ON THE MAGNETIC FIELD ORIGIN OF Ap STARS

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ABSTRACT. We study the problem of a fossil magnetic field pumping from the core into the envelopes of zero age Main Sequence stars during the star formation process. We show that the ohmic diffusion may pump a magnetic field into the external layers of stars at the stage of stellar core formation on hydrodynamical time scale.

1. INTRODUCTION

The Ap stars relate to chemical peculiar (CP) stars and represent the homogeneous group of magnetic middle mass stars.

The surface magnetic field of Ap stars is three-ten times stronger than that of normal stars with the same mass (Didelon, 1984). The absence of evolution differences for normal and magnetic stars show that the relation of magnetic energy to module of gravitational one is $\varepsilon_m = 10^{-2} - 10^{-4}$ (Dudorov, 1986). The relation of gaseous and magnetic pressures, $\beta = 8\pi P_g/B^2$ in envelope of Ap stars is small (<1, Dudorov, 1976). Apparently, the magnetic field of Ap stars is amplified in the surface layers.

The field, diluted inside and forced in the envelopes of stars is difficult to explain by the core dynamo. The chemical battery (Dolginov, 1977) of weak gradients of heavy elements operates in Ap stars very slowly. The usual treatment of the fossil theory predicts that all stars of the Main Sequence upper part have the surface magnetic field of the order of few decades - few hundred Gs (see Dudorov, this volume), with the same relations of energies, and ε [illegible]. Consequently, in the theory of fossil field the problem of the surface field amplification exists. Mestel and Moss (1984) reported that a fossil field is forced by chemical battery, that can explain the surface field of Bp stars with excess or missing of helium.

In the present paper the problem of a fossil field pumping in the star envelopes is investigated. We assume that the surface magnetic field strength may be influenced by the high energy flux of cosmic rays (CR) and by intensity of hard ultraviolet radiation (UV), changing the effectivity of diffusion processes. The rise of CR flux and ultraviolet intensity is caused by the supernova bursts and by formation of massive OB stars, occurring in the giant molecular clouds.

2. FOSSIL MAGNETIC FIELD STRENGTH

We study the dependence of the fossil field strength of stars upon ionizing radiation power with the computer program of numerical study of protostar evolution (see Dudorov, this volume). A starting model for calculations was a constant density cloud on the gravitational instability threshold threaded by a homogeneous magnetic field. The magnetic flux evolution in the starformation process is investigated in the framework of the kinematic problem statement, that is from the cloud collapse beginning up to the moment, when the central density of star becomes equal to 1--10 g cm^{-3}. At that time the stellar core has the mass $M_c \simeq 0.1\ M_0$, where M_0 is the initial mass of the protostar. The last accretion stage of envelope on the stellar core can not be studied, as the time steps of Lax-Vendroff modified code (Dudorov, Sazonov, 1981) were getting very small. The subsequent change of the magnetic field frozen in the star is estimated in accordance with the relation $B \sim \rho^k$, with k = 2/3 or 1/2.

The fossil magnetic flux of high mass stars is decreased by the ambipolar diffusion and ohmic attenuation of electric currents. The effectivity of the processes is influenced by the values of ionization fraction and by its dependence upon the density (Dudorov, Sazonov, 1987). Equation (4) from Dudorov's paper (this volume) shows that the ionization fraction is a function of ionization and recombination rates. The ionization rate by the background cosmic radiation,

$$\zeta = \sum_i \zeta_i^0 \cdot e^{-N(r)/r_i}, \qquad i = CR,\ UV, \tag{1}$$

is calculated for the parameters ζ_i^0 and r_i, cited in Tabl. 1 and for column density

$$N(r) = \int_r^R \rho\, dr,$$

where R is the cloud radius, r is the coordinate. The recombination rate is caused by the radiation recombination with the coefficient $\alpha_r = 4.14\ 10^{-11}/\sqrt{T}\ \mathrm{cm^3 s^{-1}}$ (Spitzer, 1978) and by recombination on grains with the coefficient $\alpha_g = \alpha_{go} = 4.5 \cdot 10^{-17}\ \mathrm{cm^3 s^{-1}}$ if the temperature $T \ll 150$ K, $\alpha_g = \alpha_{gm} = 3 \cdot 10^{-18}\ \mathrm{cm^3 s^{-1}}$, for 400 K<T< 1500 K. In the temperature intervals 150 K<T<400 K and 1500 K<T<4000 K α_g is interpolated linearly from α_{go} to α_{gm}, and from α_{gm} to 0, respectively.

The basic results of calculations are represented in Tabl. **1** for a number of stellar masses. The surface strength B_s has been calculated for the level $\tau = 2/3$ in star photospheres.

The first five variants of Table correspond to ionization by high energy cosmic rays (HECR), the sixth variant - to ionization by CR from supernova bursts and shock waves (MECR), the seventh variant - to ionization by diffuse ultraviolet radiation (DUV), the eighth variant corresponds to ionization by OB stars ultraviolet radiation (UVOB), the last variant - to ionization by background X-rays (XR). The analysis of the obtained results allows to draw the following conclusions.

The surface magnetic field decreases to higher masses (see variants 1-3) because of the freezing force of the magnetic field and because of the constancy of diffusion parameters (Dudorov, Sazonov, 1987). The growth of CR-flux causes the slight surface field amplification (see variants 4-6), that is connected with the decrease of diffusion velocity. The observed fields of Ap stars may be obtained, if CR ionization rate ζ°_{CR} is increased by the order of 10^2-10^3 and if the range of CR r_{CR} is constant. The falling of range r_{CR} leads to B_s decrease.

The substantial raise of CR ionization rate may lead to restoring of magnetic flux freezing and ceazing its pumping into stellar envelopes. When the protostars are ionized by the ultraviolet radiation or XR, the surface magnetic field has the small intensity (see variants 8, 9). However, in this case it is necessary to investigate the ambipolar and ohmic diffusion further at the accretion stage of protostellar envelopes. The diffusion pumping of the magnetic field from central regions into the surface layers is more effective in case of ionization by hard diffusion ultraviolet radiation, than by XR. The power dependence of ionization XR-rate on column density leads to weakening of ohmic diffusion, that amplificates the surface field. The effectiyity of ambipolar diffusion is the same in both cases. Therefore, in stars, protostars of which are irradiated by XR, $B_s \leqslant 1$ Gs.

We should underline, that the surface field intensity does not depend practically on the initial relation of magnetic and gravitational energies ε_m, since the velocity of ambipolar diffusion varies inversely as the ionization ratio and ohmic diffusion does not depend on strength of magnetic field.

3. CONCLUSION

We studied the problem of fossil magnetic field pumping into the envelopes of zero age Main Sequence stars. Several parameters characterize the problem: the ionization rate ζ°_{t} and the range, r_t of cosmic radiation, the dimensions, abundance and evaporation temperature of grains, the content of heavy elements. The results will depend on physics of stellar accretion stage. Our basic

Table 1. Strength of magnetic field

No.	$M/M_\odot$	ρ_0 g/cm^3	B_0 G	ζ^0_{CR} s^{-1}	r_{CR} g/cm^2	ζ^0_{UV} s^{-1}	r_{UV} g/cm^2	$B_s^{2/3}$ G	$B_s^{1/2}$ G	Remarks
1	2	$1.1 \cdot 10^{-18}$	$1.7 \cdot 10^{-5}$	$6 \cdot 10^{-18}$	130	0	-	220	25	HECR
2	3	$5 \cdot 10^{-19}$	$1.2 \cdot 10^{-5}$	$6 \cdot 10^{-18}$	130	0	-	163	22	HECR
3	5	$1.8 \cdot 10^{-19}$	$7 \cdot 10^{-6}$	$6 \cdot 10^{-18}$	130	0	-	142	21	HECR
4	5	$1.8 \cdot 10^{-19}$	$7 \cdot 10^{-6}$	$6 \cdot 10^{-18}$	130	$1 \cdot 10^{-6}$	0.1	145	21	HECR+UVOB
5	5	$1.8 \cdot 10^{-19}$	$7 \cdot 10^{-6}$	$3 \cdot 10^{-17}$	130	0	-	210	31	HECR
6	5	$1.8 \cdot 10^{-19}$	$7 \cdot 10^{-6}$	$8 \cdot 10^{-17}$	66	0	-	254	45	MECR
7	5	$1.8 \cdot 10^{-19}$	$7 \cdot 10^{-6}$	0	-	$1 \cdot 10^{-12}$	4.0	19	2.4	DUV
8	5	$1.8 \cdot 10^{-19}$	$7 \cdot 10^{-6}$	0	-	$1 \cdot 10^{-6}$	0.1	17.6	2.6	UVOB
9	3	$5 \cdot 10^{-19}$	$1.2 \cdot 10^{-5}$	0	-	$1 \cdot 10^{-8}$	0.1	19.7	2.8	UVOB
10	5	$1.8 \cdot 10^{-19}$	$7 \cdot 10^{-6}$		-	-	-	0.3	$4 \cdot 10^{-2}$	XR

conclusion art the followings.

The diffusion may pump the magnetic field from the central regions into the external layers of stars at the stage of stellar core formation and the envelope accretion stage. The pumping will be developed in hydrodynamical time scale, if the accreted envelope is ionized by hard ultraviolet radiation. When the ionization is caused by intense high energy cosmic rays, the stars should be born essentially magnetic.

During the formation of a rotating star the toroidal component of the magnetic field is generated, which behaviour is similar to that of the poloidal field. The magnetic field retards the angular momentum from the protostellar core (Dudorov and Sazonov, 1983). Therefore, the zero age Main Sequence, stars of middle masses will rotate more slowly than nonmagnetic ones. For determination of the final angular momentum and the surface magnetic field of stars the late stages of circumstellar envelope accretion should be investigated. The strength of the surface magnetic field of stars depends also on shock fronts and hydromagnetic waves in starformation regions.

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