FOSSIL MAGNETIC FIELD OF CHEMICALLY PECULIAR STARS

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ABSTRACT. The observational evidence and theoretical approach for magnetic fields of Ap and Bp stars ere reviewed. A detailed theoretical discussion of the theory for fossil magnetic field is given.

1. INTRODUCTION

The 10-20% of A and B start of IV, V luminosity classes are chemically peculiar (CP) stars. The observational features of CP stars in reviews of Borra et al. (1982), Khokhlova (1983), Didelon (1984), Mestel (1984), Glagolevskij et al. (1986), Moss (1986) and others are discussed in detail. We emphasize here only those characteristics of CP stars that may be connected with the origin and properties of magnetic field.

Ap and Bp stars have surface magnetic fields (B_s) from a few hundred Gs up to 35 000 Gs. No certain observations of the field have been made in Hg Mn- and Am- chemically peculiar stars and other normal stars with the lower limit of detectability of the order of 100 Gs (Borra and Landstreet, 1980; Didelon, 1983; Glagolevskij et al., 1986). Magnetic fields of CP stars, as well as their luminosity and line intensity, are variable with rotation periods from 0.5 to 10 days. In many cases the conversion of field polarity is observed.

Kurtz (1982, 1984) has found rapid photometric oscillations in several cool Ap stars on time scales Δt=6-14^m and with an amplitude $\Delta m \approx 0.01$, followed with the similar alterations of magnetic fields.

The magnetic Ap stars rotate essentially slower than the normal A stars. The rapid rotators have more feeble fields (Borra and Landstreet, 1980; Didelon, 1984). The He-r stars and CU Vir with a period $P \approx 0.^d5$ and $B_s \approx$ 7000 Gs are exceptions to this rule. Perhaps the hotter more massive CP stars have significantly stronger fields (Thompson et al., 1985). The observations showed that young magnetic stars rotate faster than their older counterparts, implying magnetic breaking on the Main Sequence (Landstreet and Borra, 1978; Wolff, 1981; Didelon, 1984; Brown et al., 1985).

A certain part of CP stars experience a substantional pre-Main Sequence breaking (North, 1984; Borra et al., 1985). Apparently the mean field strength of some CP stars declines over an evolutionary time scale (Borra, 1981; North and Cramer, 1984; Glagolevskij et al., 1987).

The locations of magnetic and normal stars on the H-R diagram are not distinguished. Therefore, the internal magnetic fields of Ap and normal stars are similar. The relation of magnetic energy to gravitational one is $\xi_m < 0.1$ (Dudorov, 1986). Consequently, the Ap-stars are the stars with considerably stronger surface magnetic fields than the normal ones.

A magnetic field of CP stars is represented conventionally by the oblique rotator model (Stibbs, 1950) in which the magnetic axis is inclined to the rotation axis at some β angle. A field of the dipole, displaced from the stellar centre, seems to explain the majority of observations, assuming that different elements are concentrated in different spots on the surface of stars. The distributions of β angles are bimodal with the primary maximum of about $\beta=90°$ and the secondary one $\beta= 0°$ (Borra and Landstreet, 1980; Didelon, 1984). North (1985) has suggested the random distribution. The element inhomogeneities can significantly affect the surface structure of magnetic field (Piskunov and Khokhlova, 1983). The multipole superposition of the surface magnetic field is physically more real and may allow to consider its toroidal component. The observations confirm the similar idea (Thompson and Landstreet, 1985). It is necessary to notice, that the magnetic field seems not to affect the internal structure and atmosphere of Ap stars in measurable way, except for the production of chemical peculiarities, which are presented also in non-magnetic CP stars.

2. MAGNETIC FIELD ORIGIN

Origin, structure, stability and temporal variation of a magnetic field; its influence on chemical anomalies, rotation and stellar structure; origin of chemical peculiarities - are the basic theoretical problems of CP stars. Three approaches have been advanced in the mechanisms of the magnetic field generation - battery, dynamo and fossil theories.

It is necessary for a battery operation, that the surface of constant pressure does not coincide with the surface of constant density (Biermann, 1950). Battery can generate a magnetic field of 10^3 Gs for 10^{10} years in differentially rotating stars (Roxburg, 1966). The effect decreases, if a weak poloidal field is present in the star. So, the Biermann battery can create only a seed Held. Dolginov (1977) showed, that the local Biermann effect due to gradient of anomalous helium abundance in surface spots of CP stars looks like more promising means of maintaining a strong surface toroidal field. The poloidal field is supposed to arise from interaction of the toroidal field with meridional circulation. Mestel and Moss (1983) estimated the azimuthal field of the local chemical battery assuming preexisting fossil poloidal field, Dolginov (1984) has extended the conception of the chemical battery to explain the magnetic fields of the Earth, the Sun and neutron stars.

The work of cosmic dynamo is demonstrated by the earth's and, apparently, solar magnetic fields (Cowling, 1981; Belvedere, 19851. The dynamo theory is in a fairly advanced stage of development and has reached the monographic stage. The state of this theory was described quite comprehensively in the books of Moffat (1978); Parker (1979); Vainshtein et al., (1980); Krause and Radler(1980); Zel'dovich et al. (1983) and reviewed by Cowling (1981); Krause (1983); Mestel (1984); Ruzmaikin and Zel'dovich (1987). Therefore, we discuss purely astrophysical aspects of dynamo evidence in CP stars.

In dynamo theory the contemporaly magnetic field is maintained by turbulent (or cyclonic) motions and differential rotation. The turbulent energy of A-star envelopes is essentially less than the thermal and magnetic ones (Dudorov, 1976). So, dynamo can not operate in subsurface layers of Ap-stars. These starsudo posses the convective cores containing about 10% of stellar mass on the stage of hydrogen burning. The field would have to be generated in the core by the " $\alpha\omega$ " dynamo and is subsequently leaking out to the surface of stars in a time slightly less than nuclear time (Schussler and Pahler, 1978). However, kilogauss magnetic fields are observed in some pre-Main Sequence stars, that may be no more than about Kelvin - Helmgolz time old (smaller than 10^7 yr for 2 $M_\odot$ stars). Classical diffusion time through a radiative envelope of these stars is of the order of 10^9 years. The buoyant rise of flux tubes may be "force* the diffusion. But this process is too slow to explain the observed magnetic field of young stars. (Dudorov, 1986). The magnetic buoyancy may also decrease the effectiveness of the core dynamo.

The dynamo theory has a number of free parameters, especially if a consistent dynamical treatment is attempted. It is impossible to predict the value of some dynamo parameters, since the structure of convective cores even in the absence of a magnetic field can be described only as an order of magnitude manner. The steady solutions of the dynamo equation exist for relatively low values of the dynamo number, $N \sim \omega^2$, where ω is the angular velocity. For larger N (and larger ω) the core field will be oscillatory and because of skin-effect will be trapped inside the stars (Parker, 1979). Thus only slow rotators may display a core dynamo field on the surface (Moss, 1986). Interesting possibilities to maintain the surface field in a rapid rotator are demonstrated by the mechanisms of semidynamo in convective (Drobyshevski, 1977) and radiative (Hinata, 1981) zones.

The theory of fossil magnetic field is based on: 1) observational data on a magnetic field of starforming regions (Dudorov, 1986); 2) investigation of magnetic flux evolution during starforming process (Dudorov, 1986 b, c; Nakano and Umebayashi, 1986; Dudorov and Sazonov, 1987) and 3) long decay time for dipolar mode of magnetic field in upper main sequence stars (Cowling, 1945; Wrubel, 1952; Mestel and Moss, 1984).

3. FOSSIL MAGNETIC FIELD

In condensation theory of starforming process the fossil fields intensity is decreased by nonhomologous contraction along the field lines to flatter configurations, by ambipolar diffusion and decay of magnetic field for low conductivity, hydromagnetic and other instabilities, turbulent convection and flux tubes buoyancy.

Dudorov andSazonov (1987), Dudorov (1986 b, c) have investigated numerically variations of magnetic fluxes during the clouds collapse, protostars contraction and stars evolution up to hydrogen burning. Me begin by considering spherical non-rotating isothermal clouds with a magnetic field immersed in an external medium of constant pressure. The way the problem is put is formulated by Dudorov and Sazonov (1981, 1987). The basic equations are:

$$\frac{d\bar{v}}{dt} = -\frac{\nabla P}{\rho} + \frac{GMr}{r^2}\frac{\bar{r}}{r}, \tag{1}$$

$$\frac{d\rho}{dt} = -\rho\nabla\cdot\bar{v}, \tag{2}$$

$$\frac{dE}{dt} + P\frac{d}{dt}\left(\frac{1}{\rho}\right) = \nabla\left(\frac{4acT^3}{3æ_R\rho}\nabla T\right), \tag{3}$$

$$\frac{dx}{dt} = (1-x)\zeta - \alpha_r x^2 n - \alpha_g x n \tag{4}$$

$$\frac{d\bar{B}}{dt} = \nabla\times[(\bar{V}-\bar{V}_{AD})\times\bar{B}] + (\bar{V}\cdot\nabla)\bar{B} - \nabla\times(\nu_m\nabla\times\bar{B}), \tag{5}$$

$$V_{AD} = \frac{\langle rot\,\bar{B}\times\bar{B}\rangle_\Theta}{2\pi\mu m_H n^2 x\langle\sigma_{in}U_n\rangle u}, \tag{6}$$

where v is velocity; ρ is mass density; P is pressure; Mr is the mass within sphere of radius,r;E is specific energy; T is temperature; x - ionization ratio; n - particle density; ζ - the ionization rate by cosmic ray (CR), X-ray and radioactive elements, αr - radioactive recombination coefficient; α g - coefficient of grain recombination; B - magnetic field strength; ν_m - magnetic viscosity; V_{AD}-velocity of ambipolar diffusion; m_H - the mass of hydrogen atom; μ - molecular weight in atomic mass units; $<\sigma_{in} U_n>$ n = $2\cdot 10^{-9}$ cm^3 s^{-1} (Spitzer, 1978); G, a, c - physical constants. In spherical coordinate system $\bar{v}$-{Vr, 0, 0}, VA1)={VAD, 0,0}, $B = \{B_r, B_0, 0]$. The calculations of energy, pressure, opacity, ionization ratio and the magnetic viscosity take into consideration the dissociation of molecular hydrogen, collisional and thermal ionization of hydrogen, helium and heavy elements, Na, Mg, Al, Si, Ca, Fe, Ni. We have omitted the dynamical effects due to grains, such as coupling of charged grains with plasma and magnetic field. So, for small ionization fraction, $x \ll 1$ the equations (1 - 6) describe two-fluid approximation in the kinematic problem - statement of ambipolar diffusion. The neutral gas, influenced by the gravitational forces, moves with $\bar{V}$ velocity. The velocity of ionizing component is $\bar{V}_t = \bar{V} \quad \bar{V}_{AD}$. The ambipolar diffusion velocity of ions and electrons, a relatively neutral component is determined from equation (6), that is the equality condition of the frictional force arising from ion-neutral collisions and spherical mean electrodynamic force, $\bar{F}_B = \frac{1}{4\pi} \langle rot\ \bar{B} \cdot \bar{B} \rangle_Q$. The magnetic field is frozen in ionizing component. Neutrals "feel" the influence of the field indirectly trough collisions with the ions. During the free collapse of protostellar clouds the ion-neutral collisions cause nearly complete coupling between the magnetic field and neutrals. In this time the field strength changes as $B \sim \rho^k$, with $1/2 \leqslant k \leqslant 2/3$. When opaque core in the cloud is formated in the region of density, $n_e > 10^5 n_o$(n_o - initial density), cosmic and X-ray fluxes are diminished. Ionization ratio is decreased up to $x < 10^{-12} - 10^{-13}$. The coupling of plasma and neutrals weakens, giving a rise to ambipolar diffusion of charged particles with the magnetic field in a sea of neutral gas. For $x < 10^{-13}$ the ohmic diffusion of the magnetic field is growing in hydrodynamical time scale. The upper limit of density region ($n_u = 10^9 n_0$) of effective loss of magnetic flux in core, by evaporation of dust and thermal ionization of metals is established. The values of n_e and n_u are influenced greatly by the ionization rate of CR, XR, K^{40} the grain parameters and opacity. The typical behaviour of the field strength in protostars is shown on Fig. 1. The magnetic diffusion is progressed in the region of high gradient of the field strength, decreasing the magnetic field in the core and increasing it in the envelope of protostars. The pumping of the magnetic field in surface layers is amplified in two limit cases that Dudorov and Tutukov (this volume) discuss.

In the processes of core heating and envelope accretion the diffusion region shifts outside reducing in dimensions. The location of this region in protostars coincides with the outer zone of hydrogen fractional ionization. When the ionization ratio raises to values $x \geqslant 10^{-10} - 10^{-8}$, the diffusion time scales will exceed the other time scales. The magnetic field is again frozen in the stellar matter.

The subsequent constancy of the magnetic flux may be broken up by turbulent motions in convective zones. However, the convection in external parts of A and B stars is so feeble, that may not change the structure and strength of the magnetic field (Dudorov, 1976). The calculations show, that A and B-stars do not pass the Hayashi stage. Therefore, we can expect that the surface magnetic field of zero age main sequence stars is the fossil field with the strength $B_{fs} \simeq 50 - 500$ Gs (Dudorov, 1986 c). The surface fossil field is minimum in late-type stars with a mass of $M < 0.5 M_{\odot}$ Along the main sequence its strength increases up to A2 - B8 stars, reaching its peak $B_{fs} = 300 - 500$ Gs. For B0 stars $B_{fs} \simeq 100 - 200$ Gs. These values depend on many factors (see above) and may be decreased about one half of ten.

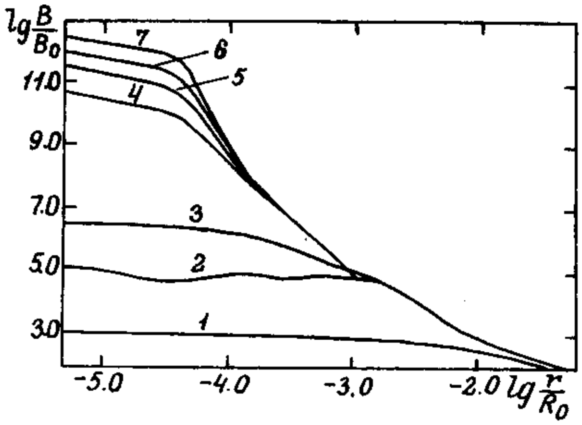

Fig.1. The run of the magnetic field, B strength in units of initial field strength, Bo versus nondimensional radial coordinate during the collapse, core formation and accretion stages of star-formation process. The lines 1- 7 correspond to relation of central density to initial, $\rho c/\rho 0 = 10^5$, $7 \cdot 10^9$, $3 \cdot 10^{14}$, $3 \cdot 10^{19}$, 10^{20}, $4 \cdot 10^{20}$, $2 \cdot 10^{21}$, respectively; $\rho_0 = 1.8 \cdot 10^{-19}$ g cm^{-3} for cloud with mass $M = 5 M_{\odot}$; $B = 7 \cdot 10^{-6}$ Gs.

The energy of the internal fossil magnetic field is, $E_m \simeq 10^{-2}$ Eg (Eg - module of gravitational energy). The mean strength of the internal field, $\tilde{B}_f \simeq 10^5 - 10^8$ Gs, is proportional to the mean density except for late-type stars.

4. DISCUSSION

The numerical calculations of the magnetic flux evolution in the star- forcing process have demonstrated, that in zero age Main Sequence stars the fossil magnetic field is retained. The ohmic attenuation of currents changes the topology and reduces the intensity of the magnetic field in hydrogen burning stars with masses $M \geq 2.0 M_{\odot}$ insignificantly. The convective motions in envelopes of middle mass stars can not diminish the fossil field.

The turbulent energy in the convective cores of upper Main Sequence stars is of the same order in comparison with the thermal energy and exceeds the magnetic energy of the fossil field. For such conditions the turbulent motions can lead to decrease of one spatial scale of the magnetic field and can induce its concentration on the boundary of convective cells in fores of screwing ropes (Galloway and Weiss, 1981). The small-scale magnetic fields in convective cores decay for turbulent diffusion time, that is ten times smaller than the nuclear time.

The rise of slender magnetic flux tubes to the surface can induce the shorttime variability of stars. This variability must be observed in young CP stars. Its energetics will be considerably smaller than energetics of flare activity of UV Cet and T Tau type stars. The flare stage of CP stars begins with hydrogen burning, since only stars with mass $M \lesssim 1.5 M_{\odot}$, can pass the Hayashi stage of intensive convection up to the Main Sequence (Larson, 1969; Kolesnik, 1979; Winkler and Newman, 1981; Stahler, 1983). Perhaps, the origin of chemical anomalies of CP stars is associated with buoyancy of magnetic flux tubes.

The joint action of convection and buoyancy is the effective mechanism of the magnetic flux loss. These mechanisms work during the nuclear time. The buoyancy effectiveness is slowed down by rotation, meridional circulation, gradients of molecular weight; It is not investigated, how the buoyancy changes the large-scale magnetic field. The estimations show, that in the Main Sequence stars with masses $M > 1.5 M_{\odot}$ there can live the fossil magnetic field of the order of 10^7 Gs.

For the theory of fossil magnetic field we need maintaining of the field stability during the evolution time 10^7 - 10^8 yr. The field of dipolar or toroidal topology has neutral lines which are circles, enclosing the magnetic axis. The local geometry of the neighbouring magnetic lines can be seen to be similar to that of classic Z-pinch. The linear analysis shows, that in the ideal plasma of low betta ($\beta = 8\pi P/B^2$) simple hydrodynamic modes can develope leading to the "sausage" and "kink" instabilities (Wright, 1973; Markey and Tayler, 1973, 1974). These topological instabilities are retarded by ortogonal components of the magnetic field. The poloidal field with strength of the order of toroidal field can probably have a stable configuration (Wright, 1973; Tayler, 1980). It should be noted, that the real fossil magnetic field in rotating stars will have the same topology. The poloidal-toroidal fields confining completely within a polytropic star can diffuse into an unstable configuration (Tayler, 1982; Moss, 1984). The rapidly rotating stars with intense meridional circulation must have such a field. However, the stars with the strong fossil magnetic field must rotate slow.

The linear hydrodynamical instabilities themselves do not destroy a magnetic flux. A nonlinear regime of instability development in magnetic stars was not investigated up to this time. But it may be expected, that the growth of linear perturbations into the nonlinear behaviour will cause a decrease in the length scale of the field. The perfect conductivity approximation will cease to be valid. The field under en ohmic dissipation will evolve to the state of magnetic energy minimun, acquiring the stable force-free field features. Pressure, compressibility and rotation exert a stabilizing influence on the magnetic field (Dicke, 1979; Pets and Tayler, 1985).

The hydromagnetic instabilities act also on the dynamo-field, which is the toroidal-poloidal field with strength relation of toroidal component to poloidal one, equal to = 100 (Parker, 1979). The fossil seed field leads to the increase of this relation (Levy and Boyer, 1982), consequently stabilizing the dynamo-field. Therefore, the stars after appearance of convective cores will have a fossil magnetic field influenced by turbulence and renewed by the dynamo-mechanises. This point of view is confirmed by observations (Glagolevskij et. al., 1986). The convection in cores of F and A stars can not destroy the fossil magnetic field and can not generate the intense dynamo-field. The convective cores dynamo of B-stars will really support the fossil seed field at some constant level.

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