MAGNETICALLY CONTROLLED SOLAR NEBULA T. F. Stepinski, Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston, TX 77058, and M. Reyes-Ruiz, Dept. of Space Physics and Astronomy, Rice Univ., Houston, Texas

It is widely believed that a primordial solar nebula, the precursor of the Sun and its planetary system, could be best described in terms of an accretion disk. Such an accretion disk is thought to be turbulent, and it is usually imagined that turbulent viscosity *alone* provides a torque responsible for the structure and the evolution of the nebula. However, it was found [1,2] that an MHD dynamo operating in a turbulent nebula can contemporaneously produce magnetic fields capable of significantly altering or even dominating the total torque. Thus, it seems that no model of a viscous solar nebula is complete without taking magnetic fields into consideration.

It was demonstrated [2] that there are usually two distinct regions of nebular disk where a dynamo can operate: the inner region, where the magnetic field couples to gas due to relatively high thermal ionization, and the outer region, where this coupling is achieved due to nonthermal ionization. Most models also show the existence of an intermediate region, "the magnetic gap," where neither thermal nor nonthermal sources can produce enough ionization to provide the necessary coupling between the magnetic field and the gas. The location and width of the gap change substantially from one model to another. At present, we can only estimate the strength of a generated magnetic field. It seems that a large-scale magnetic field is likely to be in the equipartition with the turbulent kinetic energy; however, the intense magnetic fluctuations may greatly exceed this equipartition strength on short time and length scales.

To show how a dynamo-generated magnetic field changes the structure of a viscous nebula, we consider four nebula models extensively discussed in [2]. All four models are described by the dimensionless strength of turbulent viscosity, α_{ss}, equal to 0.08 and obtained from the turbulent closure model [3]. Model I nebula is characterized by $\dot{M} = 10$; there is no magnetic gap and the magnetic field is generated everywhere in the nebula. Model II nebula is characterized by $\dot{M} = 1$; there is a magnetic gap between 2.3 AU and 4.5 AU. Model III nebula is characterized by $\dot{M} = 0.1$; there is a magnetic gap between 0.8 AU and 4 AU. Model IV nebula is characterized by $\dot{M} = 0.01$; magnetic fields cannot be maintained anywhere in the nebula. Here $\dot{M}$ is an accretion rate measured in 10^{-6} solar masses per year. We have found the physical quantities describing the state of the nebula, such as temperature, T, disk's half-thickness, h, its density, ρ, and surface density, σ_s, by solving the standard, steady-state, "thin-disk" set of equations [4]. Two of those standard equations have to be modified to take into account the presence of magnetic fields. The first is the equation of hydrostatic equilibrium, which in the presence of magnetic field is

$$h = \frac{C_s}{\omega}\left(1+\frac{1}{\beta}\right)^{1/2} \tag{1}$$

where C_s is the sound velocity, ω is the Keplerian angular velocity, and $\beta = P_g/(B^2/8\pi)$ is the ratio of gas pressure to magnetic pressure. Second, we have to take into consideration that in addition to turbulent viscous stress there is also the Maxwell stress due to magnetic fields permeating the nebula. We can incorporate the effect of magnetic stress by defining the "effective" dimensionless strength of turbulence α_{eff} (see [2]) and use it instead of α_{ss} in the standard set of "thin-disk" equations. This effective coefficient can be expressed as

$$\alpha_{eff} = \alpha_{ss}\left(1+\frac{2}{\beta\alpha_{ss}^{1/2}}\right) \tag{2}$$

Generally speaking, the presence of magnetic fields results in a cooler nebula, with smaller surface density. The nebula half-thickness is about the same as in models without any magnetic fields. Fig. 1 shows the radial dependence of nebular surface density for models I to IV described above. In those calculations $\beta = 1$ has been assumed, except in magnetic gaps, where a very large value of β was assumed to model the absence of a magnetic field.

As expected, magnetic fields with their associated stresses comparable to gas pressure ($\beta = 1$) are dynamically very important, and completely control the structure of the nebula. Surface density in the regions of the nebula pervaded by magnetic fields drops by a factor of about 7 in comparison with the same model but without any magnetic field. This is because magnetic stress raises the effective viscosity, allowing more efficient removal of angular momentum. Within "magnetic gaps" turbulent viscosity is the sole source of stress; consequently those regions have enhanced surface densities. This enhancement can be as much as an order of magnitude relative to what would be expected if magnetic fields had pervaded the entire nebula. For weaker fields ($\beta > 1$) the results are qualitatively the same; however, departures from the standard, non-magnetized nebula structure are relatively smaller.

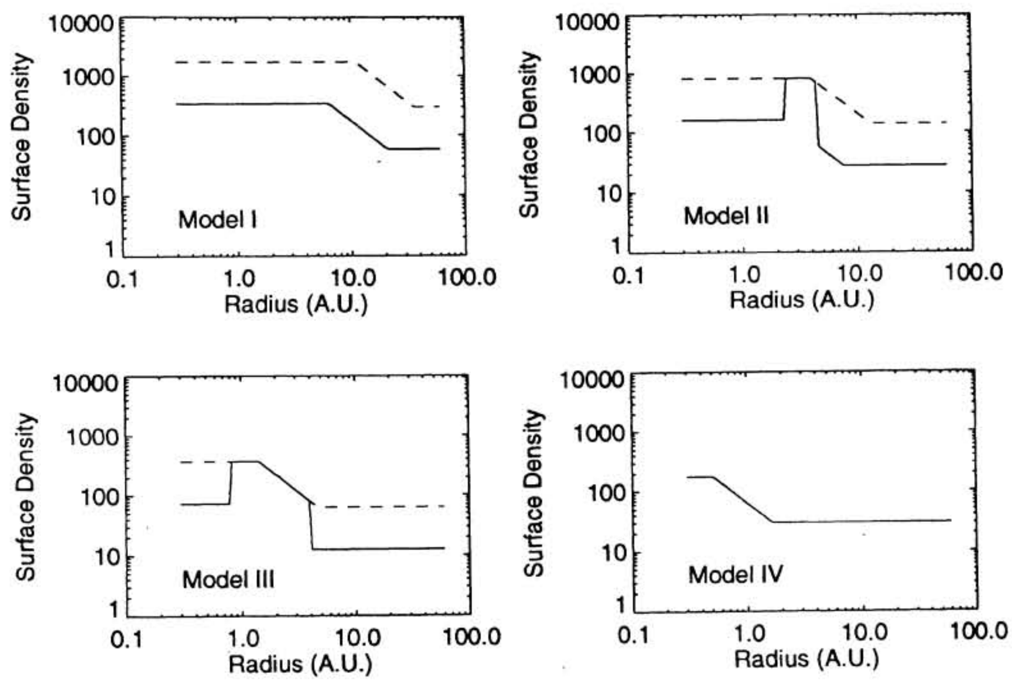

Figure 1. - Values of surface density (in g cm^{-2}) as functions of radial distance from the protosun for four different models of the solar nebula. Solid lines correspond to solutions with a magnetic field, and dashed lines correspond to solutions without a magnetic field.

In summary, the present calculations reveal basic aspects of the influence of magnetic fields on the structure of the viscous solar nebula. Further work will explore the possible influence of those fields on the nebula evolution and the process of planetary formation.

References: [1] Stepinski, T.F. (1992) *Icarus*, **97**, 130; [4] Stepinski, T.F., Reyes-Ruiz, M., and Vanhala, H.A.T. (1993) submitted to *Icarus*; [3] Dubrulle, B. (1992) *Astron. Astrophys.*, **266**, 592; [4] Shakura, N.J. and Sunyaev, R.A. (1973) *Astron. Astrophys.*, **24**, 337.