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ELECTRODYNAMIC FORCES IN STELLAR FORMATION

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ABSTRACT: Due to dynamo action of a rotating collapsing protostellar cloud in an ambient interstellar magnetic field, electrodynamic forces are created. Assuming: 1) quasi-equilibrium (i.e. slow collapse) and 2) appreciable plasma slip relative to the rotating neutrals (i.e. low ionization with the ambipolar diffusion time smaller than the rotation period), we study the created electrodynamic forces for a range of protostellar parameters, in particular, as a function of the ambient magnetic field and the radius, mass, angular velocity and temperature of the protostellar cloud. In general we find that (pinching) electrodynamic forces can be as important as gravitational forces (or even dominant in certain stages of the star formation process).

Key words: star formation, interstellar dynamo, pinching forces.

I. INTRODUCTION

The problem of star formation is a very studied one, but is far from being resolved (e.g. see the reviews of Nakano (1981), Mouschovias (1981) and Mestel and Paris (1984) and references therein). It has been treated at several levels of complexity (including rotation and/or magnetic fields) but until now the analysis of magnetized clouds concerning the coupling between neutral and charged particles has never evaluated the transverse displacement of charged particles in the existing magnetic field due to collisions with the neutrals and the electromotive effects and electric currents generated in relation to star formation.

We analyse here a general model (with an analitical approach) (section IV) for obtaining the resulting electrodynamic forces (pinch effects) created

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by the dynamo action (section II) just refered to, and apply it to a rotating magnetized protostellar cloud (section IV), for a range of protostellar parameters (cloud parameters, environmental magnetic fields, velocity fields, etc.). In section III we briefly discuss the existing previous analyses concerning this approach to the problem. In section V we discuss the main implications of our results and point out necessary further research, closing with a brief general conclusion (section VI).

II. DYNAMO CONCEPTS

In astrophysics the dynamo concept is understood from two points of view, each one having very different implications and regions of applicability from one another.

One approach is the dynamo action for "continuous" magnetic field generation. It applies for long time scale phenomena to explain "stable" magnetic fields of astrophysical bodies (e.g. stars, planets), or of galaxies (e.g. Parker (1979)). This approach, obviously, is not of interest here.

The other approach is the dynamo action for explaining ionospheric perturbations and solar flares. It applies for short time scale phenomena to explain "transient" magnetic field generation in aurorae (e.g. Kan (1982) and references therein) and flares (e.g. Kan et al. (1983) and references therein).

This last approach applies to the so called "dynamo region" that is, in short, a partially ionized magnetized plasma in the presence of some sort of macroscopic motion (turbulence, rotation, convection, etc.).

Our present discussion can be understood as an extension of these last dynamo action principles to interstellar molecular clouds.

III. RELATED PREVIOUS WORK

The existing previous analyses may be discussed in three groups. One concerns the dynamo concept that has just been commented upon. The second follows Alfvén (1982 and references therein). He pointed out several times, although in a very qualitative and general way, the possible importance of currents in the star formation process. But, to our knowledge, no such dynamo action has ever been proposed and analysed as we do here associated with the star formation process, for example.

Another previous analysis concerns the diffusion of magnetic fields in protostellar clouds (usually called ambipolar diffusion or plasma drift). This process is important mainly in helping to explain the magnetic braking for the loss of the angular momentum of the protostellar cloud; and also for the determination of the average magnetic field at the center of the cloud and the subsequent formed stars (e.g. Nakano (1981), Mouschovias (1981), Black and Scott (1982) and references therein).

IV. THE MODEL AND ANALITICAL APPROACH

The general assumption usually made is the validity of the "frozen-in" condition between charged particles and magnetic fields. Thus, the magnetic field moves, or diffuses, and opposes gravitational collapse, due to ion-neutral collisions, but the ions do not move with respect to the magnetic field (e.g. Nakano (1981), Mouschovias (1981), Black and Scott (1982) and references therein).

Our investigation can be understood as a relaxation of this "frozen-in" condition, which would be a natural extension of the previous assumptions. Thus here, the collisions with neutrals cause charged particles to move transversaly to the magnetic field.

Our model is based on the general picture for typical star-forming regions, that is: a rotating molecular cloud, under gravitational contraction, and in the presence of a magnetic field, here assumed to be initially uniform and parallel to the axial direction. In the present paper we assume quasi-equilibrium i.e. slow collapse.

We suppose that the cloud is spherical, with symmetry relative to the axis and to the equatorial plane. The neutral part of the gas has a constant angular velocity Ω, where $\vec{v}_n = r\Omega\hat{\phi}$, that is, the only significant component of the neutral gas is in the azimuthal direction (where cylindrical coordinates, r, ϕ, z are used). We need not specify any functional dependence of Ω with the coordinates for the present simplified analysis. We adopt for the density distribution the exponential of the form $\propto \exp[-(r^2+z^2)^{1/2}/r_0]$, where r_0 is a typical scale distance here supposed to be of the order of one parsec. Following Black and Scott (1982) we use for the ratio between the number density of the electrons (n_e) and the number density of the neutral particles (n_n), the relation (the called fractional ionization):

$$\chi_e \equiv \frac{n_e}{n_n} = K\, n_n^{-q}$$

where K and q are parameters to be adjusted consistently to the region considered and observational data for it. For order of magnitude estimates, the values $K \sim 10^{-5}$ and $q = 1/2$ would be very acceptable ones.

The constituents of the cloud are basically molecular hydrogen for the neutral part and a heavy positive singly charged ion (e.g. HCO^+) for the charged part. This is an acceptable constitution for a typical interstellar molecular cloud (not near the core), which we assume.

The typical observed ranges of values for star-forming molecular clouds (where care has been taken in putting together values consistent among themselves), are: $n_n \sim 10^3 - 5 \times 10^4 cm^{-3}$; $m_n \sim 2m_H$; $m_i \sim 30m_H$; $Z = 1$ (singly charged ions); $\chi_e \sim 5 \times 10^{-8} - 10^{-6}$; $T \sim 5 - 80$ K; $v_n \sim 10^4 - 10^6$ cm s^{-1}; $B_{z\infty} \sim 3 \times 10^{-6} - 10^{-4}$ G; assuming $n_e \sim n_i$. Here, $B_{z\infty}$ is the background magnetic field and m_H the hydrogen atom mass.

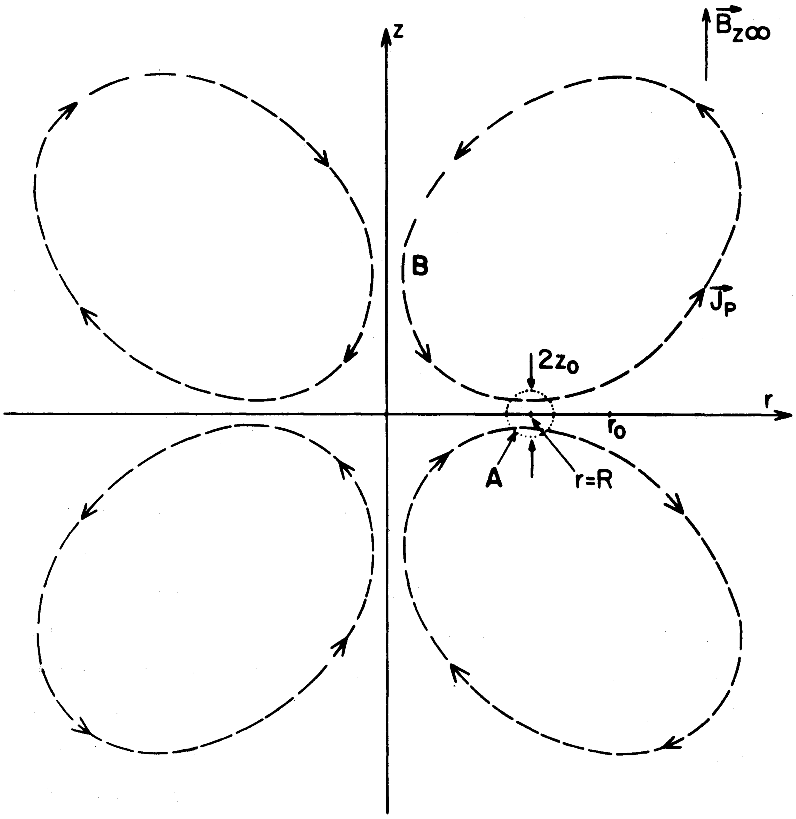

Figure 1. The equatorial current density $J_p(R,0)$ (Eq. (5)) is part of two toroidal current structures in the regions $z>0$ and $z<0$, respectively, as shown. The electrodynamic and gravitational forces are $\sim$ parallel to $\vec{B}_z$ in region A.

We consider only elastic collisions as determining the momentum transfer process (the conditions assumed here make this a very good approximation). We use the momentum transfer rate coefficient for ion-neutral collisions ($<\sigma v>_{in}$), as defined by Osterbrock (1961), and for the rate coefficient for electron-neutral collisions ($<\sigma v>_{en}$), we take that of Nakano and Umebayashi (1980). The values obtained for our conditions are: $<\sigma v>_{in} \sim 1.84 \times 10^{-9}$ cm^3 s^{-1}, and $<\sigma v>_{en} \sim 1.08 \times 10^{-7}$ cm^3 s^{-1}.

Such a medium, as specified in the above paragraphs, is a region of a partially ionized magnetized plasma in the presence of a macroscopic motion, here caracterized by the rotation. Thus it is natural to extend to this region the dynamo action principles developed for low ionization regions, as mentioned above (section II). Then the ions, because of the collisions with the neutrals, move transverse to the magnetic field. This induces an electromotive force, which generates an electric current (discussed in greater detail below).

We calculate the electric current density analytically for the region near the equatorial plane, and it is easy to show that it has a maximum value at the distance $r = R$ from the axis (see Fig. 1), that is, of the order of the typical scale distance r_o.

Beginning with the analytic approach, from the equations of motion for the electrons and ions, we obtain the relation in the ϕ direction

$$\frac{e}{c}\,(v_{ir} - v_{er})B_{z\infty} + m_e\,\nu_{en}(v_n - v_{e\phi}) + m_i\,\nu_{in}^{eff}(v_n - v_{i\phi}) = 0 \qquad (1)$$

where v_{ir}, $v_{i\phi}$, and v_{er}, $v_{e\phi}$ are the ion and electron velocities in the radial and azimuthal directions, respectively, and $B_{z\infty}$ is the background magnetic field in the cloud.(From symmetry, the magnetic field at the equator must be in the z direction.) The term ν_{in}^{eff} is defined as $\nu_{in}^{eff} \equiv \mu\nu_{in}$, where $\mu = m_n/(m_i+m_n)$ and $\nu_{in} = n_n \langle\sigma v\rangle_{in}$. For the physical conditions considered, $\nu_{in}^{eff} \simeq \nu_{in}/16$. We have neglected pressure and temperature gradient force terms relative to the other force terms, and suppose that a quasi-steady state has evolved.

We assume appreciable plasma drift (or plasma slip relative to the rotating neutrals. This is a good approximation for the typical conditions where the model is applied), such that in Eq. (1) $v_{e\phi}$ and $v_{i\phi}$ remain small compared with v_n (and we remember that we take $\vec{v}_n = v_n\hat{\phi}$, $\hat{\phi}$ being the unit vector in the azimuthal direction). If τ_D is the characteristic ambipolar diffusion time, and $\tau_{Rot} \equiv R/v_n$ is the characteristic rotation time of the cloud, we thus have

$$\tau_D < \tau_{Rot} \qquad (2)$$

Using the characteristic ambipolar diffusion time found by Mouschovias (1979), $\tau_D \sim 10^{13}\ \xi(r)\ \chi_e$ (years), with $\xi(r)$ varying from 1.0 to 0.03 in the cloud, we obtain from Eq. (2) a condition for the density of the neutrals:

$$n_n > 10^{29}\left[\frac{v_n}{R}\right]^2 \qquad (3)$$

where we used $\bar{\xi}(r) = 0.1$, and $\chi_e = K\,n_n^{-q}$ with $K = 10^{-5}$ and $q = 1/2$. From Eq.(3)

we obtain, for example, for $R \sim 1$pc and $v_n \sim 1$ km/s, the density $n_n > 10^2$ cm^{-3}.

Another relation which we assume, which is generally satisfied (for example for the previously quoted values for the typical star-forming molecular cloud conditions), is

$$m_e \nu_{en}/(m_i \nu_{in}^{eff}) << 1 \tag{4}$$

From Eqs. (1) - (4), we thus have for the poloidal electric current density:

$$J_p(R,0) \equiv en_e(v_{ir} - v_{er}) = - e\, n_e v_n \frac{\nu_{in}^{eff}}{\omega_{ic}} \tag{5}$$

where $\omega_{ic} \equiv ZeB/m_i c$ is the ion cyclotron frequency, and here Z = 1.

We obtain the magnetic field (B_ϕ) that such a current J_p generates assuming the approximate validity of Ampere's law ($\vec{\nabla} \times \vec{B} \simeq (4\pi/c)\vec{J}$).

Calling F_m the electrodynamic force per unit volume, we have

$$F_m \simeq \frac{1}{c} J_p(R,0)\; B_\phi(R,z\sim 0) \tag{6}$$

for the region called A in Figure 1.

Calling F_g the gravitational force per unit volume, where we consider just the sphere of radius z_o centered at R (Fig. 1), z_o being a small distance relative to the z = 0 plane (our final result (Eq.(8)) is independent of z_o), we have

$$F_g \simeq \frac{4}{3}\, \pi\, z_o\, G\, m_n^2\, n_{no}^2\, \exp\left[-2R/r_o\right] C_g \tag{7}$$

where the sphere has the density $\sim\rho(R,0)$, and we use $\rho_n = m_n n_n$. G is the gravitational constant and the parameter C_g is a correction factor of the order of unity.

The ratio between F_m and F_g may then be written as:

$$F \simeq \frac{3\, J_p^2(R,0)\, \exp\left[2/(2-q)\right]}{G\, c^2 m_n^2 n_{no}^2} \tag{8}$$

where we took $C_g \simeq 1$.

From the range of values given above for the important parameters, we may choose the following observationally self-consistent ensemble of values, as characterizing the region A (Fig. 1): $n_n \sim 10^4$ cm^{-3}; $\chi_e \sim 10^{-7}$; $T \sim 10$ K;

$v_n \sim 10^5$ cm s^{-1} and $B \sim B_{z\infty} \sim 5 \times 10^{-5}$ G. These are typical values for star-forming regions, excluding the central cores of the clouds.

For these values and conditions, we obtain:

$$F \simeq 2.7 \times 10^2 \tag{9}$$

This is a striking and unexpected result, which is very different from the one usually supposed to be valid for the stellar formation process. Such a result means that the electrodynamic force is, or may be, much more important than the gravitational force in the star formation process.

On the other hand, if we take the range of values given above, we may choose the ensembles of values that give us the extreme theoretical values of F for the conditions specified, that is:

$$F \simeq 10^{-3} - 10^{10} \tag{10}$$

where we call attention to the fact that the extreme values are improbable ones, in the sense that they correspond to observationally unlikely situations. Thus, also this range (Eq. (10)) emphasizes that electrodynamics forces can be dominant in certain stages of star formation.

V. DISCUSSION

There are many implications associated with the above proposed process and results. We discuss mainly the following two.

One concerns triggering mechanisms. It is expected that the process here discussed applies to stages of the stellar formation process where some triggering mechanism is needed. It is well known that, at least for some type of stars (the OB associations), the need is recognized for triggering mechanisms for collapse.

Another implication concerns equatorial fragmentation. We can see from Figure 1, that in region A, the electrodynamic and the gravitational forces are both in the z direction, and parallel to the magnetic field, which does not happen in any other region of the cloud. Thus, our model favors star formation in the equatorial plane, which is in good accordance with the indications of existing observations.

There are many important correlated subjects that should be taken into account consistently with our process here. For example, questions concerning the angular momentum problem, grains, time scales involved, ambipolar diffusion, the resulting stellar mass spectrum of the formed stars, the formation of galaxies, the relation with the intense magnetic fields recently observed at the center of our galaxy, and so on. Work on all of these subjects is now in progress.

VI. FINAL CONCLUDING REMARKS

Our model is expected to apply to stages of the stellar formation process where external, and/or internal, triggering mechanisms are needed. Also, obviously, the above results have many other implications and applications. The correct account of the always ignored dynamo-electrodynamic effects in the sense and regions of applicability exposed above, is indispensable if one wishes to have a more consistent and full comprehension of stellar and galactic formation in particular, and all astrophysical phenomena of low ionization regions in general.

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