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MAGNETIC STARS AFTER THE HAYASHI PHASE. I

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The problems of the origin and evolution of magnetic stars based on analysis of observational data are discussed. It is assumed that magnetic stars acquire their major properties during the protostellar collapse stage. The properties of magnetic stars after the Hayashi phase are examined in detail.

Keywords: *magnetic stars: origin and evolution: Hayashi phase*

1. Introduction

This paper is a further discussion of the scenario for the formation and evolution of magnetic stars examined in Ref. 1. We have briefly examined [2-4] aspects of the formation of magnetic stars during the period of the gravitational collapse of protostellar clouds prior to the nonstationary Hayashi phase and in the Main sequence. It was shown that the major properties of magnetic stars are the following: (1) predominant orientation of the magnetic lines of force relative to the plane of the equator of rotation at an angle $\alpha \sim 0^{\circ} - 20^{\circ}$; (2) a low rotation speed; (3) complicated magnetic field structures; (4) a separation of stars into magnetic and normal in a ratio of 1:10, most likely formed during the early evolutionary period. It should be emphasized that any hypothesis regarding the formation and evolution of magnetic stars must explain these properties, but this does not often happen. The articles cited above provide arguments in favor of the assumption that these properties were most likely the result of a unified process—

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a selective (with respect to the angle α) slowing down of the protostellar clouds by a magnetic field. This argument, in fact, simultaneously supports the relict hypothesis for the formation of magnetic stars. It is unlikely that these properties were acquired in later, nonstationary phases of evolution, specifically in the period of the Hayashi phase and of young Ae/Be Herbig stars. In this paper we attempt to discuss another important period in the evolution of magnetic stars: the behavior of the magnetic field in the Main sequence. This problem was examined in part in Ref. 4.

2. The magnetic field of young stars before emergence into the ZAMS

After a magnetic protostar passes through the nonstationary Hayashi phase [5], the magnetic lines of force inside the star are entangled in a most complicated way because they are frozen into the material. Turbulence can concentrate the lines of force into ropes, cells, filaments, etc. [6,7], which are not stable. The matter in the star is an ionized plasma. In magnetohydrodynamics, a plasma is treated as a continuous medium. A Lorentz force, which is proportional to the current density j and magnetic induction B, acts on charged particles (ions and electrons) moving in a magnetic field. A close current is produced. Ion-electron collisions lead to dampening of the current and the release of Joule heat. The magnetic energy sustains the current in accordance with the principle of self induction and is then expended in heating of the plasma. The damping of the current depends on j and the conductivity σ. The conductivity in stars is very high and the magnetic field damping time owing to Ohmic (Joule) losses is given by

$$t = 4\pi\sigma r^2 , \tag{1}$$

where σ is the plasma conductivity and r is the characteristic size of the magnetized region [8]. This formula shows that the small magnetic field inhomogeneities that appear during the nonstationary Hayashi phase are damped very rapidly. Given the ages of magnetic stars, only large-scale magnetic structures can remain in them. The fine magnetic structures after the nonstationary Hayashi phase vanish rapidly and their damping is accompanied by strong currents and Joule heating. If the surface through which the current flows is very large, as in the case of stars, then the damping of the overall field takes place very slowly. When r is on the order of the star's radius, the magnetic fields are conserved for up to 10^{10}-10^{11} years. For these damping times in stars with a large-scale dipole magnetic field, the current density j and the Joule heating are negligible and the effect is unobservable. (Because of their immense sizes, in interstellar clouds the magnetic field damping times are exceptionally long.)

Another factor which simplifies the magnetic field structure over time is related to the pulling of magnetic lines of force [9] by a force equal to

$$T = AB^2/4\pi , \tag{2}$$

where B is the magnetic induction and A is the transverse cross section of a magnetic tube. A nonuniform field is

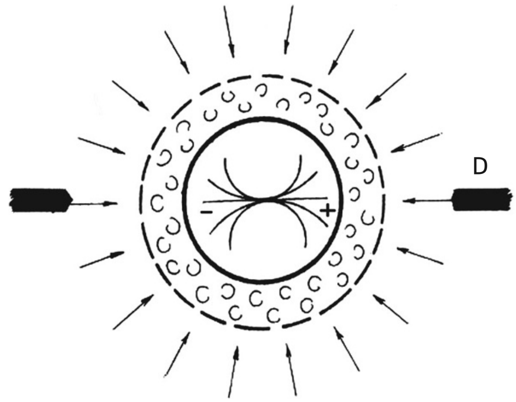

Fig. 1. Sketch of a young magnetic star after the Hayashi phase. The axis of the magnetic dipole is indicated in the plane of the equator of rotation. *D* denotes the disk.

also destroyed by other, less efficient processes. In turbulent media, part of the magnetic flux is dissipated by buoyancy, turbulent diffusion, etc. [6,9]. If small-scale magnetic fragments B_i inside a star (Fig. 1) are included in an overall large-scale structure of strength B_0, then after they have undergone Ohmic dissipation, the large-scale field will recover to B_0 at their location. Thus, this is a possible reason for an increase in the magnetic field of a star as small-scale fragments disappear.

After the Hayashi phase, in terms of the relict mechanism, a substantial magnetic flux is preserved up to the time when a young star develops with radiative energy transfer. Since there is no convection inside a young star, from the time it is formed the entangled magnetic field begins to relax, rapidly at first because of the vanishing of the small-scale magnetic fractions and then ever more slowly. Obviously, the relaxation times for stars of different types should be almost the same, since they depend mainly on the conductivity σ, which is high in all stars because of full ionization. Therefore, after the Hayashi phase in young stars we observe a combined magnetic field vector $\mathbf{B} = \mathbf{B}_0 + \sum \mathbf{B_i}$, where $\mathbf{B}_0$ is the main global relict (poloidal) field and $\mathbf{B_i}$ are the small-scale inhomogeneous fields generated by nonstationary processes during the Hayashi phase. After the Hayashi phase, there are no processes which could produce the poloidal structure that is observed now. The small-scale fractions of the magnetic field are oriented arbitrarily, so they sum to a magnetic field $\sum \mathbf{B_i} = 0$. Thus, in young stars we are dealing with a two-component magnetic field structure. Spectrum lines will be split by the poloidal component of the magnetic field $\mathbf{B}_0$ and broadened by $\mathbf{B_i}$, depending on the Landé factor, owing to the nonuniformities. The small-scale part of the magnetic field is noticeable in real magnetic stars [10]. The characteristic sizes of the large-scale observed magnetic inhomogeneities are on the order of the star's radius, so when there are no disruptive factors, such as turbulence, differential rotation, or meridional circulation, they remain essentially unchanged over the entire lifetime of the star in the Main sequence, and thus the maximum lifetime of magnetic stars is t = 10^9 years [1,3]. This is two or three orders of magnitude less than the theoretical magnetic field lifetime. It is difficult to say how high the magnetic field was up to the nonstationary Hayashi phase, but it was most likely higher [11]. Since the bulk of the lines of force are strongly deformed, $\mathbf{B}_0$ is substantially reduced after the nonstationary Hayashi phase. The component $\mathbf{B}_0$ is ensured by the fact that the magnetic inhomogeneities preserve the fraction of the predominant orientation imposed in the early phases of evolution. This is an important point because it was assumed before that any magnetic field would be completely destroyed during the convective Hayashi phase and it was also assumed that a magnetic field had to be generated inside the star by some kind of magnetic dynamo. Observational data show that a high dipole magnetic field is restored only at the time the star enters the ZAMS (Zero Age Main Sequence) [1,3,12,13]. In this situation, we cannot speak of the existence of strong magnetospheres with a simple structure (e.g., dipoles) in young Ae/Be Herbig stars. This shows that, during the evolutionary period between the nonstationary Hayashi phase and the Main sequence, the magnetic slowing-down mechanisms proposed by several authors are unlikely, especially in the nonstationary Hayashi phase. This circumstance supports the assumption that the slowing down has taken place during the gravitational collapse stage of the protostellar clouds. Since the decay time for the combined magnetic field of magnetic stars is much greater than their age, the field does not have to be supported and is conserved from the time of formation [14]. The ratio of the large- and small-scale components of the field gradually changes in favor of $\mathbf{B}_0$. In addition the preferential relict orientation $\alpha = 0^{\circ} - 20^{\circ}$ of the magnetic field lines relative to the plane of the equator of rotation is retained [1]. The large-scale relict fraction appears to be little distorted during the Hayashi phase because the currently observed distribution of magnetic stars with respect to α is fairly distinct [1] and lies mainly within a range of 0-20°. These fact show that the destructive activity of the Hayashi phase is quite moderate. It has been shown [1,4] that the predominant orientation of the magnetic lines of force develops as a result of selective (relative to α) slowing down of the protostellar cloud by the magnetic field. Those clouds in which the magnetic lines of force are parallel to the plane of rotation will be slowed down more rapidly. Since these conditions exist in only about 10% of cases, the fraction of magnetic stars is roughly the same. The mechanism of selectivity relative to the angle α explains the major properties of magnetic stars: slow rotation, orientation of the magnetic lines of force in the plane of rotation, and the 10% fraction of magnetic stars. Later (in section 7) we examine a probable mechanism, owing to slow rotation, for the separation of magnetic stars from normal stars.

A young star is surrounded by a nonstationary accretion cloud (Fig. 1) in which a poloidal magnetic field cannot exist. In addition, the cloud inhibits the outward movement of the magnetic field of young stars (in Fig. 2, *D* denotes the accretion disk). Only after the nonstationary shell and disk vanish is it possible to observe the photosphere of a young star, i.e., the magnetic field can only be measured before the star emerges into the ZAMS [15]. Two factors ensure a growth in the magnetic field of a star that has entered the ZAMS: (1) a gradual increase in the poloidal component of the field owing to the relaxation of small-scale structures and (2) a reduction in the instability and accretion which destroy the surface structure of a magnetic star and shield the internal magnetic field. The appearance of magnetic stars in the ZAMS can be seen clearly, as in the case of so-called "post-Ae/Be Herbig" stars [16,17] and of stars belonging to extremely young clusters and groups. It appears that they already have a fairly strong field which suppresses surface instabilities and thereby makes the diffusion of chemical elements easier. These

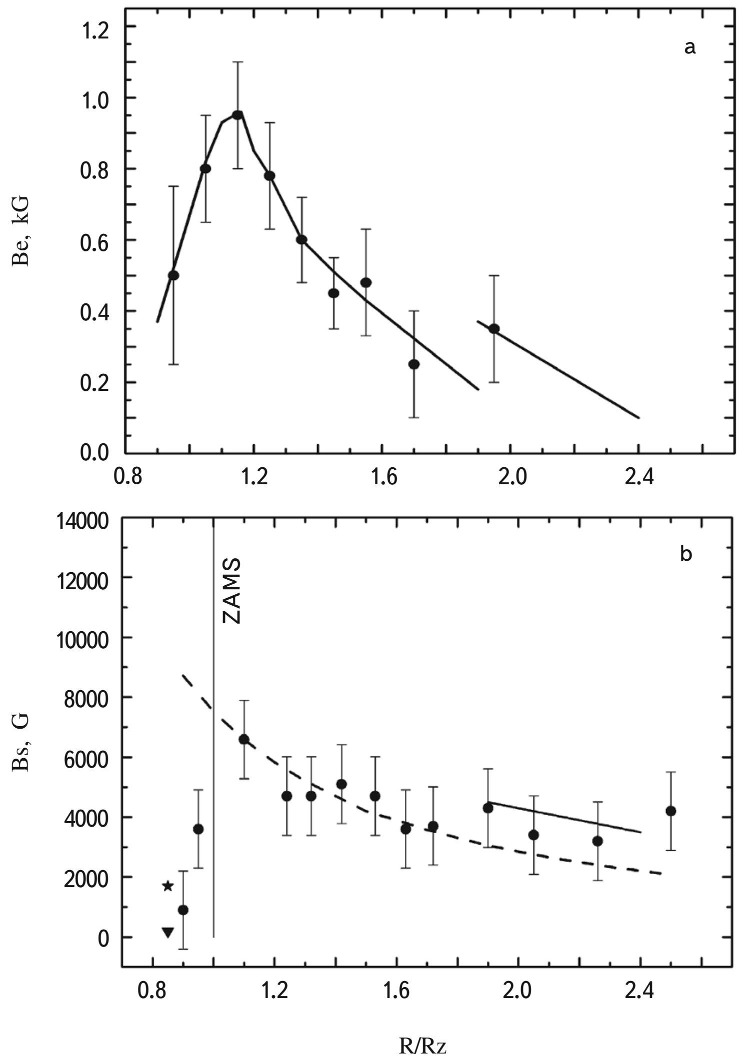

Fig. 2. Magnetic field variation during the evolutionary movement of stars (all types of peculiarity, together) perpendicular to the Main sequence. Shown here are plots constructed from (a) the mean-square values of the magnetic field and (b) mean values of the surface magnetic field. The dashed curve is for a quadratic variation in the magnetic field.

stars are distinct in that they have significant infrared excesses.

Table 1 lists data on the age of stars with different types of peculiarity in the ZAMS, followed by data on the maximum and average ages, taken from the catalog of Ref. 18. Row 4 lists the maximum theoretical times t (max) calculated with Eq. (1) for conservation of the magnetic field in stars of different types; these depend on the diameters of the stars. The same formula was used to estimate (with data from the first row and t (max)) the minimum relative sizes $L_{(ZAMS)}/L_*$ of the magnetic inhomogeneities on the ZAMS and $L_{(avg)}/L_*$ in the middle of the Main sequence zone;

TABLE 1. Average Age of Stars with Different Types of Peculiarity in the ZAMS.

	Type of star	He-r	He-w	Si	SrCrEu
1	Age in the ZAMS, years	$5 \cdot 10^6$	$1 \cdot 10^7$	$2 \cdot 10^7$	$2 \cdot 10^8$
2	Maximum age, years	$6 \cdot 10^7$	$3 \cdot 10^8$	$6 \cdot 10^8$	$1 \cdot 10^9$
3	Average age, years	$2 \cdot 10^7$	$6 \cdot 10^7$	$2 \cdot 10^8$	$6 \cdot 10^8$
4	t (max)	$5.0 \cdot 10^{11}$	$2.7 \cdot 10^{11}$	$1.5 \cdot 10^{11}$	$1.2 \cdot 10^{11}$
5	$L_{(ZAMS)} / L_*$	0.004	0.01	0.03	0.08
6	$L_{(avg)} / L_*$	0.03	0.03	0.06	0.10
7	Fraction of stars with a low field	0.60	0.55	0.40	0.20

these are listed in rows 5 and 6. This shows that rather large inhomogeneities still persist in the ZAMS, while the magnetic inhomogeneities relax to a much smaller extent in the relatively young He-r stars than in the SrCrEu objects. It is not, therefore, surprising that aside from the global dipole component of the magnetic field, inhomogeneities of average size [10] are observed in magnetic stars.

The phase prior to the ZAMS is relatively short in time for stars of all types, except for SrCrEu-type stars (Table 1, row 1). The average ages given in row 3 also differ greatly. Observations show that for stars with shorter average ages, the fraction of objects with low fields (<200-300 G) is greater [19], as shown in row 7. The effect of the field increase with time is evident, as is the relative shortness of the time for recovery of the magnetic field after the Hayashi phase, especially for stars with helium anomalies. A large fraction of them probably have structures with complicated configurations.

As noted above, the lines of force in young stars cannot move outward until the time that accretion and instability end, when the star loses its shell and approaches the ZAMS. Only after this can a dipole-type magnetosphere develop on the star. Nevertheless, efforts have been made at various times to detect a magnetic field in Ae/Be Herbig stars.

The first attempts to search for magnetic fields in Ae/Be Herbig stars were made with a small array covering a short range of wavelengths in 1997-2001 [20-22]. This could not yield measurements with great accuracy (it averaged only a few hundred Gauss). Thus, the search was limited to strong magnetic fields of a magnitude typical in magnetic stars, i.e., several thousand Gauss. No such stars were found and it was concluded that Ae/Be Herbig stars do not have fields as high as several kilogauss. This conclusion was extremely important in connection with the rapid rise in the magnetic field after the ZAMS. It also indicates that, during the Hayashi phase, the magnetic field was "suppressed" by nonstationary processes.

A serious change in the approach to this problem occurred only after a substantial improvement in the accuracy of the measurements. The first data indicating the existence of low magnetic fields in Ae/Be Herbig stars were obtained in a number of papers [23-32]. These data showed that detecting the magnetic fields depends first of all on the measurement accuracy, as well as on the lines (photospheric or shell) used to measure the field. All data accumulated up to now show that the magnetic fields in young Ae/Be Herbig stars are low, on the order of tens or hundreds of Gauss.

More interesting data were obtained [33,34] in a study in which the variability of the magnetic fields was demonstrated and phase dependences of the longitudinal magnetic field were obtained for two Ae/Be Herbig stars, HD200775 and V380Ori. Model calculations [35] showed that the rotational poles of these two stars are directed toward the observer and for this reason surface regions were observable with little distortion owing to disk accretion. Besides these two stars, two other Ae/Be Herbig stars, HD 37022 [36,37] and 101412 [37,38], have been modelled; they also turned out to have dipole magnetic field structures. These results show that up to the time young stars emerge into the ZAMS, some of them have already been able to develop a substantial field with a clearly distinct dipole structure. We estimate the ages of these stars to be $t = 0.1 \cdot 10^6$, $2 \cdot 10^6$, $0.1 \cdot 10^6$, and $0.5 \cdot 10^7$ years, respectively; that is, they are actually near the ZAMS. It is important that the magnetic field in such young stars is already oriented along the plane of the equator of rotation ($\alpha \approx 0^o$). This means that the orientation of the magnetic fields is not determined by a slow meridional circulation [6,39], but rather by the selective (with respect to the angle α) slowing down of the protostellar clouds discussed in Refs. 1 and 4. These four objects have not been measured with sufficient accuracy for detailed modelling, so that central dipole models have been applied to them as a first approximation. The exact shape of the phase dependences for Ae/Be Herbig stars would be extremely important for studying the magnetic field evolution, since the field structures of young stars should contain traces of earlier nonstationary processes that have not yet been smoothed out. The example of these stars demonstrates that a substantial, although still relatively low, dipole field may yet exist in the "pre-Main sequence" evolutionary stages and that in the central regions of young radiative stars the conditions may be sufficiently stable for onset of the recovery of a global relict magnetic field. On the other hand, the systematic weakness of the magnetic field in Ae/Be Herbig stars confirms the activity of an unstable Hayashi phase in the past where the poloidal magnetic field was highly entangled and weakened, and the nonstationary shell was shielded. This is an important result for the physics of magnetic stars and corresponds to the situation before a star enters the Main sequence. The process of recovering the dipole magnetic field should be examined theoretically in the future.

3. Magnetic field behavior in the Main sequence

The initial period of magnetic field growth in stars emerging into the ZAMS is of particular interest since there are some theoretical uncertainties in this process. Thus, a considerable amount of attention has been devoted to this problem [12,13,40,41]. We mentioned above that if the small-scale magnetic components B_i inside a star (Fig. 1) are included in a general poloidal large-scale structure of strength B_0, then after they have undergone Ohmic dissipation the large-scale field recovers to B_0 in their place. The major shortcoming of these studies is a lack of observational data for stars lying near the ZAMS because of the low magnetic fields at that time, so the chemical anomalies are weak. One of the first dependences of the magnetic field on time in the Main sequence was studied in 1988 [41]. That curve is shown in Fig. 2a, where the mean square magnetic field $\langle Be \rangle$ is plotted as a function of *R/Rz* (log proportional). In this graph, the increase in the magnetic field after the ZAMS up to the maximum at *R/Rz*=1.1 - 1.2, which corresponds to the position of stars with class *V* luminosity, can be seen clearly. Later searches for this kind of dependence have confirmed the character of the field variation in the Main sequence. In Fig. 2b the circles show the dependence *Bs*(*R/Rz*) of the average surface values constructed using the latest data [2,13] for 160 stars. Here the rise in the field after the ZAMS is also clearly evident. The dashed curve shows the observed quadratic dependence. If the structure of the magnetic field corresponded to a theoretical dipole, then this dependence would be cubic, in accordance with the formula $B = qr/R^3$ for a magnetic dipole, where q is the monopole charge, r is the distance between the charges, and R is the distance from the dipole. The smaller exponent is explained by the fact that a substantial fraction of the stars have magnetic field structures that differ from the theoretical central dipole. This leads to a weaker dependence than cubic for *Bs*(*R/Rz*).

It is interesting to study the initial point at which the magnetic field rises at the ZAMS. The strongest fields for Ae/Be Herbig stars have been observed for HD 37022, 101412, 200775, and V381 Ori, as shown above. The average surface magnetic field for these stars is *Bs* = 1725 G. The average longitudinal field *Be* for 13 Herbig stars lying near the ZAMS [34], for which the field exceeds 2s, is equal to 355 G. From the statistical relation $Bs = 6 \cdot Be$ [42], we find *Bs* = 2130 G for these 13 stars. The average of these two estimates is indicated in the plot of Fig. 2b by a star. This is the highest known value for Ae/Be Herbig stars. Taking all the other known magnetic field measurements for Ae/Be Herbig stars into account yielded a substantially lower value of the field, which is indicted in the graph by a triangle. On the Hertzsprung-Russell diagram these young stars lie near the ZAMS, so, as a first approximation, we assume the average value $R/Rz \approx -1.1$ for them. We took the value indicated by the triangle in Fig. 2b to be the initial point for the magnetic field rise. Given the curves of Figs. 2a and 2b, we conclude that after the unstable Hayashi phase the magnetic field was weak because the lines of force in the young star actually had a complicated entangled shape with significant shielding by the nonstationary shell. The small-scale fraction disappears rapidly because of relaxation with gradual conversion into a strong poloidal field with a direction of the magnetic field lines that corresponds to the large-scale relict field B_0. By the time the nonstationary shell disappears, the field of the young star is partially formed, after which it becomes noticeable. We believe that this is an important assumption for the physics of magnetic stars.

Because of a lack of data, it was not possible to plot the time dependences of the mean square $\langle Be \rangle$ and mean surface field *Bs* separately for stars with different kinds of peculiarity. In addition, because of the small amount of data and their large spread, the shape of the *Bs*(*R/Rz*) curve was not clear enough. We have attempted to confirm its variation by studying the distribution of the number of stars perpendicular to the Main sequence band, *N(R/Rz)*. We have studied [3] these distributions separately for stars of each type of peculiarity and they turn out to be similar. Thus, Fig. 3 is a plot of the combined distribution for stars with all types of peculiarity (about 470 stars). In the earlier paper it was shown that the shape of the distribution must be the same, to first order, as that of *Bs(R/Rz)*. In fact, a comparison of Figs. 2, a and b, and Fig. 3 shows that they are similar. These curves indicate that the magnetic field and the number *N* increase over *R/Rz* = 1 - 1.2, reach a maximum at *R/Rz* = 1.2, and then decrease until

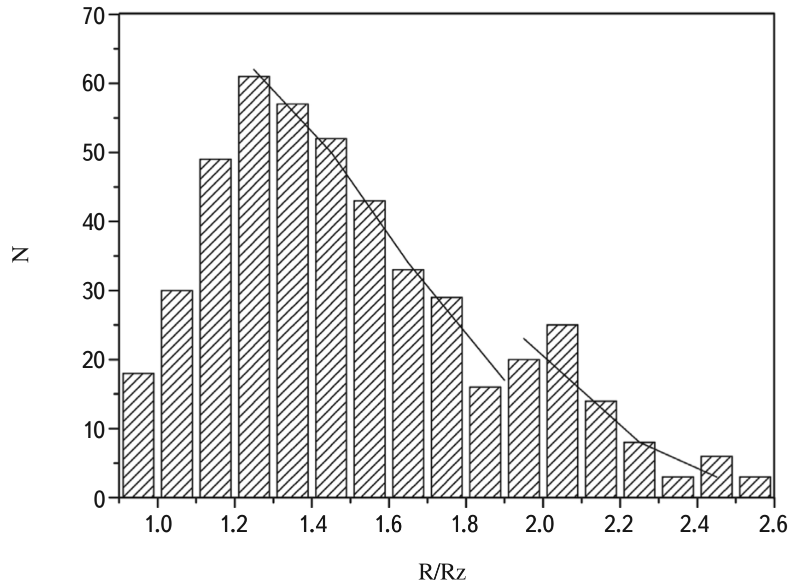

Fig. 3. The distribution of magnetic stars with all types of peculiarity transverse to the Main sequence band.

R/Rz = 1.9. After this, there is a slight jump because the stars dwell on the Hertzsprung-Russell diagram owing to the loop in the evolutionary track. The characteristic shape of the distribution of magnetic stars perpendicular to the Main sequence band can be explained in the following way. First of all, it is most likely determined by observational selection. The magnetic field near (*R/Rz*) = 1 is almost zero. But the magnitude of the chemical anomalies depends on the magnetic field [42], so the characteristic spectroscopic criteria for searching for CP stars near *R/Rz* = 1 are also weak and this lowers the probability of assigning a star to the CP-objects. As the magnetic field increases, the spectroscopic criteria become stronger and the number of CP-stars increases simultaneously. But another dependence is imposed on this curve, specifically a reduction in the number of stars with increasing *R/Rz* owing to their increased velocity across the Main sequence band, as well as because of the reduced magnetic field owing to the evolutionary increase in their diameter. As a result, after a maximum, the number *N* of stars begins to decrease with increasing (*R/Rz*).

Therefore, we eliminate the effect of a quadratic or cubic variation in the average surface field *Bs* (determined by the evolutionary change in the radius) from the observed *Bs*(*R/Rz*) curve. This yields the two dependences in Fig. 4, one for the cubic (circles) and one for the quadratic (stars) case. Both dependences show that the field initially rises rapidly, as it should because of the more rapid rate of relaxation of small-sized structures, and then the rate of increase slows down after the small-scale component "burns up." The change in the magnetic field of stars with age would look this way if the change in the field owing to the evolutionary increase in radius had no effect. The right hand part of the graph is not sufficiently reliable because of insufficient data. After the rapid disappearance of the small-scale magnetic structures, only the large-scale isolated central, shifted structures remain, along with two- and three-dipole structures [44,45]. Figure 4 shows that the surface field *Bs* appears to rise over essentially the entire

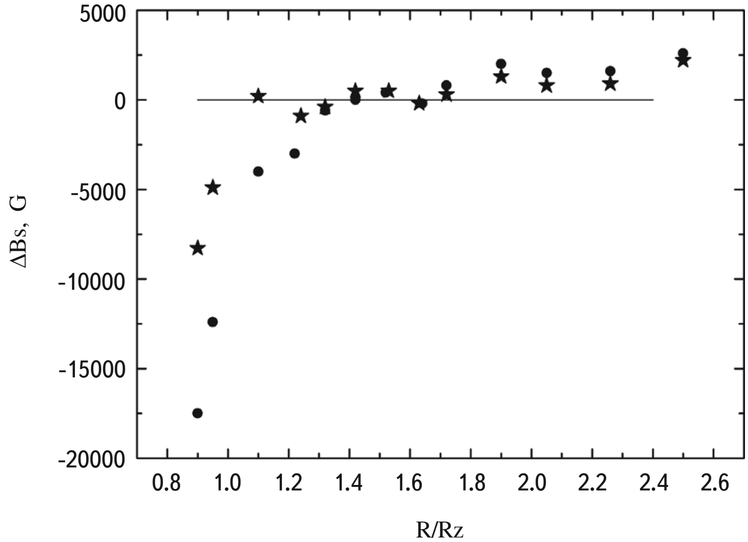

Fig. 4. The variation in the average surface magnetic field during the evolutionary movement of stars across the Main sequence band (after eliminating the effect of field changes owing to the evolutionary increase in the radius). The circles are for a cubic dependence and the stars are for the actual (quadratic) dependence.

lifetime of the star in the Main sequence, as should happen according to Eq. (1). The magnetic field may increase in the ZAMS for the following reason. If we assume that the small-scale configurations are damped out rapidly by Ohmic damping, while the large-scale configuration remains, then the field increases with time because of the decreasing fraction of distorted field lines.

As an example, we observe long-lived large structures in stars with a complicated magnetic field structure and with structures that have a large displacement Δa of the dipoles from the center of the stars; these leave the Main sequence and are conserved without changes. Figure 5a [2] shows the variation in Δa with age. The youngest stars already have an asymmetric structure derived from the initial gravitational collapse phases. It is not clear that the asymmetry of the magnetic fields has changed with age. The magnitude of the asymmetry as a function of age has an insignificant slope, $k = 0.013 \pm 0.041$. The same conclusion follows from Fig. 5b, which shows the variation in α with age (the line at $\alpha = 20°$ isolates the region with the maximum number of stars). This plot shows that the orientation of the magnetic field essentially does not change with time. Both figures illustrate the complete stability of the magnetic field structures and the absence of large-scale movements of masses of stellar matter, such as differential rotation, meridional circulation, etc. These results also confirm the hypothesis of rigid rotation of magnetic stars [46].

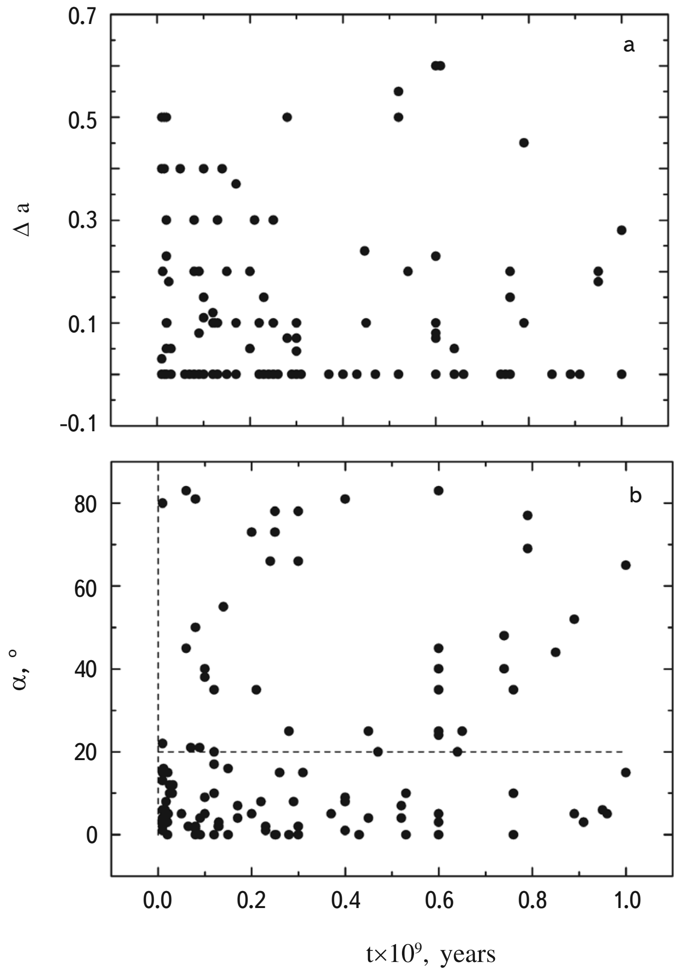

Fig. 5. Changes in magnetic structure parameters with age: (a) distance of the dipole from the star's center, (b) inclination of the magnetic dipoles.

4. Limiting age of magnetic stars

We have made a preliminary examination of this problem in Refs. 2 and 3. Here we have used the ages log*t* from the catalog of Ref. 18, which have been determined from the evolutionary tracks [47]. The oldest stars are found among SrCrEu objects, some of which are listed in Table 2. The average surface magnetic field *Bs* is taken from Refs. 3 and 13 and the other parameters, from Ref. 18. It is clear that the limiting age of magnetic stars is log*t*(years) = 9-9.30, after which their field decreases rapidly because of the convection that develops when T_{eff} of the star reaches a critical value. The greatest ages of stars with other types of peculiarity are $\log t \approx 8.7$ (Si), 8.5 (He-w), and 7.8 (He-r). The stars cease to be magnetic, essentially without having expended their magnetic energy because the theoretical Ohmic damping time is log*t*(years) = 10-11. The oldest stars at the magnetic field loss boundary have an average mass of $M \approx 1.8 M_{\odot}$ and radius $R/R_{\odot} = 2.16$, as predicted by the theory of stellar

TABLE 2. Limiting Age of SrCrEu Magnetic Stars

HD	T_{eff}, K	log$t$	$M / M_{\odot}$	Bs, G
28578	6900	>9.0	-	5600
42075	6940	9.30	1.57	8540
96237A	6990	8.94	2.78	2500
101065	6530	9.1	1.53	2300
122970	6920	9.18	1.46	2500
134214	7780	9.00	1.64	3090
147010	7400	9.00	1.75	12000
166473	7760	9.00	1.89	7650
217522	6680	9.11	1.06?	1500

TABLE 3. Stars that Have Lost their Magnetic Field at the Upper Boundary of the Main Sequence

HD	T_{eff}, K	Type	log$t$	$M / M_{\odot}$	Bs, G
3360	21050	He-r	7.36	4.34	290
5737	13570	He-w	7.90	4.38	3190
5797	7920	SrCrEu	8.90	2.08	1800
8441	8700	SrCrEu	8.63	1.92	470
18078	8050	SrCrEu	8.70	1.53	3830
18296	10920	SrCrEu	8.11	3.30	890
37479	22070	He-r	7.32	10.3	4310
40312	10180	Si	8.30		650
47103	8180	SrCrEu	8.86	1.2?	16300
51418	8470	SrCrEu	8.60	-	1130
71866	8170	SrCrEu	8.81	1.71	5180
93507	9170	Si+	8.60	1.91	7150
110274	7310	SrCrEu	8.87	2.20	4020
116458	9720	He-w	8.48	1.44	4680
147010	7400	Si+	9.00	1.75	10600
170397	9450	Si	8.54	1.77	1160
170973	10720	Si+	8.35	2.34	>1000
191742	8110	SrCrEu	8.81	1.67	1800
335238	8250	SrCrEu	8.85	2.65	8700
343872	10500	Si	8.3	-	3720

evolution [48]. A sharp boundary for the disappearance of magnetic stars is also clearly evident in the plot of $Bs(\log t)$ discussed in Ref. 3. The average magnetic field for the stars at the boundary is $Bs \approx 5000$ G. There are no signs of a slow reduction in the field prior to its disappearance.

Table 3 is a list of stars that have moved to the upper convective boundary of the Hertzsprung-Russell diagram and have $R/R_{\odot} > 2$ [3]. It is interesting that their magnetic fields also vanish rapidly. The average magnetic field of the stars at the boundary is $Bs \approx 4000$ G. This means that convection develops rapidly and has enough energy to entangle the lines of force over a short time. It is difficult to suppose that magnetic stars with $M/M_{\odot} > 2$ leaving the Main sequence would lose their magnetic fields for any other reason than the onset of convection.

5. Time to reach the maximum in the distribution of magnetic stars

The distributions of magnetic stars of (He-r+He-w), (Si), and (SrCrEu) types perpendicular to the Main sequence band have been examined separately in Ref. 3. Each distribution has a maximum. It is not possible to determine the position of the maxima of *Bs* directly from plots of *Bs*(R/Rz) for the different types of peculiarity because there are insufficient data. If we assume that the positions of the maxima of the distributions perpendicular to the log*t* axis are the same as the positions of the maxima of the magnetic field, then it is possible to estimate how much time the stars spend before reaching the maximum of *Bs*. The age of the maxima (which is approximately the same as the average age) and the maximum age are taken from Table 1. The second row of Table 4 shows the fraction of a star's lifetime on the Main sequence before it reaches the maximum.

As a comparison it has also been found [4] that SrCrEu stars take 0.3 of their lifetime to reach the maximum. As shown above, this long time interval is the consequence of two contrary processes: the growth in the average surface field owing to relaxation and its simultaneous decrease owing to the evolutionary increase in radius. There are not enough data to obtain reliable results for He-r stars.

6. Structures of the magnetic fields

An important result from the series of papers on modelling the magnetic fields of CP stars [2] concerns the inner and surface structure of the magnetic fields. The characteristic shape of the rotational phase dependences of the magnetic fields of stars led Babcock [49] to the conjecture that the structure of the magnetic fields of stars

TABLE 4. Fraction of Lifetime on the Main Sequence Before Reaching the Maximum

Type	He-r	He-w	Si	SrCrEu
Time to maximum	0.27	0.17	0.25	0.5

corresponds to the structure of a theoretical magnetic dipole. We have studied the global structure of the magnetic fields of more than 100 CP stars by modelling them on the basis of the known phase dependences of the longitudinal field, *Be*(F), or of the average surface field, *Bs*(F), under the assumption that the source of the magnetic field is a virtual magnetic dipole with charges $\pm q$ separated by a distance l [50,51]. The computational program makes it possible to choose any position of the charges inside the stars by specifying the longitude λ and latitude δ of each of the charges, as well as their distance r from the center. The star's surface is broken up into N elements by the meridians and parallels. The magnetic field vectors for both of the magnetic monopoles are calculated in each element. The sum of the vectors on the visible hemisphere, with limb darkening and the visible area of the element taken into account, gives the average surface magnetic field *Bs*, which is measured in practice using the total splitting of spectrum lines in unpolarized light. The sum of the vectors directed toward the observer yields the average longitudinal field *Be*, which is measured from the Zeeman spectra. By successive variation of the angle of rotation of the visible hemisphere by the required angle it is possible to calculate the phase dependences $Be(\Phi)$ and $Bs(\Phi)$. It is possible to obtain agreement between the calculated and observed phase dependences within 3σ for the measurements over all phases by varying the parameters in successive approximations. In almost all the 100 model calculations the deviations are within the measurement errors and this confirms the validity of the resulting approximations. We note that in the central dipole models, the parameters are essentially the same as the results of applying the Stibbs-Preston method [52]. Experience with the model shows that for almost all of the stars studied here, the distribution of the surface magnetic field can easily be described by a suitable choice of the position and orientation of the magnetic dipoles. The important point for the physics of magnetic stars is that the region of maximum intensity lies at the site of the dipole. The above properties cannot be obtained by the other known methods. The calculated and observed $Be(\Phi)$ and $Bs(\Phi)$ curves for a given star generally agree within 3σ for the same specified parameters. It also turns out that the model values of the average surface magnetic field *Bs* agree with the data obtained from direct measurements to within the measurement error. This confirms that the magnetic field configuration inside a star is close to that of a theoretical dipole. Real stars have stable large-scale magnetic structures in which unstable small-scale components are substantially attenuated. The existence of small-scale components of the magnetic field has been demonstrated in Ref. 10.

The characteristic feature of Ap and Bp magnetic stars is a large difference between the structures and intensities of the magnetic fields [45]. It is assumed [1,2,4] that magnetic stars are most likely formed from protostellar clouds that are highly nonuniform in terms of magnetic field, and that the magnitude of the magnetic field must not be proportional to the density of the clouds; otherwise the result would always be stars with a maximum field intensity at their centers, where the density is highest. In addition [53], during formation of a star from a magnetized protostellar cloud, the magnetic field prevents mergers of dense regions, so magnetic inhomogeneities may appear in the formed star. In most stars the position of the magnetic dipole is not coincident with a star's center. This leads to various characteristic structures of the magnetic fields, which can be divided into four types in a first approximation: (1) a central dipole, (2) a dipole shifted along its axis, (3) a dipole shifted perpendicular to its axis, and (4) two or more dipoles. As noted above, the magnetic structures consist of a global dipole magnetic configuration plus a small-scale component [10] which is a relict from the nonstationary Hayashi phase. It is evident from Eq. (1) that an older star will have a smaller fraction of the small-scale magnetic field component. It is interesting that in multidipole configurations the signs of the monopoles alternate. There were no cases in which the dipoles were positioned with the same signs to one side. This kind of configuration is probably unstable during the compression period of protostellar clouds [54].

It is not clear how a nonsymmetric magnetic field structure can coexist with a density that is symmetric with respect to the star's center. The star HD 21699 with a magnetic field structure that is highly asymmetric with respect to the star's center has been studied [55] as part of this problem. The magnetic dipole lies in the plane of the equator of rotation and is shifted from the star's center by a distance $\Delta a = 0.4 R_*$ from the center, so that the magnetic poles lie on the equator of rotation, separated by 55° in longitude (Fig. 6). The region with the maximum magnetic field strength lies between the monopoles. The positions of the magnetic poles ($Bp = \pm 21900$ G) are indicated by semicircles in the figure. To within the limits of error, the depth distributions of the temperature in the hemispheres with maximum and minimum magnetic fields turned out to be the same. It was concluded [56] that the magnetic field does not affect the structure of the atmosphere and that we are dealing with a stable magnetic field and conditions do not exist which would disrupt the hydrostatic equilibrium. A study [57] of magnetic stars by the growth curve method also shows that in magnetic stars the excitation and ionization temperatures are similar and the relationship between the two is normal. This implies that in the atmospheres of magnetic stars there is no significant disruption of thermodynamic equilibrium. Magnetic stars are old enough that the strong electric currents in the strong physical inhomogeneities that appear during the Hayashi phase have almost all disappeared. No inhomogeneities in the physical conditions on the surfaces of magnetic stars have been noticed, except those related to the nonuniform distribution of chemical elements. The small variability in the structure of the atmosphere is related solely to a different covering effect owing to the nonuniform chemical abundance distribution.

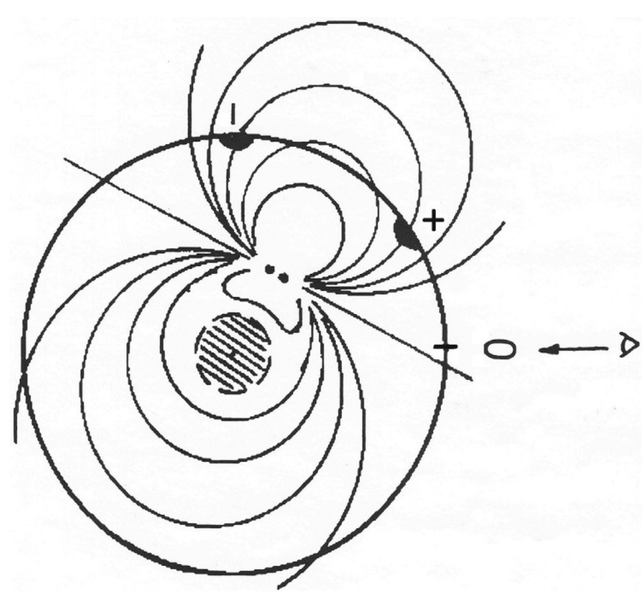

Fig. 6. Illustrating the position of the magnetic dipole inside the star HD 21699.

At present, the problem relates to the structure of the magnetic field in the center of a star around the convective core. It is obvious that the magnetic lines of force of the global dipole field will somehow pass around the central region of the star. Our model technique shows that for the 3-rd and 4-th model variants, good agreement with observation is obtained only in those cases where the distance between the monopoles is specified to be rather large, $l \sim R_*$; that is, we are dealing with "long dipoles," and not with "point" dipoles, for which $l << R$. In these cases, the positions of the monopoles are determined by the singular points at which the lines of force converge, and the position of the dipole is determined by the symmetry point of the magnetic configuration. In model variants 1 and 2, unlike in models 3 and 4, l has little effect on the shape of the phase dependence, so there is no need to determine l precisely. Based on a study of models 3 and 4, we may assume that l is also large for models 1 and 2, especially since the convective core cannot contain magnetic lines of force. This method does not provide information on the influence of a convective core on the internal structure of the magnetic field.

7. Conclusion

This paper, along with Refs. 1-4, indicates that the formation of magnetic stars proceeds from a protostellar cloud that is highly turbulent, with a nonuniform density and magnetic field. The major properties are: (1) predominant orientation of the magnetic lines of force in the plane of the equator of rotation; (2) low rotation velocity; (3) complicated magnetic field structures; (4) separation of stars into magnetic and normal in a proportion of 1:10; and, (5) rigid-body rotation. These properties are most likely formed during a period of evolution where they have been subjected to a single mechanism— selective (with respect to the angle α) slowing down of the protostellar cloud by a magnetic field. Only those protostellar clouds for which the direction of the lines of force is predominantly parallel to the plane of rotation will be slowed down efficiently. Confirmation of this conclusion actually supports the relict hypothesis. "Normal" stars are most likely separated from magnetic and nonmagnetic chemically peculiar stars by differential rotation of the protostellar cloud when a critical rotation velocity v_c is exceeded. Differential rotation twists the magnetic lines of force into a toroidal shape. After the unstable Hayashi phase, the magnetic field in a young star is strongly entangled and attenuated. The upper layers of a compressed radiative young star are unstable; they are subject to strong accretion, while relaxation of the complicated magnetic structures begins in the radiative star itself. It is evident from observations that significant ordering of the magnetic field takes place over the time from the unstable Hayashi phase to the ZAMS. The nonstationary shell shields the field of the young star throughout this time. Thus, as the shell vanishes, the upper layers of a young magnetized star gradually become visible. During this period of evolution, conditions do not exist for formation of a magnetosphere with a simple dipole configuration around the star. A noticeable magnetic field and chemical anomalies show up only as the star approaches the ZAMS, when the star is freed from the surrounding gas-dust cloud and the upper layers are stabilized. The entangled system of magnetic lines of force begins to vanish because of Ohmic dissipation and other instabilities. This period is characterized by the appearance of a large-scale dipole relict component which controls the diffusion of chemical elements. This is the most probable brief scenario for the initial phase of evolution of the magnetic fields of CP stars. The weakness of the magnetic fields in Ae/Be Herbig stars confirms the existence of the unstable Hayashi phase, in which the relict magnetic field was highly entangled and attenuated. The instability of this phase, however, is rather mild, so it allows the major poloidal relict structures to be preserved. Given this, we may assume that chemically peculiar stars with no magnetic field are formed from nonmagnetic protostellar clouds with subcritical angular momenta.

During the period when stars arrive at the ZAMS, the magnetic dipole field increases rapidly owing to relaxation of the small-scale magnetic field inhomogeneities and stabilization of the outer layers. Then the rate of rise of the surface field decreases, depending on the Ohmic dissipation of the small-scale structures, and the large-scale structures are preserved. Complete dissipation of the large structures does not continue until the end of the star's lifetime, which has a maximum of 10^9 years. The increase in the field at the star's surface is compensated by its reduction with time owing to the evolutionary increase in the star's radius, so that the initial rapid rise in the field continues only until the V-class luminosity band is reached in the Main sequence; after that the reduction in the field begins to predominate. After the star reaches the Main sequence band with R/Rz = 1.9-2.0, a jump is observed in the magnetic field and in the number of stars in the distribution because of stoppage of the star's motion owing to the characteristic zig-zag in the evolutionary track. Throughout the lifetime of a star on the Main sequence, its magnetic field is made up of two components – global dipole and small-scale.

The rise in the dipole component of the magnetic field takes place essentially throughout the star's lifetime in the Main sequence, with a maximum age of $t = 10^9$ years, after which the star reaches convection onset boundary. Some of the coldest stars lose their field because of convection without reaching the upper boundary of the Main sequence. The stars cease to be magnetic, essentially without having expended their magnetic energy, because the possible Ohmic dissipation time is 10^{10}-10^{11} years. Thus, reduction of the field by Ohmic damping can be neglected in most theoretical studies.

Since the total magnetic flux remains essentially invariant throughout the time a star is in the Main sequence and its damping is determined exclusively by Ohmic dissipation, this indicates that there are no other possible reasons for its destruction, such as meridional circulation, differential rotation, turbulence, etc. The magnetic star rotates as a rigid body (solid).

The structure of the magnetic field of chemically peculiar stars differs from that of an ideal central magnetic dipole, so that the field does not have an inverse cubic dependence on the distance from the star's center, but varies more slowly, roughly in proportion to $1/R^{2.5}$.

The complicated behavior of the magnetic field and chemical anomalies with age means that the maximum of the distribution of stars perpendicular to the Main sequence band and the magnitude of the magnetic field in stars with different types of peculiarity correspond to different ages, averaging from $0.2 \cdot 10^8$ (He-r+He-w) to $4.5 \cdot 10^8$ years (SrCrEu).

It is probable that the loss of angular momentum by protostellar clouds with the aid of a magnetic field leads to the well-known shortage of close binaries among magnetic stars.

Magnetic stars with $\alpha = 0^o - 20^o$ are formed from slowed-down magnetic protostellar clouds. Magnetic stars with $\alpha > 20^o$ are mostly formed from slowly rotating magnetized clouds. The nonmagnetic AM, HgMn, etc., stars are formed from nonmagnetized protostellar clouds with weak initial rotation.

The properties of magnetic stars examined here and in Ref. 4 require further study based on more complete observational data. It should also be noted that the early periods of evolution of these stars have not yet been studied adequately.

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