div 1$ seems incomprehensible. A small number of stars with the maximum field appear to be slowed-down weakly. This gives the impression that some protostars are slowed down weakly, despite a high field (arrows C and D). Thus, some of the protostars are braked in accordance with the two causes examined above (arrows A and B), while the reasons for the weak braking of most magnetized protostars are obscure. These kinds of parent protostars

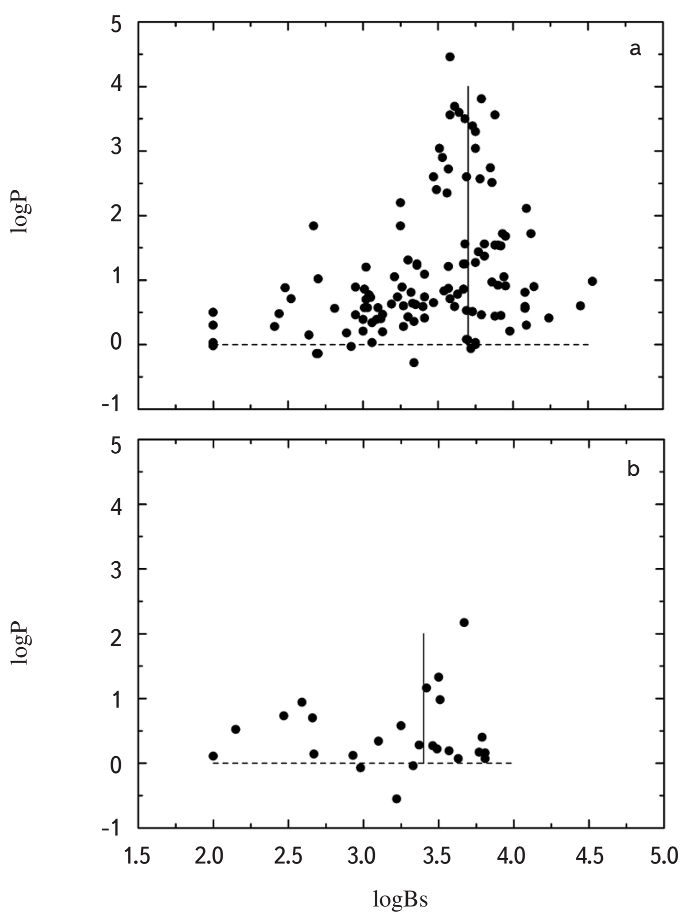

Fig. 6. Distributions of the number of stars (periods P) with respect to magnetic field *Bs*: (a) (Si+SrCrEu)-stars, (b) (He-r+He-w) stars.

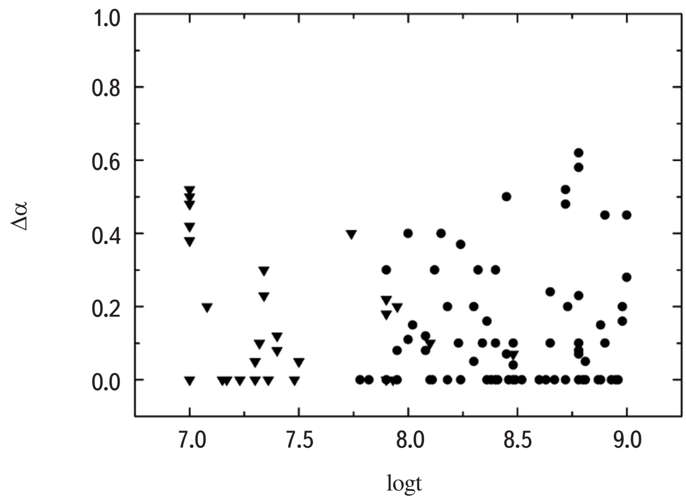

Fig. 7. Displacements $\Delta\alpha$ of monopoles from the center of the stars for stars with different ages.

are slowed down weakly and have only moved slightly away from the boundary with normal stars. They represent about 8.5% of the overall number of stars. No other features distinguish them from the other magnetic stars. It seems that there is some cause which attenuates the braking of parent protostars with high fields. In particular, this might be an atypical structure of the protostellar clouds. The problem requires detailed study.

The maximum efficiency of braking at Bs = 5 kG is much more noticeable in Fig. 6a, where the (Si+SrCrEu)-stars are plotted on log*Bs*-log*P* axes. The vertical line indicates the direction of the maximum braking corresponding to Bs = 5 kG and the horizontal line separates the magnetic and normal stars. It is evident that in this figure the stars undergo braking from the bottom upward. The analogous plot for (He-r+He-w)-stars is shown in Fig. 6b. There are few of these stars, but the distribution seems similar. For stars of this type, the maximum braking efficiency occurs at Bs = 2.5 kG. The degree of slowing down for the massive protostars is considerably less.

The distribution of the magnetic plus nonmagnetic CP-stars with respect to *v*sin*i* (instead of log*P*) has been studied [33]. The maximum of their distribution occurs at *v*sin*i*~25 km/s, and the maximum for the normal stars at *v*sin*i*~200 km/s. The maximum magnitudes of the rotation velocities, therefore, occur at 150 and 350 km/s. The relative numbers of magnetic (points) and nonmagnetic Ap and Bp-stars (stars) [33] for different *v*sin*i* were plotted separately , but it is clear that they are similar [Fig. 8]. These curves correspond to the distribution *Bs*(log*P*). Since the dependences for magnetic and nonmagnetic CP-stars are the same, this shows that their variation is independent of magnetic field, i.e., the field is not involved in the process of separating the stars into chemically peculiar and normal. We thus conclude that the main, if not only, contributor to separation of the stars is the rotation speed; the separation boundary lies roughly at *v*sin*i* = 120 km/s, which corresponds to a rotation period $P \approx 1^{d}$. In Fig. 7, it is indicated by a vertical smooth line. It this regard, it is proposed (see below) that among the protostellar clouds there is a corresponding critical angular velocity v_c at which the magnetic and nonmagnetic CP-stars are separated from the normal stars. The existence of such a boundary requires the assumption that a separation mechanism dependent on the rotation velocity is operating. Most likely, this is differential rotation of the protostars which bends the magnetic lines of force and thereby forms "normal" nonmagnetic stars [3]. A meridional circulation in young stars "before" the ZAMS is less likely as a possible field-free mechanism for separation of normal stars from magnetic and CP-stars. This problem requires further serious study.

It is probable that the loss of angular momentum of protostellar clouds under the influence of a magnetic field also leads to the well known shortage of close binaries among the magnetic stars. At the same time, the normal number of close binaries among metallic stars may be a sign that they have not been slowed down by the magnetic field. The nonmagnetic Am, HgMn, λ Boo, and other stars have most likely developed from nonmagnetic very "slow" protostellar clouds, while the magnetic stars develop from magnetized slowed-down magnetic clouds or initially "slow" magnetic rotators. The difference between magnetic and chemically peculiar stars without a field appears only to be that with a completely stable atmosphere, in the former case, the diffusion of chemical elements is driven by radiation pressure, gravity, and wind in a magnetic field [34] and in the latter, by the same mechanisms but without involvement of a field.

8. The magnetic field structures of stars do not change with age

Figure 7 is a plot of $\Delta a(\log t)$, where Δa is the displacement of a magnetic monopole from a star's center. When it is larger, the magnetic field structure of a star is more complicated. If $\Delta a = 0$, the magnetic field structure corresponds to a central dipole. The circles denote SrCrEu- and Si-stars, and the triangles, He-r+He-w-stars. Figure 7 shows that there are objects with a complicated magnetic field structure among the youngest and oldest stars; on the average, the displacement Δa is the same for massive and low-mass stars. There is only one conclusion: the structures do not vary with age. The stars rotate as rigid bodies. Even in the initial stages of research on magnetic stars, it was proposed that magnetic stars rotate rigidly [35-36]. Nevertheless, in order to explain the predominant orientation of the magnetic fields and other properties, the hypothesis of a slow meridional and other circulations has been proposed [37], which should change the magnetic field structure over time. We have advanced arguments [1] in conflict with the assumption of any kind of large-scale motions inside magnetic stars. In Ref. 3, for example, models of the magnetic fields of two stars, HD37776 and HD137909, are discussed. The magnetic dipoles in these stars lie in the plane of the equator of rotation and their ages differ by about two orders of magnitude. When large-scale motions existed inside the stars, the orientation of the dipoles was different. Other, similar examples can be adduced. In Refs. 3 and 35, and in this paper, the distribution of the angles α is examined. It has a distinct maximum at $\alpha = 0^{o} \div 20^{o}$. Since stars of all ages are included in this distribution, the maximum would inevitably be "smeared out" if there were large-scale motions of matter inside the stars. This should be supplemented by modelling of Ae/Be Herbig stars [38], which shows that the dipoles are oriented along the plane of the equator of rotation in the youngest stars and that there are no large-scale motions that could change their orientation. It has been shown [1] that the magnetic field of CP-stars is damped only after ohmic (Joule) losses to an age of at least 10^{10}-10^{11} years. This indicates that damping of the field occurs under conditions under which there are no additional disruptive forces such as meridional circulation, differential rotation, turbulence, or any large-scale motions inside the stellar plasma.

Four characteristic types of magnetic structures are observed in stars of all ages. They could not be preserved over the lifetime of magnetic stars, the largest of which is $t = 10^9$ years, if large-scale flows existed. Because there are no large-scale motions of matter in magnetic stars, we observe long-lasting, large structures in the example of stars with nonsymmetric magnetic field configurations Δa (Fig. 7) which leave the Main sequence while retaining their shape. This figure also shows that the youngest stars have the same nonsymmetric structure produced during the initial phases of gravitational collapse. Thus, plots of the distributions of stars with different structures with respect to age show that they are uniformly distributed. This means that the structures essentially do not change with age. All of this shows that magnetic stars rotate rigidly, as has long been assumed [35]. The large-scale magnetic structures are extremely long-lived [1]. They easily survive the entire period from the time of formation to the time of leaving the Main sequence.

9. Comments on the nature of nonmagnetic CP-stars

In Figs. 3, a, b, and c, it is clear that magnetic and normal stars are separated at $\log P(c) \approx 0^{\mathrm{d}}$ (1 day) owing to differential rotation in the protostars at velocities in excess of the critical value V_c. This problem has been discussed previously [1]. As opposed to the conclusions of that earlier work, here we assume that the separation most likely takes place in the protostar collapse phase, rather than in the stages after the Hayashi phase. We cannot

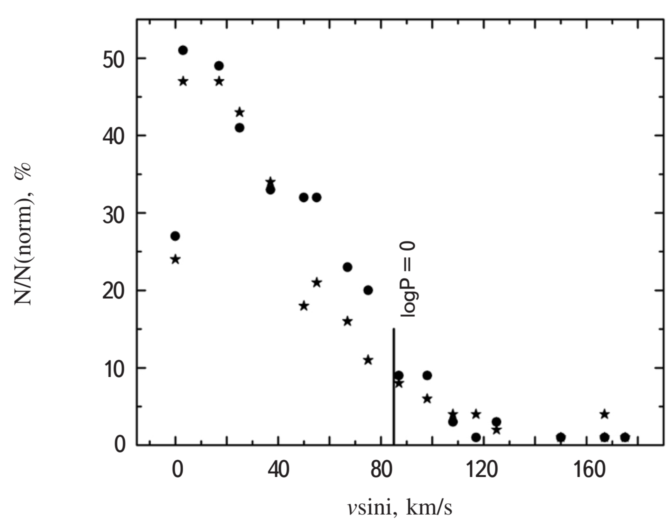

Fig. 8. Relative number of magnetic (circles) and nonmagnetic (stars) CP-stars as a function of $v$sin$i$.

construct plots of *M(logP)* for nonmagnetic CP-stars because the rotation periods are not known. But a comparison of the ratio *N/N*(*norm*) of magnetic and nonmagnetic CP-stars for different *v*sin*i* relative to normal stars shows that they are the same (Fig. 8 [38]). This confirms that (1) the magnetic field is not involved in the separation of the stars and (2) the boundary $\log P(c) \approx 0^{d}$ is the same for both types of stars. In Fig. 8 this boundary is very fuzzy because of the effect of the angle of inclination *i* and it lies near $v \sin i \approx 80-85$ km/s. The magnetic fields slow down the rotation of the protostars, so that a large number of them cross the boundary $\log P(c) \approx 0^{d}$. The situation is different for nonmagnetic Am, HgMn, and other objects. Their rotation velocities must be below critical from birth.

10. Conclusion

(1) The properties of magnetic stars discussed above do not conflict with the hypothesis of selective magnetic braking of protostellar clouds. Braking is more efficient in clouds where the magnetic lines of force are parallel to the plane of rotation.

(2) The degree of slowing down of the protostars may depend on the mass of the cloud, with stronger braking when the mass is lower. Low-mass stars have maximal rotation periods.

(3) The degree of slowing down of the protostars depends on the magnitude of the magnetic field. When the field is higher, the braking is stronger.

(4) The above data show that the boundary between magnetic and normal stars does not depend on mass; it corresponds to $\log P \approx 0$. This fact is consistent with the hypothesis of differential rotation in the parent protostellar cloud at a certain rotation velocity V_c where the magnetic field lines are bent into an “invisible” toroidal shape. The situation is different for nonmagnetic Am, HgMn, and other objects. The rotation velocities of the parent protostars must be lower than critical from the start.

(5) The difference between the distributions $N(\alpha)$ for stars with high and low masses has been pointed out for the first time. It is suggested that because of the difficulty in slowing down large masses and their relatively lower fields, only the small fraction of protostars with the most favorable orientation of their magnetic field lines in the range $\alpha = 0^{o} \div 20^{o}$ will be slowed down.

(6) The long-studied *Bs*-log*P* distribution of the stars has a convincing explanation. This distribution is a consequence of the dependence of the degree of slowing down on stellar mass and magnetic field (Figs. 3 and 4). This problem requires theoretical analysis.

(7) The magnetic field structures in magnetic stars are constant over their entire lifetime in the Main sequence. There are no large-scale motions inside the stars which might distort the magnetic field structure during their time in the Main sequence.

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