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REVIEWS

PROGRESS IN STUDIES OF THE EVOLUTION OF THE MAGNETIC FIELDS OF CP-STARS. I

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In this review (part I) the most important results of research on the properties of the magnetic fields of chemically peculiar stars prior to 2000 are examined critically. The properties of the magnetic fields are examined from the standpoint of their conformity with the relict hypothesis. Later results will be discussed in part II.

Keywords: *magnetic stars: stellar evolution*

1. Introduction

This review shows how our ideas about the nature of magnetic stars have changed as the precision of research data has gradually improved. The latest results make it possible to construct a preliminary scenario of the origin and evolution of magnetic stars based on the relict hypothesis. The mean square values <Be> of the observed magnetic

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field were used in early work. Their dependence on the angle of inclination *i* of a star led to large scatter of the points in the derived dependences and to unreliable results. In later papers it became possible to use mean surface values Bs of the magnetic field for 160 stars which actually determine the physical conditions on the surfaces of the stars. The earlier work had the character of a probing of the properties of magnetic stars in different directions in a search for some sort of new dependences and correlations, which might shed light on the nature of magnetic stars. The early papers had the shortcoming that they were studying isolated properties, apart from other properties, while many of these are interrelated. Naturally, the initial scattered bits of data could not support a general analysis. In the data examined below, it can be seen well how interest in various problems relating to the physics of magnetic stars has changed over time. Work on the surface structures of magnetic fields is reviewed in our earlier paper [1]. In this review we concentrate mainly on studies of the physical properties of magnetic fields. Here we try to order the data obtained over a long time and study their mutual influence. We also attempt to collect the accumulated data into a unified system consistent with the relict hypothesis, which we accept. Thus, we have, by no means, analyzed all the published research on magnetic stars. The main results and statements are distributed by year in the text. The results which we regard as most reliable are indicated in **bold face type**. In a number of cases, discussions of papers from earlier years in this article are referred to in the text and are enclosed in parentheses.

2. Basic studies of the properties of magnetic fields

1945. One of the fundamental principles upon which research on magnetic stars is based in Cowling's idea [2] that the ohmic damping time for the magnetic field is comparable to the lifetime of Main sequence (MS) stars because of the high conductivity of stellar matter in these immense large-scale magnetic structures. Thus, the magnetic field of a star can be a slowly decaying **"relict"** of the field that existed in the interstellar gas from which the star was formed. This is the main idea behind the formation of magnetic stars. For many years there has been a discussion of a possible dynamo mechanism for the origin of stellar magnetic fields. It has been shown [3] that, as opposed to the relict mechanism, the dynamo mechanism cannot explain a majority of the most important properties of magnetic stars.

1951. Babcock [4] found a real explanation for the variability in the period of the magnetic field in stars by introducing the concept of **an inclined magnetic rotator**, in which the axis of a magnetic dipole is inclined to the axis of rotation. This hypothesis is confirmed by all subsequent experience. Babcock also suggested that, based on the shape of spectral line profiles, the magnetic field does not belong to a single spot, as on the sun, but the star is magnetized **as a whole** and the field has a **dipole structure**, although a small-scale fraction may be present. Subsequent observations and studies have repeatedly confirmed this proposition (see the discussion of 1997).

1963. Glagolevskij [5] studied the continuum spectra of magnetic stars. It was found that there is a depression at $\lambda 5200$ Å in the continuum, and that the energy distribution in the continuum spectrum, including the size of the Balmer jump; these are **anomalous** and vary with the rotation period [6-8]. The spectral classification was found to be inconsistent with the temperature scale. Initially it was assumed that these features arise from the suppression of microturbulence by the magnetic field, so that the structure of the atmosphere is disrupted. This, in turn, leads to a reduction in the size of the Balmer jump and to a change in the energy distribution. The anomalous character of the Balmer jump was confirmed later [9].

With further studies it turned out that the anomalous continuum energy distribution of magnetic stars is actually a consequence of anomalies in chemical composition. In particular, this problem was examined in Ref. 10, where it was shown that the continuum energy distribution is distorted by an enhanced abundance of metals in the upper layers of the atmosphere. The role of the main absorbing element, hydrogen, is correspondingly reduced and blockage of radiation by enhanced absorption lines takes place, especially in the ultraviolet part of the spectrum. This leads to a change in the model for the atmosphere and, thereby, to a change in the energy distribution. The depression at $\lambda 5200$ Å is evidently a consequence of the overlap of a large number of spectrum lines. The anomalies in the energy distribution in the continuum spectrum of magnetic stars create major problems for photometric temperature determinations.

1965. Abt [11] studied spectrally binary systems among the Am-stars. It is noteworthy that the equatorial rotation velocities of normal A-stars are inevitably high (50-250 km/s), while those for Am-stars are substantially lower (0-100 km/s). It was concluded that tidal interactions in close pairs, which include the Am-stars, lead to **low rotational velocities.** At the same time, isolated stars or members of wide binaries have high rotation velocities. The very first problem is to explain why rapidly rotating stars have spectra characteristic of a normal chemical composition, while slowly rotating stars have anomalous chemical compositions. Abt concluded that **slow rotation** is the critical property that makes it possible for chemical anomalies to show up in Am-stars.

By now, it has been quite firmly shown that **slow rotation of magnetic and nonmagnetic chemically peculiar (CP) stars creates the conditions under which normal and CP-stars are distinguished** [3,12,13]. It is assumed that for rotation velocities above critical there is a differential rotation (and other instabilities) in parent protostellar clouds which twists the lines of force into an “invisible” toroidal shape. Differential rotation does not occur in slow protostellar rotators and stars. The observed field has a **poloidal character** [4,14] which is described by a dipole model to an accuracy corresponding to the measurement accuracy. Multipoles of higher order can also make a small integral contribution [4,15], but the **dominant component is dipole.** These most important conclusions of Babcock and Preston are the basis of our method for modelling the magnetic fields of CP-stars [16].

1967. Preston [17,18] discovered a predominant inclination β of the **magnetic dipole** axes to the axis of rotation in magnetic stars.

This property has a most important theoretical significance because it turns out to be related to another fundamental property of magnetic stars— the process by which the parent protostellar clouds lose angular momentum [3,19,20] (see the discussion of 1970). The latest studies of the distribution of the angle of inclination [3,17] include ~160 stars. Figures 1, a and b, show that there is an excess of stars with angles $\alpha \sim 0-20^{\circ}$ ($\alpha = 90^{\circ} - \beta$). This is because the efficiency with which α protostellar magnetized cloud is slowed down is greater when the angle of inclination α of the magnetic field to the plane of the equator is small [19] (see 1979). The angles a are determined from models of magnetic stars. The first graph was constructed for low-mass stars in the (Si+SrCrEu)-group (average mass $M = 2.6\,M_{\odot}$) and the second, for massive objects in the (He-r+He-w)-group (average mass $M = 5.4\,M_{\odot}$). These

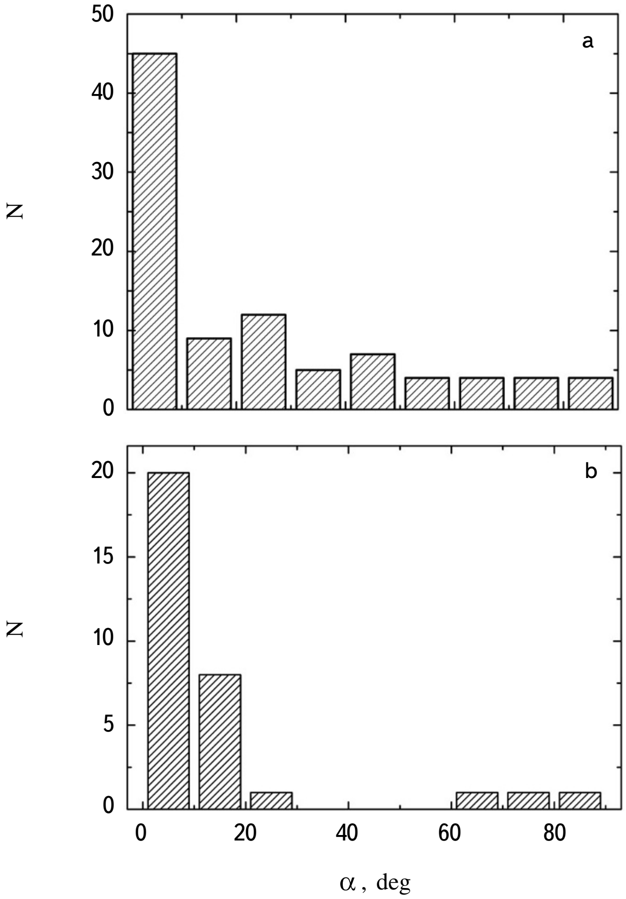

Fig. 1. The distribution of stars with respect to the angle α in (a) Si+SrCrEu stars and (b) He-r+He-w stars.

groups differ fundamentally from those obtained by Preston. A comparison of these graphs suggests a common mechanism for formation of these dependences in massive and low-mass stars, although some authors mistakenly suspect that different mechanisms are operating [22]. The small difference in the number of stars with large angles α in Figs. 1, a and b, may be a consequence of the small amount of data on stars in the (He-r+He-w)-group. A physical cause for the small difference is also possible: in the nonstationary Hayashi phase for stars in the (He-r+He-w)-group (average age $t = 4 \cdot 10^7$ years) the global magnetic structures are distorted less because of their order-of-magnitude shorter evolution time (the average age of low-mass stars is $t = 3 \cdot 10^8$ years) (see 1981).

1970. Landstreet [23] studied the structure of stellar magnetic fields assuming a central dipole inclined by an angle β to the axis of rotation and a **shifted dipole.** Data were obtained confirming Preston's result [14] regarding the predominant orientation of the magnetic fields. This work was pioneering, but at that time still employed primitive approaches for studying the structure of magnetic fields.

Various structures with different orientations of the magnetic axes are described in more detail in later papers

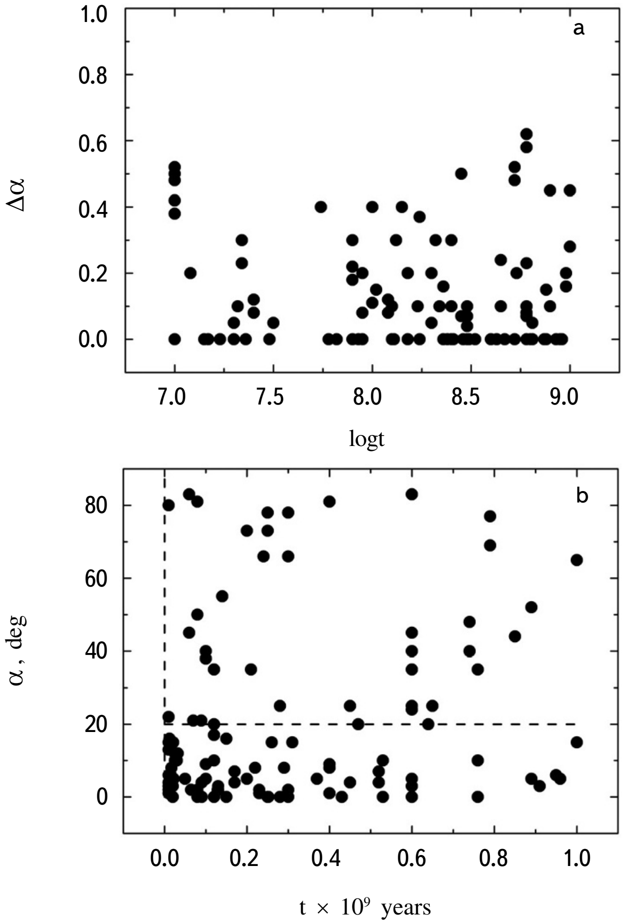

Fig. 2. The distributions of (a) $\Delta\alpha$ and (b) α with respect to age.

[1,24] devoted to models of magnetic field structures. Studies of the orientation of magnetic structures are of great significance for explaining the initial stages of evolution. It turns out that the process whereby the angular momentum of magnetic protostars is lost, the separation of magnetic from normal stars, and an explanation of the 10% of magnetic stars arise from a single mechanism proposed in Ref. 19 (see 1967 and 1979). The study of dipoles shifted from the center by Landstreet, as well as studies of complex structures by modelling, are of interest in relation to the origin of magnetic fields. They are formed from nonuniformly magnetized protostellar clouds in which the center of gravity in the cloud is **not coupled** to the primordial structures of the magnetic field.

1971. Based on a paper by Stibbs [25], Preston [14] developed the simplest version of an **inclined rotator model** with the dipole at the star's center. In the early stages, this model was successfully used in many papers by various authors.

Later work showed that the magnetic field of a central dipole is only observed in ~20% of stars; in the remaining cases the field structure is described by a shifted dipole or is a multidipole structure. It was shown [1]

TABLE 1.

Structure	Age log*t* (min)	Age log*t* (max)
Central dipole	7.0	8.9
Shifted dipole	7.0	9.0
Two dipoles	7.0	8.9
Three dipoles	6.0	8.4

that modelling could be used to divide the observed magnetic structures into **4 types** with: (1) a magnetic dipole located at the center of the star; (2) a dipole shifted from the center along the axis of the dipole; (3) a dipole shifted from the center perpendicular to the lines of force; and, (4) complicated structures described by two or three dipoles. At present, we try to explain this variety in terms of the complicated structure of protostellar magnetized parent clouds. There are no signs that complex magnetic field structures could be formed in later stages of evolution (see details below).

1973. Abt [26] studied the frequency of close binaries among Ap-stars. It turned out that among the Am- and HgMn-stars this frequency is normal at 40%, but for Si- and SrCrEu-stars it is very low, 20%. Thus, for the latter, slow rotation cannot develop because of tidal interactions. The **nonmagnetic Am- and HgMn-stars** lose **angular** momentum because of tidal interactions. This important conclusion shows that there are at least two ways for protostellar clouds to lose angular momentum: by "magnetic" slowing down [19,27] and by tidal interactions for non magnetic stars [26].

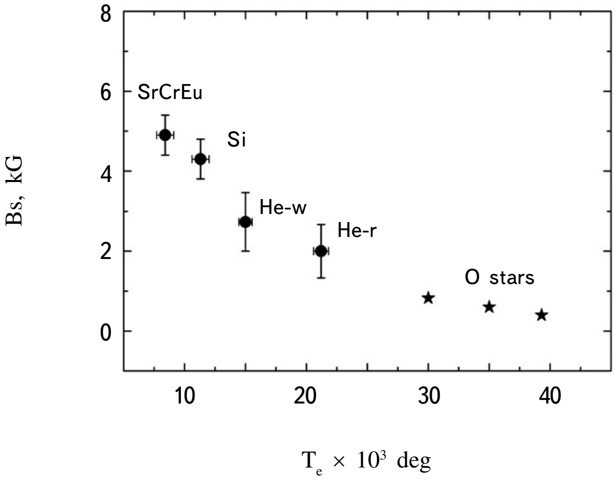

Fig. 3. Average magnetic field Bs for stars with different types of peculiarity. The stars denote type O objects.

1974. Moss [28] examined the possibility of an Eddington-Sweet meridional circulation in magnetic stars. Because the magnetic field is frozen into the stellar matter, circulation **must inevitably lead** to a secular distortions in the primordial magnetic field structures. This very important conclusion must be taken into account in studies of magnetic stars.

At present, the situation in this regard is somewhat clearer. A certain conclusion regarding the **invariability of the magnetic field structure** throughout the entire lifetime of MS stars can be reached from Fig. 1, Fig. 2, and Table 1 [3,29]. In Fig. 2, $\Delta\alpha$ is the average distance of the magnetic dipole from the star's center in units of the radius (for a central dipole $\Delta\alpha = 0$) and α is the angle between the axis of the dipole and the equatorial plane. These two parameters characterize the degree of deviation of the field structure from the structure of an ideal central magnetic dipole. Data for both figures have been determined by modelling (see 1997). Figure 1 was plotted for two groups of stars which differ in mass and, especially, in age [3], which differs by more than an order of magnitude between the two groups. Nevertheless, there is no fundamental difference between them. Figure 2 and Table 1 also show that the typical magnetic field structures do not change over time, and **log*t* = 9.0 is the limiting age** for magnetic

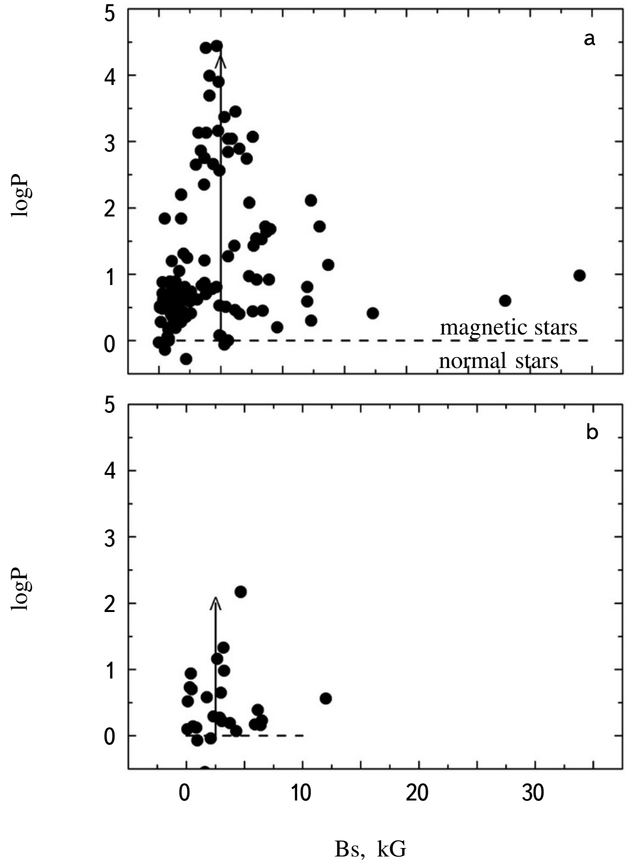

Fig. 4. Distributions of the rotation period logP with respect to average surface magnetic field Bs for (a) Si+SrCrEu-objects, (b) He-r+He-w objects.

stars. These figures and the data in the table show that **magnetic stars have a magnetic field structure that does not change with time, i.e., the stars rotate as solids.** This property was usually assumed in all papers on magnetic rotators. This result shows that **there are no large-scale motions of matter inside magnetic stars** (except the convective core), which, because the magnetic field is frozen-in, would inevitably distort the primordial structures. For example, a meridional circulation that appears during rapid rotation of a star can drive the magnetic field inward [30], after which it may become "invisible."

1975. Landstreet, et al. [31], concluded that (1) **rapid magnetic rotators have lower fields than slow rotators** and that (2) **an inverse correlation between the rotation velocity and the magnitude of the field** had been found.

This result, which is important for the theory of magnetic stars (see 1981) will be discussed repeatedly below. The first dependence can be seen clearly in Figs. 3 and 4 [21], which show that slow rotators, the (Si+SrCrEu)-group, have a field twice that of the fast rotators in the (He-r+He-w)-group (some authors, e.g., Ref. 32, have the opposite point of view). The weaker field in the fast rotators is explained by their larger radii and lower age (see 1988).

It has been shown [21] that massive, rapidly rotating stars of type (He-r+He-w) have an average magnetic field Bs = 2.5 kG, while low-mass slow rotators of type (Si+SrCrEu) have a field Bs = 5 kG (see Fig. 4). The average rotation period is P = 2 days for (He-r+He-w)-stars and 16 days for (SrCrEu)-stars. We have proposed [21] that the difference in the rotation periods P for these two groups is affected by the following factors: (1) the parent protostellar clouds of Si- and SrCrEu-stars slow down more strongly because of their lower mass (Figs. 5, a, b, and c); (2) low-mass clouds slow down more strongly because, on the average, the magnetic field is higher; (3) the degree of slowing down depends on the duration of the slowing-down period, which is an order of magnitude greater for low-mass protostars. Thus, the dependence includes several factors. Massive stars have a weaker field, probably mainly because of their larger radius and shorter lifetime, over which the field entangled during the Hayashi phase has relaxed to a lesser degree (see 1988). As for the second dependence, it should be noted that the proportionality logP(Bs) assumed by these authors holds only to **Bs = 5 kG**, after which it is destroyed, while for the massive stars the proportionality holds down to **Bs = 2.5 kG**. For fields higher than these maxima, angular momentum is lost to a lesser degree by the protostellar clouds. One gets the impression that, in the case of fields exceeding the maximum effectiveness, the slowing down process for protostellar magnetic clouds becomes weaker. The calculation of angular momentum loss by protostellar magnetic clouds in Ref. 19 probably needs refinement.

1977a. Hartoog [33] used 25 stars in various clusters to search for angular momentum loss on the MS. Because of the large spread in the points on this plot, only a preliminary conclusion could be reached: angular momentum by magnetic stars **took place up to the MS**. This conclusion was subsequently confirmed [34,35]. This was an important result because a number of researchers have tried to find signs of angular momentum loss right on the MS, although the conditions for that do not exist there.

1977b. Mestel and Moss [30] made a theoretical study of stationary models of axially symmetric, uniformly rotating stars with a poloidal magnetic field and stable self-consistent thermally driven circulation. We now discuss their conclusions:

1) The claim that a large-scale circulation exists inside magnetic stars is incorrect [3], as we saw earlier when

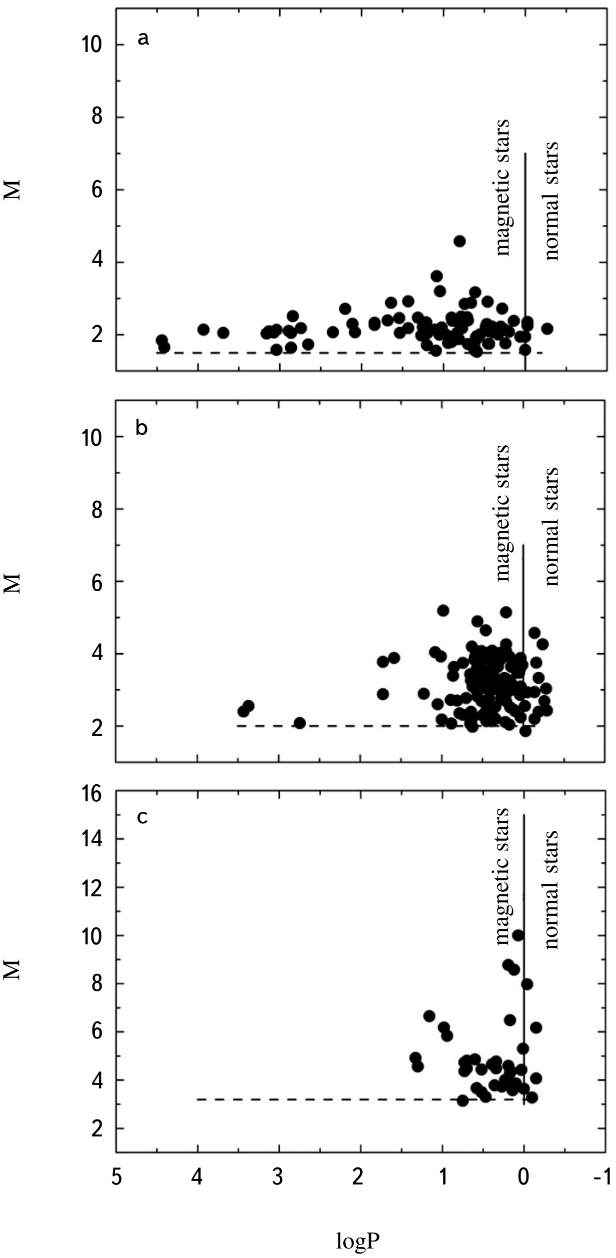

Fig. 5. Rotation period logP as a function of stellar mass for (a) SrCrEu-stars, (b) Si-stars, (c) He-r+He-w-stars. The magnetic and normal stars are separated by a smooth line, the dashed line shows the lower boundary with respect to mass.

discussing Ref. 28 (see 1974). We showed that the magnetic field rotates **as a solid body** (except for the convective core).

2) These authors propose a possible explanation for why rapidly rotating normal A-stars do not have significant magnetic fields; i.e., the meridional circulation produced during rapid rotation of a star drives the magnetic

field inward. This hypothesis is an alternative to the proposal discussed in this review in which a differential magnetic rotation develops during rapid rotation of protostellar clouds and entangles the magnetic field into **an invisible toroidal shape** [3,12,13]. This is the same as the mechanism which separates normal and magnetic stars at the boundary $P \approx 1^d$ (Fig. 5) [21]. Our subsequent work (see paper II) shows that the separation of normal and magnetic stars most likely takes place before the nonstationary Hayashi evolution phase, where there can be no question of meridional circulation [3,24].

3) These authors attempt to decide whether the magnetic fields of A-stars are relict fields or are produced by a dynamo. Arguments are advanced in favor of the **relict field** hypothesis. Current data on the properties of magnetic fields correspond uniquely to the relict mechanism [3].

1977c. In a theoretical study Moss [36] examined the possibility that a meridional circulation could be formed in magnetic stars with $\alpha = 0^o$.

Comments on the papers by Mestel and Moss (see 1974, 1977b) show that there is no reason to study the possibility of a meridional circulation in magnetic stars that rotate as solid objects during their entire lifetime on the MS, as can be seen from Figs. 1 and 2 and Table 1. It has been shown [3] that typical complex structures with $\alpha = 0^o$ are observed in young, as well as old, stars (Fig. 2) that differ in age by two orders of magnitude; that is, the large-scale magnetic structures do not change with time, which proves the absence of motions of matter inside magnetic stars.

1979. It was shown [19] that **magnetic slowing down of protostellar clouds** in the case of $\mathbf{j} \perp \mathbf{B}$ can change the angular momentum of the cloud by at least several orders of magnitude over a time less than 10^6 years. This time decreases if compression continues. The efficiency of magnetic slowing down is much higher when $\mathbf{j} \perp \mathbf{B}$ than when $\mathbf{j} \parallel \mathbf{B}$. Prior to the Hayashi phase, protostellar clouds have densities less than 10^4 and under these conditions **slowing down is more efficient** than under the conditions in young stars. Thus, if stars are formed during collapse and fragmentation of interstellar clouds, then a mechanism should exist that can extract angular momentum efficiently from a collapsing fragment of matter toward the surrounding matter [37]. Thus, a **frozen-in magnetic field** can **slow down** the rotation of a protostellar cloud by transferring angular momentum outward and twisting the lines of force.

That paper [19] is one of the foundations of the theory of the origin and evolution of magnetic stars developed by us in Ref. 20. This mechanism explains the following in a natural way: 1) the low rotation velocities of magnetic stars, 2) the predominant orientation of the magnetic lines of force, and 3) the small fraction (10%) of magnetic stars among normal objects. As for nonmagnetic type Am, HgMn, λBoo, etc., stars, their low rotation velocities can develop during interactions with a close component [26] or if they had low rotation velocities from the beginning. The slowing down efficiency depends in a complicated way on the magnitude of the magnetic field (see 1975). It is proportional to the magnitude of the field up to a certain time, after which it begins to decrease (Figs 4, a and b). The spread in the points is somewhat larger because of the Bs(R/Rz) dependence shown in Figs. 6, a and b [12,38]. (R is the star's radius and Rz, its radius on the ZAMS.) Observations also show that the degree of slowing down is inversely proportional to the mass of a star (Figs. 5, a, b, and c), and, accordingly, of the protostellar cloud, and is proportional to the duration of its evolution (Fig. 7 [3]), which we assume to be proportional to the star's age.

1981a. Attempts were made to find signs of magnetic field damping on the MS in Refs. 32 and 37. Damping can be caused by ohmic dissipation, and can occur during large scale motion of matter inside a meridional circulation, differential rotation, or other instabilities. Too few stars with known <Be> (a total of 13) from various clusters and associations were used. It was concluded that the relict field may decay with time, but the results obtained from such sparse data obviously cannot be regarded as reliable. This conclusion was based on the fact that the field of the young massive stars was 3 times that of the low-mass old stars.

In fact, massive stars have a field that is **weaker by a factor of two** than that of low-mass stars (Figs. 3 and 4), as discussed above (see 1975). It has now been firmly established that near the ZAMS (Zero Age Main Sequence)

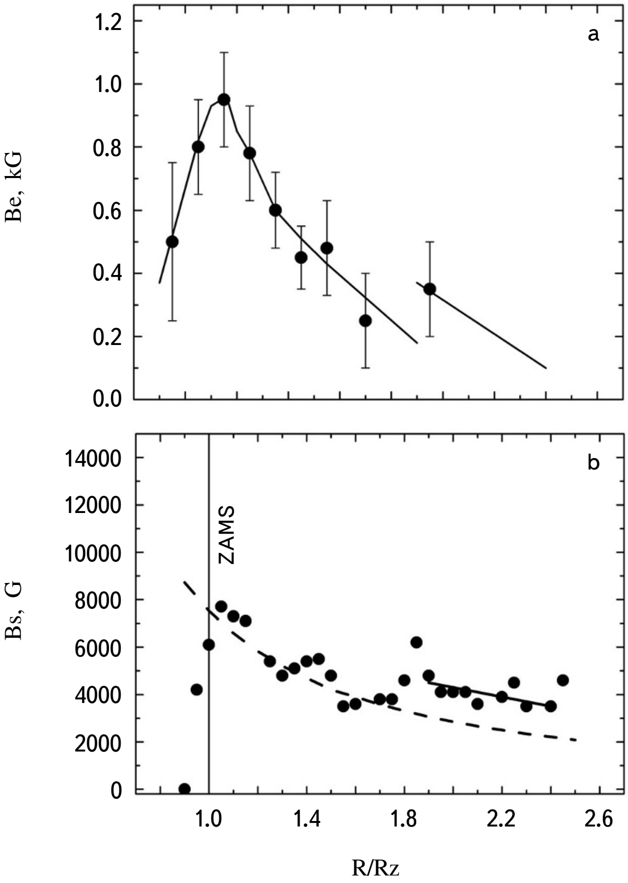

Fig. 6. Variation of the magnetic field during the evolutionary motion of magnetic stars across the MS band: (a) mean square values of the magnetic field Be, (b) average surface magnitudes of the magnetic field Bs, (c) variation in the average surface magnetic field Bs without the effect of increasing radius, (d) variation in the parameter Z0, which is sensitive to the degree of chemical anomalies.

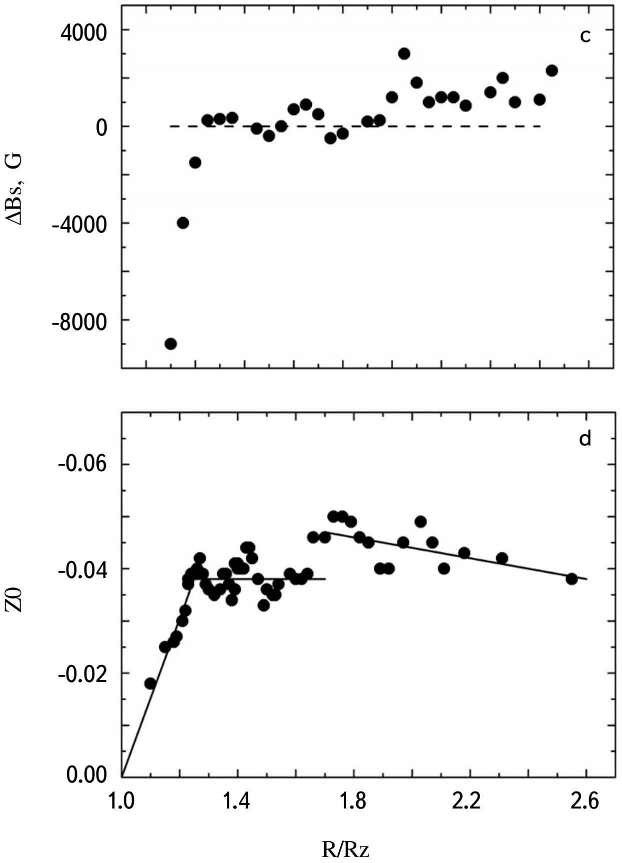

Fig. 6. Conclusion

after the HAeBe (Herbig AeBe) phase there is a rapid increase in the average surface magnetic field Bs (Fig. 6, a and b; 160 stars) and only later does the field decrease after reaching a maximum value, mainly because of the evolutionary growth of the radius [12,38] (see 1988, 1998b). The observational data discussed above (see 1974) show signs of the absence of large-scale motion of matter in magnetic stars which could destroy the magnetic field over their lifetime on the MS. The dependence for massive stars differs from that for low-mass stars because of the field is lower by a factor of two (Fig. 6) [12,38]. To account for this property, in Fig. 6, which was constructed from data for all types of peculiarity, the magnetic fields for (He-r+He-w)-type stars are magnified by a factor of two.

1981b. Wolff [39] studied the possibility that angular momentum is lost by magnetic stars on the MS with participation by the magnetic field; this is an extremely important problem in the theory of magnetic stars. Slowing-down has been examined either in terms of an accretion mechanism or as mass loss in the presence of a magnetic field. The interaction of a magnetic field with interstellar matter should change the rotation velocity by a factor of ~1/e on the MS. A study of 38 stars showed that, of the SrCrEu (14 stars) and Si-stars (24 stars), the latter follow this behavior, but the correlation is weak for the SrCrEu-stars.

Experience with later studies showed that this result cannot be treated seriously when such a small amount of data is used. Let us examine the latest data. It has been found [13] that the slope of the logP(R/Rz) plot for SrCrEu-stars is insignificant, i.e., angular momentum loss **does not occur** (the angular coefficient is 0.9σ R = 0.1) on the MS. Magnetic stars already have low rotation velocities on the ZAMS, but not at the end of their life on the MS. Data showing that slowing down takes place **during the period of evolution prior to the MS** have been published [33-35,40]. Other studies [13,41] argue that during the evolution period of young HAeBe stars, slowing down also **could not take place**, because they do not have magnetic fields that are strong enough (see 1987b). Thus, angular momentum loss could take place only during a **gravitational collapse** phase (see 1979, 1987b). In addition, it has been pointed out [19,42,43] that in the evolutionary phase of young radiative stars the concentration of particles is $>10^4$, so their magnetic slowing-down becomes inefficient compared to the gravitational collapse phase (see 1979). This is an important conclusion because the possibility of angular momentum loss in later phases of evolution has been examined in a number of papers. For example, other possible mechanisms for angular momentum loss of stars have been discussed, but they all require the presence of a strong field and a sufficiently dense surrounding envelope; these conditions are not adequately met. These results do not confirm Wolff's hypothesis [39] regarding the loss of angular momentum by magnetic stars in the MS.

In the various peculiarity groups the average rotation period is P = 2^d for (He-r+He-w)-stars, $2^d.14$ for (Si)-stars, $5^d.13$ for (Si+)-stars, and P = $16^d.2$ for (SrCrEu)-stars. The logt(logP) curve rises rapidly (Fig. 7) with average age (data for 290 stars were used). This curve shows that the degree of loss of angular momentum of a protostellar cloud is **proportional to the slowing-down time** (which we assume is proportional to a star's age) and **inversely proportional to a star's mass** (Figs. 5, a-c). It has also been shown [3] that the degree of loss of angular momentum of a protostellar cloud is **related in a complicated way to the magnitude of the field** (Figs. 4, a and b). As noted above, the spread of the points in Figs. 4, a and b, is somewhat greater because of the dependence Bs(R/Rz) shown in Figs. 6, a and b [12,38]. (R is the star's radius and Rz its radius on the ZAMS.) This does not conflict with the hypothesis according

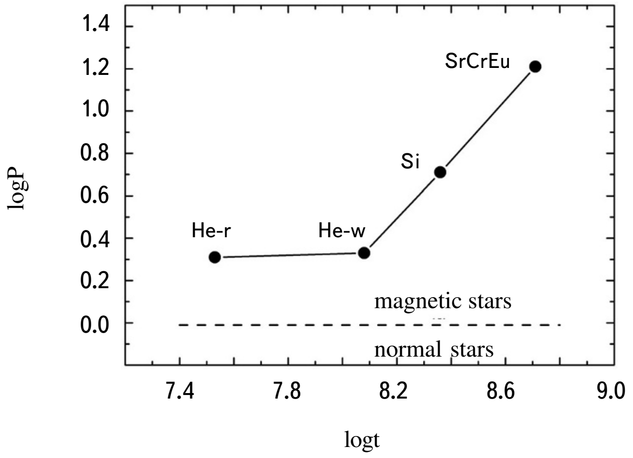

Fig. 7. Average rotation period of magnetic stars with various types of peculiarity as a function of their average age.

to which magnetic protostellar clouds lose angular momentum in a gravitational collapse phase and confirms the reality of the idea that the major properties of magnetic stars are formed during this period of evolution. It has been shown [19] that the most probable mechanism for the loss of angular momentum in protostellar clouds is the **transfer of angular momentum** from a collapsing volume of matter to surrounding material in the presence of a magnetic field. Here the efficiency with which the cloud is slowed down is much greater when the magnetic field is oriented parallel to the plane of rotation. This kind of selective slowing down leads to the **well known excess of stars** with a magnetic field parallel to their plane of rotation (Figs. 1, a and b), and the small fraction of stars with a favorable orientation of the magnetic field is responsible for the well known 10% effect [3]. This hypothesis can, therefore, simultaneously explain several of the major properties of magnetic stars.

1984a. North [44] states that: (1) magnetic stars **lose angular momentum before the MS** or they are slow rotators from the start. The rotation periods of old Si-stars are entirely the same as those of the young stars, so it is evident that there is no slowing down on the MS. (2) An anticorrelation has been observed between rotation velocity and magnetic field. Thus far, no mechanisms have been found for effective slowing down of stars and the observed anticorrelation may be related to other properties.

Thus, the same conclusion as before in Ref. 33 was confirmed.

An anticorrelation was also noted in Refs. 45-47. The actual connection between the magnitude of the magnetic field and the rotation period is best seen in the plots of Fig. 4a for low-mass (SrCrEu) stars and Fig. 4b for massive (He-r+He-w) stars [3]. The arrows indicate the direction of maximum slowing down. The maximum slowing-down efficiency for stars in the first group is at Bs = 5 kG, and for those in the second, at Bs = 2.5 kG. It is also clear that the degree of slowing down is smaller for massive stars. The dependence of the degree of slowing down on the magnitude of the magnetic field is complicated; up to the maximum it increases with rising field and after the maximum it falls. Given the complicated relationship between he magnitude of the field and the rotation velocity, many authors have not been able to reach a definite conclusion. It is evident that the theory of angular momentum loss by magnetic protostars proposed in Ref. 19 needs improvement. As the mechanisms for angular momentum loss, we hold to the variant proposed in Ref. 19. We have discussed this mechanism repeatedly in this review (see 1967, 1970, 1973, 1979, 1981) because of its extreme importance for the evolution of magnetic stars.

1984b. North and Cramer [40] tried to find signs of a reduction in magnetic field with age on the MS using photometrically determined values of the magnetic field. It was concluded that the **magnetic field of Si- and SrCrEu-stars decreases with increasing log*t***, with the field varying as R^{-2}. This conclusion is generally the same at that of Refs. 32 and 37.

A first comment is that the photometric estimates of the magnetic field are proportional to the measured values only to $Bs \approx 3\text{-}5$ kG [29], which leads to substantial spread of the points in the plots and distorts the dependences. A second comment: photometric field estimates cannot be obtained for He-r and He-w stars, so these dependences only apply to low-mass stars. Subsequent studies have revealed a more complex behavior of the magnetic field on the MS, as can be seen in Figs. 6, a and b [12,38,48] (see 1998b). In fact, the **field increases rapidly near the ZAMS**, reaches a maximum at R/Rz ~ 1-1.1, **and only after that does it begin to decrease**, mainly because of the evolutionary increase in the radius. The magnetic field decreases in proportion to R^{-2} (see 1998) [12,38,48].

1985. Glagolevskij [49,50] tried to find the dependence of the average surface magnetic field on the rotation period, as others have attempted. It was assumed that if the field was generated by a dynamo, then its magnitude B should be proportional to the rotation velocity Ω. If the field is a relict field, then the two cannot be related. It was found that the maximum field is observed for stars with periods P~10 days and it falls toward lower and higher P. The latest data [3,21], however, show that a pure Bs(logP) dependence is meaningless, since it includes various components: (1) parent protostellar clouds for SrCrEu-stars slow down more strongly and have maximal values of logP owing to their lower mass compared to massive stars (Fig. 4 and Fig. 5); (2) low-mass protostellar clouds (like SrCrEu-stars) have a stronger field on the average than massive stars (Fig. 3); (3) the degree of slowing down depends on the duration of the slowing-down period (is proportional to age), which is an order of magnitude greater in low-mass than massive stars (Fig. 7) (see 1975, 1984a).

1986. It was proposed that data on <Be> and the ages of stars in various clusters be used to find the reduction in the magnetic field with age **caused by ohmic** dissipation [51,52]. A large scatter of the points in these plots was noted that makes it difficult to find the desired effect. No signs of ohmic dissipation were found, but **signs of a decrease in the field were detected** during the evolutionary motion across the MS, as in Refs. 32, 37, and 44. In fact, this dependence is complicated, as can be seen from Figs. 6, a and b [12,38,48]. The surface field increases near the ZAMS, reaches a maximum, and begins to decrease only afterward, mainly because of the evolutionary increase in the radius (see 1981a, 1984b, 1985).

1987a. The effect of meridional circulation on the primordial magnetic field distribution was examined in Ref. 53.

Our comment on the absence of a meridional circulation in magnetic stars is the same as for the earlier papers by Moss (see 1974 and 1977).

1987b. The properties of magnetic stars were studied statistically [54]. The following basic results were obtained:

1) It was noted that the rotation period P of magnetic stars is **proportional to their age t**.

In fact, this dependence shows up clearly in Fig. 7. Rapidly evolving stars with helium anomalies differ substantially less from normal stars in terms of rotation period than SrCrEu-type stars which have been evolving for a long time. The boundary between magnetic and normal stars lies at logP = 0. But it should be kept in mind that the degree of slowing down depends both on the duration of the evolution and, in a complicated way, on the magnitude of the field, as can be seen from Figs. 4, a and b, and on the mass (Fig. 5) (see 1985).

2) Arguments that magnetic stars **rotate as solids** are advanced in this paper. If they rotated differentially, then, because the magnetic field is frozen in, a substantial realignment of the field configuration would be observed over time together with its rapid destruction [55] (see 1974), which does not actually occur. The discussion of (1974) and Figs. 1, a and b, Figs. 2, a and b, and Table 1 show that the magnetic field structures are perfectly stable over the entire lifetime of the stars.

3) There is a discussion of the idea that the hypothesis of magnetic field generation in a convective core should be rejected because its subsequent removal by diffusion would take 10^8 years according to Parker [56]. This is much longer than the age of a substantial fraction of magnetic stars. This, therefore, confirms the idea of the **relict**

nature of magnetic stars.

1988. The statistical study of magnetic stars was continued [12] using a fairly large amount of data (238 stars) on <Be> [50]. The following results were obtained:

1) The <Be>(logt) plot for all the types of stars showed that the magnetic field does not change with age on the MS. Later, however, based on studies of the average surface magnitudes Bs of the magnetic field, it became clear that the field actually changes on the MS in a complex fashion, as can be seen from Figs. 6, a and b [12,38,48,57] (see 1998b). When magnetic HAeBe stars reach the start of the MS (ZAMS), the magnetic field is only a few tens, sometimes hundreds, of Gauss. Early studies [12] had already shown (Fig. 6a) that there is an initial rise in the field after the ZAMS that reaches a maximum after 20-30% (see below) of their lifetime on the MS. This fact was later confirmed using data on Bs for 160 stars (Fig. 5b) [13,38,41,58,67] (see 1998b). After passing the maximum, **the magnetic field on the surface decreases** as R^{-2}. It is evident that the reduction occurs because the radius of stars increases by a factor of 2-2.5 from the time of ZAMS to the time they arrive at the upper boundary of the MS. The conclusion is definitely that the magnetic field decreases owing to the **evolutionary increase in the radius**. This rate can occur only when the magnetic field has a dipole structure and the total magnetic flux is conserved with age. If the effect of the quadratic variation in the magnetic field owing to the increase in radius is eliminated from the curve of Fig. 6b, then the dependence takes the form shown in Fig. 6c. This curve shows how the magnetic field would vary if the radius remained constant. This takes place because of the evolutionary variation in the radius and ohmic damping of structures of various sizes. As long as fine structures are present, the field changes rapidly. As they disappear, the rise in the field slows down because the rate of ohmic damping is proportional to l^2, where l is the characteristic size of the magnetized volume. If the magnetic field structure corresponded to a theoretical dipole located at the star's center, then as the star's radius increased the field would decrease as the cube of the radius, rather than the square. But stars with a central dipole form only 17-20%, while the remainder have a complicated configuration. This explains the square law decrease in the magnetic field. The dependence of Fig. 6c also reduces the power of R. A jump in Bs at $R/Rz \approx 1.9$ can be seen clearly in Fig. 6b. This is the time at which the evolutionary track enters a loop. The growth in radius ceases for a time and even decreases, but the field continues to increase in accordance with the dependence of Fig. 6c and undergoes a jump. After the evolutionary motion is renewed, the field continues to vary as R^{-2}.

In Fig. 3, which is taken from Ref. 38, one might suspect that Bs is proportional to age, because long-lived low-mass (Si+SrCrEu)-type stars have a field that is a factor of two higher than the massive stars (He-r+He-w). But why does the magnetic field of low-mass stars grow so strongly if no field is generated? It is, therefore, necessary to search for the reason for the weak field in massive stars. Given that the ratio of the average radii of stars of these two types is ~1.5, we find that the ratio of the magnitudes of the magnetic fields must be on the order of 2, as is observed. In addition, because of their low age, the large-scale magnetic field of (He-r+He-w)-stars has not been able to develop to the same degree as that of the low-mass stars, in accord with Fig. 6c.

Figure 6d shows the variation in the multicolor photometry parameter Z0(R/R/z), which is proportional to the depression at $\lambda 5200\,\text{Å}$. Consequently, the intensity of the depression is proportional to the degree of chemical anomalies. The similarity of curves b and d is clearly noticeable and confirms the relationship between the anomalies and the magnetic field. These dependences will be discussed in detail in part II of this article.

2) In the paper examined above, it was stated that **no decrease in the field owing to ohmic dissipation was noticeable.** In fact, the maximum age of magnetic stars is $t = 10^9$ years (Fig. 2), while the theoretical ohmic decay time of the magnetic field for stars with masses $M > 2M_\odot$ is $t = 10^{10}$-10^{11} years, or one or two orders of magnitude greater than the lifetime of magnetic stars. In theoretical studies it can, therefore, be assumed that for all magnetic stars the magnetic flux **remains constant** with age.

3) A comparison of the rotation periods of normal and magnetic stars shows that the periods of massive magnetic stars differ from those of normal stars with the same temperature and are an order of magnitude shorter that those of low-mass stars (Figs. 4 and 7). Given the above remarks (1987b), it can be stated that this happens because the slowing down of massive protostars took place to a lesser degree because of the shorter slowing-down time owing to their larger mass and a field that is smaller by a factor of two.

4) It has been said that the pluses in favor of a magnetic dynamo are bigger than those in favor of a relict field. This conclusion was most influenced by the previous view that convection completely destroys the field during the nonstationary Hayashi phase. The situation changed, however, after the papers of Larson [59] and Palla and Stahler [60]. It turned out that among stars with $M > 2M_\odot$ the nonstationarity in the Hayashi phase can be **extremely weak.** A detailed analysis [3] convincingly demonstrates the impossibility of dynamo operation in magnetic stars. This is primarily because magnetic stars rotate as solid objects, while operation of a dynamo mechanism requires differential rotation. A dynamo does not explain the complicated magnetic field structures that are observed, does not explain why only 10% of stars have a magnetic field, cannot explain how a field is generated in many non-rotating magnetic stars, etc. At the same time, many facts confirm the opinion that magnetic field structures pass through a nonstationary phase **without particular changes** [3]. The predominant orientations of the angles of inclination of the magnetic field which have not been disrupted after exposure to a nonstationary phase is well illustrated in Figs. 1, a and b. If the magnetic field structures were disrupted, a substantial fraction of the small angles would become larger. It is also known that about 17-20% of magnetic stars have central dipole magnetic field configurations. If these structures were destroyed in a nonstationary Hayashi phase, these kinds of stars would not remain.

1989. Moss [61] examined the dynamo and relict mechanisms for the development of magnetic stars theoretically. The hypothesis of a dynamo in a convective core **encounters difficulties** related to the fact that the field cannot be transferred to the surface over the lifetime on the MS, especially for young stars. Parker asserts the same [56].

Relict fields with a bundle shape were studied theoretically. “Single-bundle” models yield a surface magnetic field distribution similar to those for shifted dipole models.

1990. Dudorov and Tutukov [42] maintain that stars with $M > 2M_\odot$ are not convective and that relict magnetic fields can exist in them. They begin with the assertion that the intensity of the relict field in the protostellar cloud and star is proportional to the density. They then assume that in the interior regions of a star the magnetic and thermal energies are comparable, and this should lead to instability.

Our comment on these two statements is that in this case all magnetic stars would have a dipole magnetic field located in the star’s center. But these kinds of stars form only 17-20% of the total, so it must be assumed that the magnetic field in parent protostellar clouds is most often **not proportional to the density.** As for the second comment, our model results [3] show that **magnetic stars are stable over their entire volume** throughout their lifetime on the MS and they rotate as solid objects (except for a convective core) [54].

These authors assert a need for intensification of the relict magnetic field by means of powerful ionization owing to a flux of cosmic rays or hard ultaviolet radiation from nearby O- and B-stars during the period when a magnetic star is being formed. Sources of this kind are not obvious for most stars, and nor is the need for intensification of the magnetic field. This problem should now be reexamined in light of the latest data.

1994. Glagolevskij [29] raises an important problem for the theory of magnetic stars: the dependence of the degree of chemical anomalies on the magnitude of the magnetic field that was discovered by Kramer and Maeder [62]. A dependence of this type was also found for the Balmer jumps, the intensity of the l5200 depression, and the degree of peculiarity *P*. It was found that a direct dependence on the magnitude of the magnetic field exists only to Bs~3 kG, after which the degree of chemical anomalies remains constant. It was concluded that **microturbulence is completely suppressed at high fields** in the upper layers of the atmosphere and the diffusion of chemical elements is enhanced. It was also shown that **there is no meridional diffusion in magnetic stars.** This can be seen from the fact that the angle α is constant in time, and this conclusion is confirmed by Figs. 1, a and b, Figs. 2, a and b, and Table 1.

1997. Gerth and Glagolevskij [16] developed a method for modelling magnetic field structures of stars assuming a dipole field character [4,14]. (More will be said about this in the next article.)

1998a. North [34] states that the rotation period of Si-stars does not change over time on the MS and that the **angular momentum has been lost prior to the MS.** This is consistent with the conclusion of Ref. 33. We have also confirmed it in Ref. 63, where it is also shown that the **rotation period on the MS does not vary** during the evolutionary movement of stars across the MS band. The angle of inclination of the linear fit to logP(R/Rz) is 0.9σ (R = 0.1). The same conclusion for young HAeBe stars (see 1979) led to a firm solution: the loss of angular momentum by magnetic stars took place during the gravitational collapse phase of the magnetic protostars.

1998b. Glagolevskij and Chountonov [41] studied the variation of the field on the ZAMS based on values of <Be>. This confirmed the result of Ref. 12 that the magnetic **field increases after the ZAMS, reaches a maximum, and then begins to decrease** (Figs. 6, a and b) [12,38,48]. Final confirmation of this dependence was obtained in Ref. 58 using reliable data on Bs for 160 stars. Figure 6b is a plot of Bs(R/Rz) where the points were obtained by averaging values of Bs within narrow ranges of R/Rz. A detailed description of this dependence is given in the discussion 1988.

1998c. A series of articles by Glagolevskij and Chountonov [13,41,64] is devoted to a search for strong magnetic fields in young HAeBe stars. It turned out that there were **no objects with strong magnetic fields among stars of this type.** This result is of fundamental significance for the theory of the evolution of magnetic stars because it shows that young HAeBe stars could not lose angular momentum with participation by a magnetic field and that slowing down could occur only during a period of gravitational collapse prior to the nonstationary Hayashi phase. This result is confirmed in a series of papers [13,41,65-74].

3. Conclusion

Based on the data introduced in this paper, the following propositions can be advanced regarding the formation of magnetic stars from magnetized protostellar clouds (see 1945, 1977b, 1981b, 1987b, 1989):

1) Angular momentum loss is most probable in the gravitational collapse stage of magnetized clouds because, as opposed to young stars, their density is $<10^4$ (see 1979, 1981b, 1987b).

2) The loss of angular momentum by magnetized protostellar clouds is easily explained by the theory of Mouschovias and Paleologou (1979) (also see 1965, 1977b, 1979, 1981b).

3) Only the mechanism of Mouschovias and Paleologou (1979) provides a natural explanation of the predominant orientation of the magnetic fields with $\alpha \approx 0-20^{\circ}$ (1967, 1970, 1979, 1981b).

4) Only the mechanism of Mouschovias and Paleologou (1979) provides a natural explanation of the 10% fraction of stars that are magnetic (1981b).

5) Angular momentum loss during early phases of evolution provides a natural explanation for the small fraction of close binaries among magnetic stars (1965, 1977b).

6) Angular momentum loss prior to the nonstationary Hayashi phase provides a natural explanation for the separation of magnetic and normal stars (1965, 1977b).

7) Angular momentum loss during the HAeBe phase is impossible because of the weak dipole magnetic field (1981b, 1998c).

8) The loss of angular momentum by stars on the MS is not confirmed by observational data (1977a, 1981b, 1984a, 1998c).

9) Complicated magnetic field structures are explained naturally by complicated structures of the parent protostars. There are no mechanisms which could create the observed structures during the nonstationary Hayashi phase and during the period of HAeBe-stars (1970, 1971, 1988).

10) If the data shown here are true, then it can be concluded that in the nonstationary Hayashi phase there are no significant distortions of large-scale magnetic configurations (1974, 1987b, 1988).

11) Young HAeBe stars contain a two-component magnetic field structure: large- and small-scale. The latter arose during the nonstationary Hayashi phase (1988).

12) The magnetic field changes on the MS because of two processes: enhancement of the large-scale dipole component owing to ohmic dissipation of a small-scale component and a reduction because of the evolutionary increase in radius (1984b, 1988, 1998b).

13) One of the most important properties of magnetic stars is that they rotate as solid objects (1974, 1977, 1987, 1990, 1994).

Other research results in support of these statements will be provided in part II of this review.

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