ORIGIN OF THE MAGNETIC FIELD

A. Z. Dolginov
A. F. Ioffe Physical-Technical Institute
Leningrad, USSR

Some progress has been achieved in recent years in the theory of the stellar magnetic field generation but a lot of questions remain unanswered. I would like to give here a brief critical review of the current state of the problem.

1. The Fossil Field Theory

The simplest is the suggestion that the stellar field is of a primordial nature. It needs, however, some special assumptions: 1) the conductivity of the stellar matter must be high during all period of the star formation. In the course of its evolution the star, apparently, passes the phase of intensive turbulent motions. The turbulent conductivity is low and the fossil field decays; 2) the field configuration must be stable against perturbations, leading to the decrease of the field scales. The stable configuration of the field must have both poloidal B_p (dipole, quadrupole, etc) and toroidal B_t components. The toroidal field B_t is maintained by the poloidal electric current j_p. If j_p has a component not parallel to B_p, then torques arise which produce motions suppressing this component, so that only $j_p = kB_p$ survives. The poloidal current, following magnetic lines of the poloidal field, cross outer stellar layers which have lower conductivity, provided the star does not possess a hot corona. In this case j_p and consequently B_t decay in a short time. The component B_p alone, without B_t, becomes unstable and all the field configuration decays (L. Mestel, D. Moss 1984[a]).

C. R. Cowley et al (eds.), Upper Main Sequence Stars with Anomalous Abundances, 11–21.
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https://doi.org/10.1017/S0252921100091120 Published online by Cambridge University Press

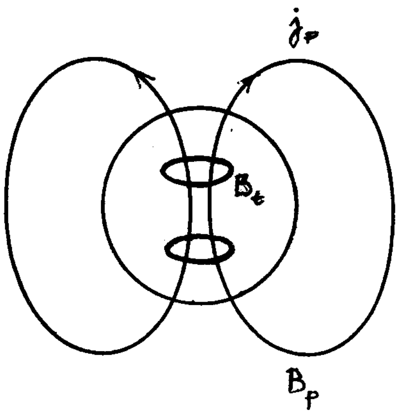

Fig. 1

In this case some external sources are needed to maintain the field. Hence, the fossil field theory in its classical form is rather inefficient.

2. The Dynamo Theory

The essence of the dynamo action in a conductive medium may be explained in a few words as follows. Consider a closed electric current loop which is frozen into plasma and, thus, follows all plasma motions. The current circuit may be expanded by motions and then twisted (e.g. by coriolis forces) into the geometrical form which looks like a number eight. After this the motions may put both parts of the twisted circuit together, restoring the initial single loop configuration, but with redoubled current. Motions of such kind are common in covective zones of rotating stars. The above process may be repeated many times, leading to the 2^n-fold amplification of the current and the field after the n-th cycle. The field configuration may be stable because both B_p and B_t are present. The convection developed in the star together with fast rotation create obviously favourable conditions for the dynamo to operate. However, Ap stars have either no outer convective zone or a very thin one, and possess, as a rule, slow rotation.

Appropriate conditions for the dynamo may be realized in the convective inner core (F. Krause, R. H. Rädler 1980). If the field is actually generated in the core, it

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must be transported upward, manifesting itself as the observed field. The time necessary for the field to penetrate through high conductive stellar layers to the surface exceeds the age of the star. However, the field may readily be lifted upward together with the hot plasma by buoyancy forces. Unfortunately this attractive possibility has not been considered quantitatively, and no evidence has been obtained that in Ap stars there exist some mechanism of the heat transport aside of that provided by the radiation. The field decreases toward the surface roughly proportional to some power of the density ($\sim\rho^{2/3}$). This means that the initial field near the core should be about several millions of gs. All up-to-date versions of the dynamo-theory make use of the linear approximation which does not permit calculations of the field value, but only the field growth rate at the very initial stage.

Thus, the dynamo origin of Ap star fields cannot be excluded but the current theory is far from being entirely conclusive.

3. The Biermann Effect

Magnetic fields in rotating bodies may also be generated by so called "Biermann effect" (L. Biermann 1955). This field is produced by the vortex electric field $E_B = \nabla P_e / eN_e$, P_e - being the electron pressure and N_e the electron number density. The Ohm law for a plasma may be written as

$$\vec{j} = \sigma \left[\vec{E} + \frac{\vec{v}}{c} \times \vec{B} - \frac{\vec{j} \times \vec{B}}{ecN_e} - \frac{\nabla P_e}{eN_e} \right] \qquad (1)$$

where all the symbols have their standard meanings. For the fully ionized plasma $\nabla P_e/N_e$ is proportional to $\nabla P/\rho$ where P is the total pressure and ρ the plasma density.

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From hydrostatic equilibrium, one has $\nabla P/\rho = \vec{g} + \vec{\Omega} \times (\vec{\Omega} \times \vec{r})$, where $\vec{g}$ is the gravity and $\vec{\Omega} \times (\vec{\Omega} \times \vec{r})$ is the centrifugal acceleration. If the rotation is differential, i.e. the angular velocity $\vec{\Omega}$ depends on coordinates, then $\nabla \times (\nabla P/\rho)$ 0. This means that the field E_B has vortex component and cannot be compensated by the electric field $E = -\nabla\phi$ produced by plasma polarization. The persistent electric current $j_B = -\sigma \nabla P_e/eN_e$ creates the magnetic field which may be large. However, the time of the field growth to the observed values exceeds, as a rule, the age of the star. That is why this mechanism has not be regarded as effective.

4. The Effect of Chemical Inhomogeneity

The following new mechanism of the field generation has been proposed by Dolginov (1977). If the mean molecular weight on a star is not distributed spherically symmetrically, then, in general, the partial pressure gradient per electron is not curl-free. In this case the equation which govern the magnetic field B has the form

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left[\vec{V} \times \vec{B}\right] - \nabla \times \left[\frac{c^2}{4\pi\sigma} \nabla \times \vec{B}\right] - \nabla \times \frac{\vec{j} \times \vec{B}}{eN_e} - \frac{c}{e} \frac{\nabla N_e \times \nabla P_e}{N_e^2} \qquad (2)$$

The last term on the right-hand side of eq. (2) describes the effect of molecular weight inhomogeneity. For Ap stars, the condition $\nabla N_e \nparallel \nabla P_e$ holds because of the presence of abundance patches on stellar surfaces and, first of all, of helium abundance patches. An axially symmetrical distribution of the patches leads only to the toroidal field generation. The poloidal field may be created in the following cases: (a) the helium distribution

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is not axially symmetric; (b) the surface temperature gradient ∇T has a tangential component nonparallel to that of ∇N; (c) a poloidal circulation of the stellar matter (e.g., meridional circulation) is present.

Calculations performed by Dolginov (1977), also by Dolginov and Urpin (1979) on the basis of observational data on chemical abundance patches of Ap stars yield the fields 10^3-10^4 gs, in agreement with observations. The time required to reach these values is about 10^5-10^6 years. Hence, the proposed mechanism is effective, if the lifetime of helium abundance patches exceeds 10^5-10^6 years. More than 10 year-long observations of Ap stars show no noticeable change in the surface abundance distribution. This means that the lifetime of patches exceeds 10^2-10^3 years. However, there exist no observational data concerning time scales $\sim 10^5$-10^6 years. This problem is closely connected with the problem to understand the nature of chemical anomalies.

The most elaborated model of abundance patches is based on the assumption that the patches are created by some diffusion process in the magnetic field (G. Megessier IAU Coll. 90, G. Alecian IAU Coll. 90). However, various instabilities which may lead to fast escape of the plasma from the magnetic trap have not been analysed and the lifetime of heavy elements in the traps has not been determined.

Dolginov (IAU Coll. 90) pointed out that the abundance patches may be created due to the thermal instability. Let us assume the existence of some initial local excess of atoms which can be easily excited by electron impacts. Then the blanketing effect of spectral lines may lead to the local cooling of the matter near the stellar surface. It may result in the local increase of the number density

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of the atoms which cause the cooling, i.e. in the abundance patches creation. This instability provides an example of a selforganizing process. The lifetime of the patches in this case may be rather long.

5. Combined Effect of Fossil Field and Chemical Inhomogeneity

L. Mestel and D. Moss (1983[b]) have made an attempt to use the effect of chemical inhomogeneity as a source for maintaining the fossil field. They have considered two possibilities: (a) The redistribution of mean molecular weight may be due to the meridional circulations which exist in rotating stars. In this case the redistribution is axially symmetric and may be responsible only for a toroidal field. If the fossil field is poloidal, then the generated toroidal component may provide the stability of the total field configuration. However, this effect is able to maintain observed fields only in rapidly rotating stars which possess hot coronae. Ap stars do not fit to these conditions: (b) As has been shown in previous section, helium abundance patches may be responsible for total Ap star fields. If the poloidal component is of a fossil nature, then the helium patches may be sufficienty effective to maintain the required toroidal component. This possibility has been considered in detail by L. Mestel and D. Moss (1983[b]). It has been shown that the effect of chemical inhomogeneities is important in the theory of Ap star fields without its having necessarily to be the explanation of the total surface field.

6. Role of Chemical Inhomogeneities in Various Cosmic Objects

Chemical inhomogeneities may be important not only for

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such peculiar objects as Ap stars. They may be efficient also in the stars with developed convective zones. Near the boundary between the convective and radiative zones convective motions are slow, and the heat transport mechanism changes very sharply. Such conditions are favourable for the development of some instability which leads to chemical separation and produces, in this way, the field generation (Dolginov 1984).

It is highly likely that large scale chemical inhomogeneities at the core-mantle boundary inside the Earth play an important role for the terrestrial magnetic field generation. As has been shown by Dolginov (1984) even a 10% large scale tangential variation of the electron number density at the core-mantle boundary caused by chemical inhomogeneity is sufficient to generate the terrestrial field of the observed strength. Any theory of the Earth's field should take into account even a 1% large-scale variation of N_e.

7. Magnetic Field Generation in Binary Stellar Systems

(A) Tidal velocities in close binary stars whose rotational axes are non-parallel have been calculated by Dolginov (1974) and also by Dolginov and Yakovlev (1975). The tidal flow has a complicated geometry which is favourable for the dynamo action. In sufficiently close systems the time for the field growth by the dynamo mechanism driven by tidal forces is much shorter than the age of the star.

Tidal flows in close binary systems are capable of mixing the matter in surface layers and destroying chemical abundance patches on peculiar stars. That is why Ap stars are absent in close systems. Fast rotation may generate circulations which also can mix the matter. The absence of intensive mixing near the surface is apparently a necessary condition which enable the star to belong at Ap type.

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(B) The inductive mechanism of field generation in close binary systems has been proposed by Dolginov (1973) and considered in detail by Dolginov and Urpin (1979). If one of the stars has some small initial field, then the stellar rotation and orbital motion induce electric currents in the counterpart. These currents produce a magnetic field which, in its turn, generates the current and additional field in the first component. This effect leads to the initial field amplification. The increment is proportional to the angular velocities of the orbital

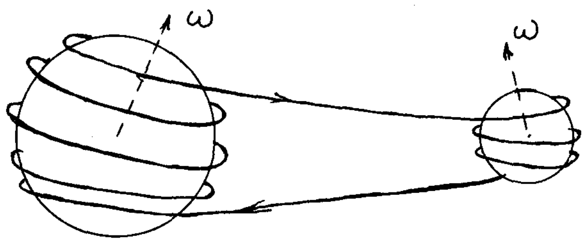

Figure 2

and axial rotation and inversely proportional to the fourth power of distance between the companions. If, for example, one component is a red dwarf with radius $\sim 10^{10}$ cm, the other one is a white dwarf with radius $\sim 10^{8}$ cm, the component sepration is 5.10^{10} cm, angular rotational velocities are equal to $\omega \sim 10^{-3} s^{-1}$, $\Omega \sim 3.10^{-4}\ s^{-1}$, and inclination of rotational axes is about 45^{o}, then the time of field growth is about 10^{5} years. The field amplification is suppressed by nonlinear effects. It is quite possible that the observed strong fields $\sim 10^{5}$-10^{7} gs in some close binaries which contain two dwarfs are produced by the inductived mechanism.

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(C) Let us consider the close binary system with the matter outflow from one star to the other. Let the first star possess the field, generated, for instance by the dynamo mechanism. Then, the accreting star may acquire the field together with the accumulated plasma (Drobyshevsky 1976). In this case the scale of such field seems to be small. The application of this mechanism to Ap stars is thought to be doubtful because there are no indications that Ap stars enter close binary systems in the course of their evolution.

8. The Thermomagnetic Instability

In the objects, where heat and electric current are provided by electrons, the field may be generated by the thermomagnetic instability (Dolginov and Urpin 1979, 1980, Blandford et al. 1983; Urpin et al. 1986). The instability operates as follows. Consider a thermodynamically open system with a temperature gradient ∇T_o (which is mainstained, for example, by nuclear reactions in the centre of the star). Any small initial magnetic field $\vec{B}_o$ induces the heat flow $\vec{q}_o$ perpendicular to both ∇T_o and $\vec{B}_o$. The flow $\vec{q}_o$ creates the thermoelectric field E_{th} and corresponding electric current. The current, in its turn, generates magnetic field $\vec{B}_1$, which amplifies the intial field $\vec{B}_o$. This instability has been investigated in laboratory. For example, a small grain ($\sim$0.01 cm) irradiated by an intensive laser beam acquires a field 10^6–10^7 gs in $\sim 10^{-9}$ s. It has been shown in the above mentioned papers that the thermomagnetic instability may very effectively generate magnetic fields in white dwarfs, neutron stars and hot stellar coronae. The considered instability does not operate in regions with radiative or convective heat transport.

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Conclusion

We have made an attempt to show that large variations in physical conditions in cosmic objects may lead to quite different ways of the magnetic field generation. In some cases the fossil field may be most important, whereas in other cases the field may be generated by chemical inhomogeneities, by the dynamo-process, etc. One may hope that unambigous choices of the field generation mechanisms for certain objects is possible in the near future.

As for the case of the Ap stars, the following questions are most urgent: (a) What is the fine structure of the magnetic field? (b) What is the nature of an association between the magnetic field and chemical anomalies? (c) To what depths do the chemical anomalies penetrate and what is their lifetimes and space structure? (d) What is the relative role of diffusion and hydrodynamical motions in the process of chemical separation? (e) What is the role of various instabilities?

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