DYNAMO MAGNETIC FIELD GENERATION IN THE SOLAR NEBULA T.F. Stepinski, Lunar and Planetary Institute, 3303 NASA Road 1, Houston, TX 77058

The magnetic effects in the primordial solar nebula provoke our interest because the Lorentz stress associated with them could become a major factor in the structure and dynamical balance of the nebula. In particular, magnetic torques can assist viscous and gravitational torques in redistribution of angular momentum. In addition, explosive reconstruction of magnetic fields can be responsible for energetic transient events - a possible cause of the sudden heating of chondrules (1). However, magnetic fields, even if originally present in the nebula, decay on a time scale short in comparison with typical radial infall time due to low electrical conductivity of nebular gas (see abstract entitled *Ionization State and Magnetic Fields in the Solar Nebula* in this volume). In view of these results, it is difficult to see how any magnetic field contained in the nebular gas can persist long enough to produce significant dynamical effects. In order for the nebula to contain a significant magnetic field, a dynamo regeneration is required to offset the losses due to resistive and turbulent dissipation.

I have recently considered the so-called $\alpha\omega$ dynamo mechanism (2,3) operating in the primordial solar nebula which already settled into an equilibrium state and is rotating around the protosun with Keplerian angular velocity ω_k. I adopt a phenomenological model (4) to calculate resistive diffusivity η_r (see previous abstract). In $\alpha\omega$ process the poloidal magnetic field regenerates the toroidal magnetic field through differential rotation. The basic idea is to use the local motions, often thought to be due to some kind of turbulence, to close the dynamo loop thus allowing the poloidal field to be regenerated from the toroidal field through the so-called "α-effect". The quantity α measures the helicity of turbulence. Qualitative, order of magnitude arguments can be applied (5,6) to show that $\alpha \approx hM_{turb}^2\omega_k$, where h is the nebula half-thickness and $M_{turb} = v_{turb}/c_s = l_{turb}/h$ is a turbulent Mach number. Here c_s is the speed of sound, v_{turb} and l_{turb} are the turbulent velocity and turbulent mixing length, respectively. The presence of turbulence further destroys the magnetic field by means of anomalous or turbulent diffusion with coefficient $\eta_{turb} = h^2M_{turb}^2\omega_k$ (6,7). The ability of $\alpha\omega$ dynamo to maintain the magnetic field in the nebula is measured by dimensionless dynamo number $D = \alpha\omega_k h^3/(\eta_r + \eta_{turb})^2$, which characterizes the strength of regeneration mechanisms as compared to total diffusion. In the zeroth approximation, the radial diffusion is considered to be negligibly small because of the great difference between vertical and horizontal dimensions in the solar nebula. The resulting "local" dynamo approach (8,9) yields field generation threshold D_{crit} below which the dynamo mechanism is unable to maintain a magnetic field. A number of different calculations (7,8,9) put the value of D_{crit} at about 10. Consequently, the magnetic field can be generated only in those regions of the nebula where $D > 10$.

Figure 1 shows the variation of D as a function of the distance from the protosun for a number of different values of M_{turb}. According to these results a magnetic field cannot be generated in nebular regions $r < 5$ A.U. where, locally, the rate of magnetic field dissipation exceeds the rate of generation. In the regions beyond 5 A.U. the dynamo number is generally above the regeneration threshold D_{crit}, thus a magnetic field can be maintained for as long as there is a turbulent flow in the nebula, presumably much longer than diffusion time for those regions, and possibly throughout the total nebula lifetime. It is important to keep in mind that we are presently limited to guessing the physics of turbulence in the solar nebula. The turbulent Mach number M_{turb} is a repository of most of the unknown physics of the turbulence. The estimate values of M_{turb} differ substantially (10) from as much as 1 to as little as 0.0001; however, the values in the range 0.05 - 0.3 are most often quoted. Inspection of Fig. 1 readily shows that the inner limit on the region where the magnetic field can be maintained depends very weakly on the strength of turbulence in this most often quoted range. This is because the increase in the vigor of turbulence increases the α-effect but it also increases the turbulent diffusivity, resulting in only a small change to this limit. However, if turbulence is very weak ($M_{turb} << 1$), the loss of the α-effect strength is not balanced by the smaller diffusivity because, for such a small value of M_{turb}, the turbulent diffusivity is dominated by resistive diffusivity (which does not depend on the value of M_{turb}) everywhere in the nebula. Consequently, for such a weak turbulence, magnetic field generation would be restricted to only outermost parts of the solar nebula. Results presented on Fig. 1 were obtained assuming the presence of radioactive ^{26}Al in the nebula; its absence, however, would not change the conclusions, since resistive diffusivity at 5 A.U. and beyond is governed by cosmic rays rather than by radioactive isotopes. I also assumed that solid material has accumulated into grains of centimeter size, assuming significantly smaller grain size (5×10^{-5} cm) would preserve general conclusions but would shift outward (by about 2 A.U.) inner limits on magnetic field generation regions. The principal implication of these calculations are: 1) In the framework of the nebula model considered here it is not possible to maintain a magnetic field by means of turbulent $\alpha\omega$ dynamo in the inner region of the solar nebula. The field can only be maintained from about 5 A.U. outward. 2) The presence or absence of ^{26}Al in the nebula has no influence on this conclusion. 3) The size of grains does influence the result, as the existence of small grains further limits the field generation region. 4) The strength of turbulence in the range $M_{turb} = 0.05 - 0.3$ has an insignificant influence on the conclusion. 5) Very weak turbulence, $M_{turb} << 1$, would restrict the region of magnetic field generation to only the outermost nebula.

Finally, I estimate the possible magnetic field strength that might be generated in such a dynamo. In order of magnitude, the field intensity is given by the balance of Lorentz force and the Coriolis force acting on a turbulent eddy (11). Substituting the radial dependencies of relevant physical quantities as predicted by a nebula model considered here I obtain magnetic field strength of 0.3 - 0.8 Gauss at 5 A.U. from the protosun. This is an order of magnitude less than the previous estimation (11), yet still consistent with the residual magnetization of primitive chondrites (12) used to estimate the intensity of nebular magnetic fields. If these primitive meteorites were in fact magnetized by magnetic field generated by the nebular dynamo, the results of my calculations would require that they originated from the regions of solar nebula beyond 5 A.U. It would be interesting to examine whether considering other nebula models would significantly change these conclusions. Also, it has been suggested recently (13) that $\alpha\omega$ dynamo in accretion disks can be driven not only by turbulence but also by inertial density waves. Whether this mechanism is applicable to the solar nebula and, if so, how it will influence my conclusions, have to be investigated in the future.

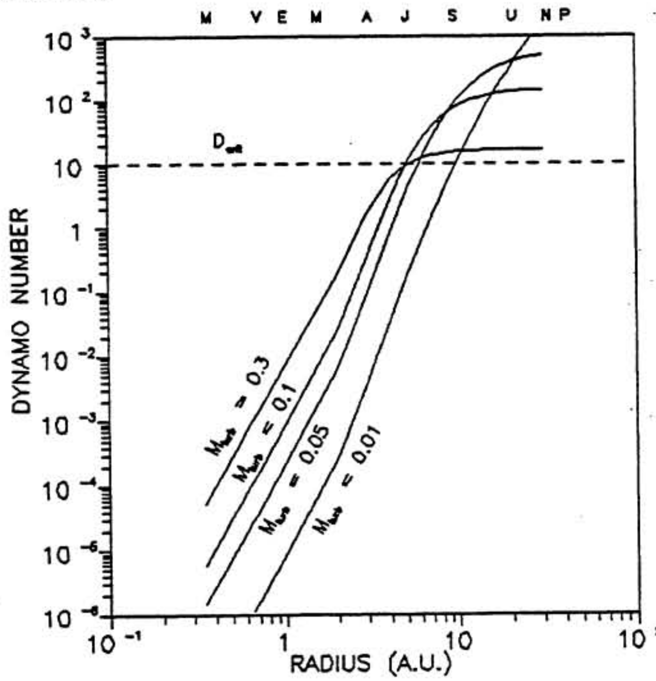

Figure 1 - Dynamo number D as a function of the distance r from the protosun (solid curves) for different values of M_{turb}. Dynamo number is independent of r in the outer nebula where turbulent diffusivity dominates over resistive losses. Dashed line corresponds to the generation threshold D_{crit}.

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