FOSSIL MAGNETIC FIELDS AND ROTATION OF EARLY-TYPE STARS

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1. Theory of fossil magnetic fields

Observational data of the last 10 years allow two main conclusions:

a) Main sequence stars can be separated in two classes: – magnetic (Bp) stars with surface strengths of a dipole or quadrupole magnetic field of $B_s \approx n \cdot (10^2 - 10^3)$ G, $n = 2, 3, 4...7$, and – normal main sequence stars (F–O) with magnetic fields $B_s \approx 1 - 100$ G (< 300 G);

b) Typical star formation takes place in interstellar molecular clouds with magnetic field strengths $B \approx 10^{-5}$ G (See Dudorov 1990).

These observations form the base of the theory of fossil magnetic fields. The main goals are the study of the evolution of magnetic flux in the case of ambipolar and Ohmic diffusion and its interaction with rotation and turbulence, where various MHD instabilities may develop during the various stages of the protostellar-cloud collapse and (proto)star contraction.

For these investigations we use the MHD equations with the "diffusional" variables with additional equations (Dudorov 1990) for nonstationary equilibrium of ionization by cosmic and X rays, and the equation for nonstationary magnetic ambipolar and Ohmic diffusion (MAD). We used the weak-magnetic approach (Dudorov and Sazonov 1981, 1986). The numerical simulations are carried out with the help of a modified Lax-Vendroff scheme.

The calculation shows that the magnetic field is frozen in the collapsing gas in case of a transparent collapse and reaches after some time a quasi-radial geometry outside the core. If the ionization state is determined by cosmic rays and radioactive elements, the magnetic field in the opaque protostellar MAD decreases the magnetic flux in the opaque protostellar core if the central density $n_c \approx [10^5 \cdot n_0, 10^9 \cdot n_0]$, with $n_0 = 10^4 - 10^5$ cm^{-3} the initial density. Adiabatic heating of the opaque core switches on the thermal evaporation of grains and the thermal ionization of lighter elements like K, Na, Al etc. (Dudorov 1976), and in regions with temperature $T \approx 4000 - 5000$ K the magnetic field will be immersed into the whole gas again. A zone of powerful MAD moves to the surface in the case of protostars and young-star evolution, coinciding with the region of minimal ionization degree. The attenuation of the frozen-in magnetic field is $\approx 10^{-2}$ for a $5M_\odot$ star on the stellar birth line. The surface magnetic field (before interaction with convection) is

$$B_s \approx B_{s0} \cdot (M/M_\odot)^{0.25-0.35}, B_{s0} \approx F(\tau_{CR}, Z_{RE}, Z_q).$$

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For typical values for the "optical" depth due to cosmic rays τ_{CR}, the abundance of radioactive elements Z_{RE} and radius and abundance of grains a and q, $B_{s0} \approx 1 - 100$ G for normal stars and $\leq 2000 - 3000$ G for the magnetic Bp stars. The magnetic field strength increases towards the center of the star and is in the core $\approx (0.1 - 10) \cdot 10^6$ G depending on the stellar mass.

2. Rotation

Be stars rotate very fast, near to their limit of centrifugal equilibrium. Variable Be stars rotate more slowly. These stars have surrounding disks and possibly a magnetic field, which may connect with the disk. The angular momentum evolution of such a system depends on the existence of a magnetosphere and various phenomena similar to the case of accretion from a stellar wind.

We consider the evolution of angular momentum of a magnetic star with a surrounding thin Keplerian disk. The magnetic field of the star may have three types of geometry: an open fossil magnetic field, a dipole or a quadrupole field. Accretion from the disk feeds angular momentum to the star. The magnetic coupling of the star with the disk diminishes the accretion acceleration of the stellar rotation and may decelerate the star if the magnetospheric radius R_m exceeds the radius of centrifugal equilibrium R_{co}. Therefore, the possibility of a so-called equilibrium rotation occurs when $R_m = R_{co}$. Determining the magnetospheric radius from the balance of magnetic and kinetic energy densities and the corotation radius from balancing the gravitational and centrifugal accelerations, we obtain:

$$V_r = V_{r0} \cdot (B_s/10^3)^{-6q_m} \cdot (\dot{M}/10^{-7})^{3q_m} \cdot (M/M_\odot)^{q_{Mv}} \cdot (R/3R_\odot)^{-q_{Rv}},$$

where

$$V_{r0} = (A_m^{-2q_m} \cdot A_{co})^{\frac{2}{3}} (\mathrm{km/s}), q_{Mv} = \tfrac{3}{2}(q_m + \tfrac{1}{3}), q_{Rv} = \tfrac{3}{2}(5q_m + \tfrac{1}{3}).$$

For a multipole field with $B \approx r^k, q_m = (4k-5)^{-1}, A_m \approx 92, A_{co} = 40$. From this we find for Be stars with $R/2R_\odot = (M/M_\odot)^{q_R}, q_R \approx 1/3$, $B_{s0} = 10^3$ G, $\dot{M} \approx 10^{-7}$ M$_\odot$/yr, $k = 2, V_{r0} = 9.3$ km/s and $q_M \approx 2/3$. For $k = 3$ and the same values for the other parameters, $V_{r0} = 69$ km/s and $q_M \approx 2/11$. For $k = 4, V_{r0} = 120$ km/s and $q_M \approx 2/33$.

This shows that the existence of disks surrounding Be stars and its magnetic field leads to a decrease of their rotational velocities. This conclusion is consistent with the formation of a closed magnetosphere and with the theory of fossil magnetic fields.

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