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Theory of fossil magnetic field

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Abstract

Theory of fossil magnetic field is based on the observations, analytical estimations and numerical simulations of magnetic flux evolution during star formation in the magnetized cores of molecular clouds. Basic goals, main features of the theory and manifestations of MHD effects in young stellar objects are discussed.

Keywords: Young stars; Accretion disks; Magnetic fields; Diffusion

1. Introduction

Hypothesis of fossil magnetic field was proposed by Cowling (1945), who showed that time scale of Ohmic dissipation of the magnetic field in the stars with masses $M \geqslant 1.5-2\,\mathrm{M}_{\odot}$ exceeds time scale of their evolution. From this fact, Cowling concluded that stellar magnetic fields could be remnant (relic) of the magnetic field of protostellar clouds.

Hypothesis of the fossil magnetic field (Spitzer, 1958; Mestel, 1967) in its original form predicted that stellar magnetic fluxes exceed observational fluxes in 10^3-10^4 times. From the other hand, estimations of Mestel and Spitzer (1956) and Spitzer (1968) showed that fossil magnetic flux can dissipate almost completely during protostellar clouds evolution.

Investigations performed since 1970 transformed hypothesis of fossil magnetism into the theory proving that, at least in young stars, magnetic field has fossil nature.

Nakano and Tademaru (1972) made first quantitative estimations of the magnetic field defreezing factor, determined as relation $\beta_f = B/B_f$, where B_f is the frozen-in field, B – real field. Inclusion of ionization by cosmic rays and assumption about constancy of recombinations coefficients let them obtain any arbitrary small values of defreezing factor β_f.

Dudorov (1977a) included mineral grains and thermal ionization of metals with low ionization potential (K, Na, Mg, Al, Ca) into consideration and estimated defreezing factor of the fossil magnetic field in collapsing interstellar clouds. He concluded that Ohmic diffusion and magnetic ambipolar diffusion are the main factors of fossil magnetic flux dissipation. Intensive dissipation of the magnetic field occurs in the density range $n = 2\times10^9-2\times10^{11}\ \mathrm{cm}^{-3}$, where $B \propto \rho^{2/5}$. In this density range, Ohmic diffusion and magnetic ambipolar diffusion reduce intensity of the magnetic field by factor $\beta_f = 10^{-2}-10^{-4}$ comparing to the frozen-in field. Ruzmaikina (1985) obtained similar estimation only for the potassium. These papers as well as paper by Black and Scott (1982) showed that defreezing factor of magnetic field in collapsing protostellar clouds is determined by their ionization and thermal structure, and also by degree of their non-uniformity and anisotropy.

Nakano and Umebayashi (1986a,b) carried out numerical estimations taking into account thermal processes and non-uniformity of the self-similar collapse. They estimated

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conditions of magnetic field defreezing assuming that typical time scale of Ohmic diffusion is equal to the free-fall time, $t_{od} = t_{ff}$. Obtained intensities of the magnetic field inside stars $B \simeq 1 - 10$ Gs are too small comparing to the magnetic field intensity given by the battery effect.

The theory of the fossil magnetic field has been further developed by Dudorov and Sazonov (1981, 1982, 1987). We present main result of these works in the following section. Main purpose of the fossil magnetic field theory is investigation of the magnetic field evolution of the protostellar clouds in process of its induction amplification and dissipation due to Ohmic diffusion and magnetic ambipolar diffusion. Dudorov and Sazonov (1987) calculated not only surface ($1 - 100$ Gs), but also internal magnetic field $\sim 10^5 - 10^6$ Gs of young and main sequence stars.

Evolution of fossil magnetic field in process of protostar formation has been investigated by Mouschovias group (see Desch and Mouschovias, 2001; Kunz and Mouschovias, 2010 and references therein). They considered magnetic ambipolar diffusion as the main factor of fossil magnetic field evolution (Fiedler and Mouschovias, 1993). Magnetic decoupling causes concentration of magnetic flux outside the regions of magnetic ambipolar diffusion (Tassis and Mouschovias, 2005a,b). Kunz and Mouschovias (2010) investigated evolution of protostellar cloud core using numerical simulations in frame of multicomponent 2D approach. They traced formation of the protostar. Characteristics of the protostar formed are close to observational, core density $n \simeq 10^{14}$ cm^{-3}, mass $M \simeq 0.01$ M$_\odot$, temperature $T = 300$ K.

Applications of the theory of fossil magnetic field are discussed in many papers (see Dudorov, 1995; Glagolevskij, 2003; Moss, 2003; Alician et al., 2008; Braithwaite, 2012 and references therein). Dudorov and Tutukov (1990) concluded that magnetic Cp stars are formed under the intensive action of cosmic rays. Dudorov (1995) showed that convection in T Tauri and Ae/Be Herbig stars may lead to removal of fossil magnetic flux excess and to switching on the dynamo on the level of non-linear stabilization. Estimations and discussions of Moss (2003) correspond to fully convective stars on the Hayashi track (Hayashi et al., 1962) and cannot be applied to the Ae/Be Herbig stars considered as the prototype of Cp stars. Glagolevskij (2003) and Alician et al. (2008) discussed observational data on magnetic fields and rotation of Cp stars and concluded that magnetic field of such stars may be the fossil magnetic field of pre-main-sequence stars.

The paper is organized as follows. In the Section 2, we review main statements and conclusions of the fossil magnetic field theory. In the Section 3, we discuss role of dynamo mechanisms in the magnetic field evolution during star formation. Main results of the 2D MHD numerical investigations of the magnetic protostellar clouds evolution are presented in the Section 4. In the Section 5, equations of the MHD model of accretion disks of young stars are formulated. Then, we present results of calculations of the fossil magnetic field intensity and geometry in accretion disks of young stars. In the Section 6, we outline main problems for the future investigations in frame of fossil magnetic field theory.

2. Outline the theory of fossil magnetic field

Analysis of observational data on the magnetic field in the star forming regions (see Dudorov, 1990, 1991b, 1995) shows that there is correlation between the intensity, B, and numerical density of clouds, n, for the star forming clouds,

$$B/B_0 = (n/n_0)^k. \quad (1)$$

Parameters B_0 and n_0 are associated with cloud formation conditions. A large part of the observational data for regions with densities $n \approx 1 - 10^{10}$ cm^{-3} is described by formula (1) with parameters

$$B_0 = 5\ \mu\mathrm{Gs}, \quad n_0 = 50 - 200\ \mathrm{cm}^{-3}, \quad k = 1/2 - 1/3. \quad (2)$$

Optical and infrared polarimetry of dense molecular and protostellar clouds give very important confirmation and extension of Zeeman's observations (see Vallee, 1997; Girart et al., 2006; Li et al., 2009; Chapman et al., 2013). Polarimetrical data show that the magnetic field geometry is changed during the formation and evolution of interstellar clouds.

Magnetic field of the diffuse interstellar clouds is quite homogeneous with magnetic strength $\mathbf{B} \perp \mathbf{a}$ in ≈60% of cases and $\mathbf{B} \| \mathbf{a}$ in ≈30% of cases, where $\mathbf{a}$ is the direction of cloud elongation. In ≈10% of cases, the magnetic fields of diffuse clouds have a tangled geometry. In more dense inhomogeneous cores of molecular clouds magnetic fields may have a quasi-radial, hourglass, twisted or pinched geometry.

The comparison of "magnetic" observational data for stars and for interstellar molecular clouds (and their cores) allows us to make the following conclusion. Contemporary star formation takes place mainly in the magnetized molecular clouds. Magnetic flux of young and some part of main sequence stars may be a relic of the magnetic flux of molecular or protostellar clouds. Therefore the basic goals of the theory consist in investigations of protostellar clouds and star formation in the sufficiently magnetized matter and in proof that the magnetic field of young stars may have the fossil origin. We discuss below the outline and base consequences of the theory of the fossil magnetic fields developed by author with collaborators during last 30 years.

Theory of fossil magnetic field is based on the numerical investigations of star formation in protostellar clouds with magnetic fields. The main goals of the theory are the study of evolution of magnetic flux in the processes of ambipolar and Ohmic diffusion, interaction with rotation, turbulence and MHD instabilities that may develop on the various stages of protostellar clouds collapse, protostar and star contraction. For these investigations we use the system of MGD (magneto-gas-dynamical) equations in the