IONIZATION STATE AND MAGNETIC FIELDS IN THE SOLAR NEBULA T.F. Stepinski, Lunar and Planetary Institute, 3303 NASA Road 1, Houston, TX 77058

The existence, origin, structure, and importance of magnetic fields in extended parts of the solar nebula, away from the protosun, pose a great challenge to our understanding. The principle uncertainty concerns the electrical conductivity of the fluid. Under typical and steady accretion conditions, the low gas temperature in such a nebula, as well as the high density of gas and dust, results in very low levels of thermal ionization. Significant levels of electrical conductivity require some nonthermal ionization source to produce mobile electrons. Cosmic rays can provide such ionization in unshielded regions (1,2); the decay of radioactive nuclei may provide an adequate ionization source even in dense regions (1,2,3).

Although some work has been done on the process of ionization of nebular gas by cosmic rays and ^{40}K (1,2), and separately by ^{26}Al alone (3), the combined effect of cosmic rays and all relevant radioactive nuclei, as well as its sensitivity to assumed physical quantities, have not yet been evaluated. To clarify the question of ionization degree in the solar nebula, as well as the related question of existence and character of nebular magnetic fields, I have recently computed an ionization degree in the solar nebula using three ionization sources: cosmic rays, ^{40}K, and ^{26}Al. ^{26}Al, if present in the nebula, is the most ionizing radioactive element, ^{40}K is the next most ionizing species. Two mechanisms of the loss of electrons have been included: reaction with positively ionized species, and recombination upon grains. An equilibrium ionization degree is obtained by equaling the number of free electrons which are created and destroyed at any given time. Both sources and "sinks" of free electrons depend crucially on physical quantities prescribed by a nebula model, such as temperature, gas density, and disk thickness. In addition recombination upon grains depends strongly on the grain size. In these calculations I adopt a widely accepted model (4) of the solar nebula which has already settled into an equilibrium state and is rotating around the protosun with the nearly Keplerian velocity. Assuming a particular solar nebula model reduces the number of free parameters to only two: grain size and existence or nonexistence of ^{26}Al in the nebula.

Figure 1 shows the resulting ionization degree $x = n_e/n_H$, where n_e and n_H are the number density of electrons and hydrogen respectively. Electrical conductivity σ_e of nebular gas is about $10^{16}x$ in the Gauss units. If solid material has accumulated into grains of centimeter size, due to inelastic collisions in the turbulent nebula (5), the electron losses due to recombination upon grains are unimportant in comparison with losses due to electron-ion reactions. The resulting ionization degree (solids lines on Fig. 1) shows that the presence or absence of ^{26}Al results in about two orders of magnitude difference in an electrical conductivity of the gas in the inner nebula. This difference starts to decrease at about 1 A.U. outward due to decrease of nebula surface density and corresponding increase of ionization by cosmic rays. At about 3 A.U. ionization of nebular gas is totally dominated by cosmic rays.

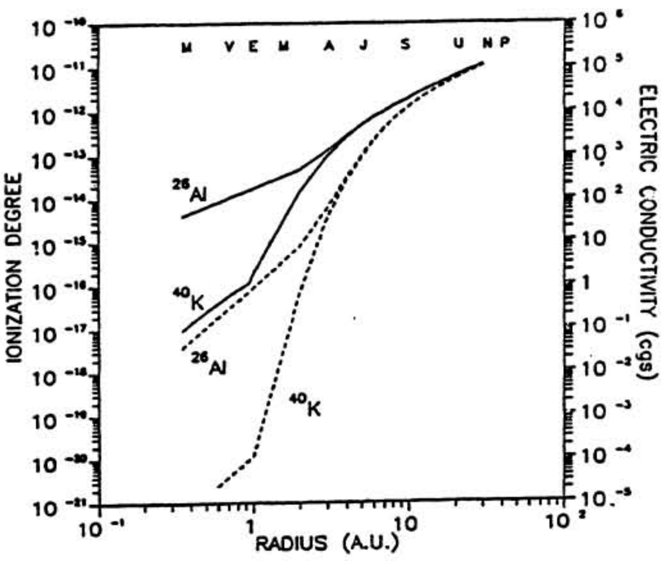

Figure 1 - Ionization degree x and electrical conductivity σ_e as functions of the distance r from the protosun near the equatorial plane of the solar nebula. Solid curves correspond to the nebula where grains are large (1 cm), dashed curves correspond to the nebula were grains are small (5×10^{-5} cm).

The size of grains in primordial solar nebula is uncertain, yet the losses due to recombination upon grains depend strongly on it. For grains whose size is 5×10^{-5} cm (typical of interstellar dust and a likely lower limit for the grains size in the solar nebula) they are large enough to dominate over losses due to electron-ion reactions in nebular regions up to 10 A.U. As a result, an ionization degree in those regions is further decreased (dashed line on Fig. 1). Regions located beyond 10 A.U. are still dominated by electron-ion reaction losses, and degree of ionization there is unaffected by the size of grains. The implications of these calculations can be summarized in the following way: 1) The electrical conductivity of the gas in the solar nebula beyond 10 A.U. is of the order of 10^5 sec^{-1} independent of grain size and the presence or absence of ^{26}Al. 2) In the intermediate region of the solar nebula, at 3 A.U. to 10 A.U., the value of electrical conductivity depends mostly on the size of grains. When grains are large, and their total number is relatively small, σ_e is about an order of magnitude larger than when grains are small, and their total number is relatively large. 3) In the inner nebula, at radiuses below 3 A.U., σ_e is very low, and its value depends strongly on the grain size, as well as the presence or absence of ^{26}Al.

Having determined σ_e, I estimated the decay time of magnetic fields due to resistive magnetic diffusivity. This characteristic diffusion time is given by $t_d = 4\pi\sigma_e h^2/c^2$, where c is the speed of light, and h is the nebula half-thickness which increases with the distance from the protosun.

Figure 2 shows how steeply this diffusion time increases with the increasing distance from the protosun. The fact that magnetic fields in the outer solar nebula decay orders of magnitude slower than in the inner parts is the result of a difference in the values of σ_e and h between those two regions. Notwithstanding the few orders of magnitude difference in time needed for magnetic fields to decay at say 1 A.U. and 10 A.U., we can conclude that the magnetic field everywhere in the nebula decays fast in comparison with the characteristic lifetime of the solar nebula, which is estimated to be about 10^6 years (6). Moreover, turbulent diffusion enhances resistive diffusivity and causes magnetic fields to decay even more rapidly. This is especially evident in the outer parts of the nebula.

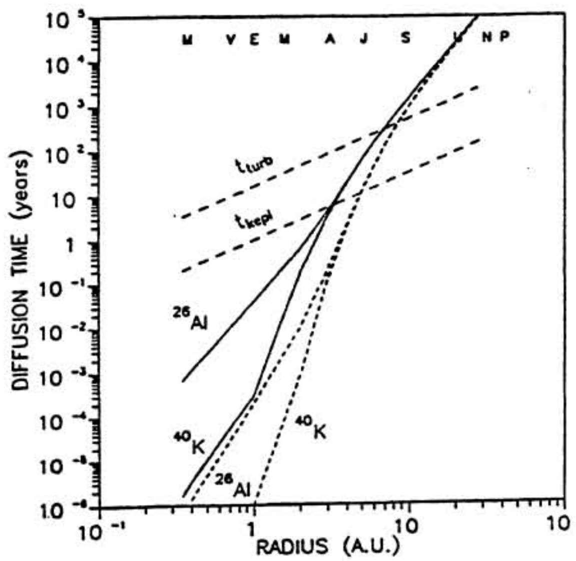

Figure 2 - The diffusion time t_d of magnetic fields as a function of the distance r from the protosun in the solar nebula. Solid curves correspond to r_g = 1 cm, dotted curves correspond to $r_g = 5\times10^{-5}$ cm, where r_g is the grain radius. Kepler time, and turbulent diffusion time are indicated by dashed curves.

If the existence of magnetic fields, originally present due to their compression during collapse (7), was not limited to just a transient moment in the lifetime of the nebula, it had to be contemporarily generated and maintained by some sort of dynamo mechanism. It has been suggested (1,2) that dynamo mechanism amplifies magnetic field on Kepler timescale $t_{kepl} = 2\pi/\omega_k$, where ω_k is Keplerian angular velocity. Correspondingly, magnetic fields could be maintained only in the parts of the nebula where $t_d > t_{kepl}$, or according to Fig. 2 from about 3-5 A.U. outward. However, it is doubtful that the characteristic time of magnetic field amplification can be approximated by t_{kepl}. In fact, the dynamo process is a collective action of differential rotation (which occurs on Kepler timescale) and local fluid motions often thought to be due to turbulence (which are not occurring on Kepler timescale). The magnetic field will be amplified if the strength of these sources is sufficient to overcome the field dissipation. The proper dynamo formalism has to be used in order to determine the existence and character of dynamo generated magnetic fields in the solar nebula. The description of such calculations are presented in an abstract (in this volume) entitled *Dynamo Magnetic Fields Generation in the Solar Nebula.*

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