N92-10939

GENERATION AND BEHAVIOR OF SOLAR SYSTEM MAGNETIC FIELDS.

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Many solar-system bodies possess intrinsically generated magnetic fields. The magnetic remanence carried by lunar rocks and chondritic meteorites contains a record of early solar-system magnetic fields. Both planetary and large-scale, solar-nebula fields may be recorded in this paleomagnetic record. In either case the evidence points to the early presence of magnetic fields perhaps as intense as or more intense than a Gauss. In the case of Moon or of meteorite parent bodies, the possible existence of a one Gauss surface field in a body of such dimensions challenges our understanding of the generation process. The possible existence of a general, nebula-scale magnetic field challenges us to discover its origin, its dynamical behavior, and its possibly startling influences on the evolution of the protoplanetary nebula and on physical processes that built the solar system.

The solar system is thought to have been born out of a dissipative disk nebula. Such disks seem to occur frequently as intermediate structures during the gravitational collapse and accumulation of cosmical matter. The usual picture of this dusty, gaseous protoplanetary disk suggests that it was a relatively quiet, well-behaved object. However, evidence found in meteorites suggests that this picture is likely to be oversimplified. The abundance of chondrules indicates that the protoplanetary nebula was the site of many short-lived, episodic events that were able to raise the temperatures of small pieces of silicate rock to the melting point for just a few minutes. The presence of high-temperature inclusions in meteorites, the thin, highly refractory rims found on these inclusions, and other manifestations also suggest that transient, very-high-temperature events, involving excursions far from the prevailing thermodynamic equilibria, were a common feature of the protoplanetary nebula. These phenomena, and others, challenge our basic understanding of the physical processes and the conditions out of which our planetary system was born. Experience with a variety of cosmical systems suggests that the mechanisms most commonly responsible for the transient and rapid release of energy involve the generation and explosive dissipation of magnetic field structures, although other phenomena may also be important. In this respect, it should be remembered that astronomical studies of star forming regions indicate that they are seats of intensely energetic phenomena, including high-speed, bipolar gaseous outflows associated with protostellar disks, Herbig-Haro objects, etc. There is probably no reason to believe that our solar system was a less interesting object during its birth.

This research covers a range of problems, aimed primarily at elucidating the character and consequences of magnetic-field generation in the solar system and at testing our ideas against the known properties of natural magnetic fields. Among the specific subjects currently under investigation are the magnetohydrodynamic character of the protosolar nebula, including the generation and behavior of magnetic fields, the electrical conductivity of dusty nebular gas, transient magnetodynamic and electrodynamic nebular phenomena, and the generation and dynamical behavior of planetary magnetic fields. During the past year, this project has focused on disk magnetic field generation and transient MHD heating events possibly associated with the protoplanetary nebula.

LARGE-SCALE NEBULAR MAGNETIC MODES. Although much remains to be learned about meteorite remanence, the magnetization of carbonaceous chondrites, as well as other meteorite types, suggests the presence of a nebula-scale magnetic field with an intensity that could have exceeded one Gauss during the formation of solar-system solids. Earlier we showed that such a field could be produced by hydromagnetic dynamo action under conditions thought likely to typify the disk-shaped protoplanetary nebula if a sufficient source of nonthermal ionization were present. During the past year, we developed an adiabatic approximation for calculating normal modes of MHD dynamos in thin disks. Among the advantages of such an adiabatic computational approach is its wide applicability, providing a way to obtain critical dynamo numbers and radial, as well as vertical, distributions of magnetic field in disk-dynamo normal modes for arbitrary distributions of the differential rotation, helical convection, electrical conductivity, etc. In the first investigation exploiting this technique, we focused on temporally stationary magnetic modes. However, this restriction is not dictated by the mathematical technique, and can be relaxed in the future, with the penalty of a heavier computational burden. We anticipate future efforts exploiting this technique to be directed toward understanding dynamical effects of the generated magnetic fields. In order to understand the general character of disk dynamo modes, we explored disks having effective dynamo numbers that remain constant, that decrease, and that increase as a function of increasing radius in a disk.

Disks with effective dynamo numbers that are independent of radius excite a large number of normal modes once the dynamo number exceeds some critical value. Although the stationary modes in such systems are global and encompass the entire disk, it is noteworthy that the magnetic field growth rate—even in disks with constant local dynamo number—vary strongly with position. This leads to a situation in which, even while the stationary modes have a global scale, dynamo modes that grow or decay appear to be highly localized. Although these mode characteristics were computed in the kinematical limit, the implications for dynamical behaviors of disks are likely to be profound. Even in the singular case—*viz.*, stationary modes in disks with dynamo numbers independent of radius—the magnetic field is not likely to behave as a single, globally extended state, evolving with a well defined time scale. Instead, as the disk fluid and magnetic field attempt to find an equilibrium, the system is better described as a set of many quasilocalized states each evolving on a different time scale. We suspect that in such a system, a quietly evolving near-equilibrium is unlikely to be achieved. It seems more likely that such systems will be characterized by highly variable and episodic dynamical behaviors.

Dynamo modes in disks having local dynamo numbers that vary with radius should display this kind of behavior even more strongly. In such disks even the stationary modes are highly localized. The nonstationary modes—with amplitudes growing or decaying—also have growth rates that vary strongly with radial position in the disk. Again, even within the regions capable of generating magnetic fields, these modes are best described as a set of quasilocalized magnetic states, each evolving with its own time scale. For disks with local dynamo number decreasing as a function of radius, we found that normal modes are localized, as expected, in the innermost part of a disk. Similarly, for disks having an effective dynamo number that increases with increasing radius, we found that normal modes are localized in the outermost parts of a disk.

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Although there remain many uncertainties about the characteristics of protoplanetary disks, the results of these idealized model calculations suggest that dynamo-generated magnetic field can occur at distances of several astronomical units from the central star; this thus supports the idea that meteorites, which formed at several astronomical units from the protosun, could be carrying a record of ancient nebular magnetic fields. To proceed further in this work, it will be necessary to compute more realistic models of nebulae, something which will be taken up in future years.

NEBULAR DISK FLARES & METEORITE DISEQUILIBRIUM PHENOMENA. We have investigated the possible occurrence magnetic reconnection flares in the nebula's corona. In recent work we found that such flares occurring in a tenuous corona of the protoplanetary disk could produce transient energy fluxes capable of melting preexisting dust accumulations and thereby make meteoritic chondrules. For this work, we assumed the existence of the magnetic field that seems to be implied by meteorite remanence. The magnetic field is wound, by the Keplerian differential rotation, to an intensity at which magnetic buoyancy causes flux tubes to rise through the steep gas density gradient toward the faces of the disk. As flux tubes emerge through the disk faces, they find themselves in a region where fluid stresses are insufficient to prevent the field structure from evolving toward a vacuum (or, at least, a force-free) configuration. However, since the field's topological evolution is hindered by the high conductivity, singular regions can be expected to develop and become the sites of explosive rearrangement of the magnetic field line topology. Indeed, this seems to be the process that gives rise to many solar flares and and has similarities to mechanisms responsible for planetary magnetospheric outbursts. The flares discussed here release large amounts of energy in relatively brief times, of the order of 10^{33}–10^{36} ergs in minutes to hours. During the next phase of this research we plan to investigate the externally observable manifestations of such flares and compare these with outbursts observed in association with protostars.