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Magnetohydrodynamic Puzzles in the Protoplanetary Nebula

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ABSTRACT

Our knowledge of the basic physical processes that governed the dynamical state and behavior of the protoplanetary accretion disk remains incomplete. Many large-scale astrophysical systems are strongly magnetized and exhibit phenomena that are shaped by the dynamical behaviors of magnetic fields. Evidence and theoretical ideas point to the possibility that the protoplanetary nebula also might have had a strong magnetic field. This paper summarizes some of the evidence, some of the ideas, some of the implications, and some of the problems raised by the possible existence of a nebular magnetic field. The aim of this paper is to provoke consideration and speculation, rather than to try to present a balanced, complete analysis of all of the possibilities or to imagine that firm answers are yet in hand.

INTRODUCTION

Magnetic fields are present and dynamically important in a wide variety of astrophysical objects. There are at least three reasons why such magnetic fields provoke interest: 1) The presence of a magnetic field invites questions as to the conditions of its formation, either as a relict from some earlier generation process, carried in and reshaped, or as a product of contemporaneous generation; 2) the Lorentz stresses associated with magnetic fields are important to the structure and dynamical evolution of many systems; and 3) magnetic fields can store, and quickly release, prodigious quantities of energy in explosive flares. The possible presence of a magnetic field in the protoplanetary nebula raises questions in all three of these areas.

MAGNETIZATION OF METEORITES

Perhaps the most provocative, yet still puzzling and ambiguous, evidence for strong magnetic fields in the protoplanetary nebula comes from the remanent magnetization of primitive meteorites. Our ignorance of the detailed history of the meteorites themselves, including the processes of their accumulation, and ambiguities in the magnetic properties of the meteorite material, causes difficulties in interpreting the significance of meteorite magnetization. These latter ambiguities are especially confusing to neat interpretations of the absolute intensities of the magnetic fields in which the meteorites acquired their remanence. A further complication arises because the meteorites exhibit a diversity of magnetizations, blocked at different temperatures and in different directions on different scales. It seems clear that a thorough understanding of meteorite magnetization, and its unambiguous interpretation, has yet to be written (Wasilewski 1987).

A variety of primitive meteorite materials carry remanent magnetization (Suguira and Strangway 1988). Of the wide variety of characteristics of meteorite remanence that have been measured, two regularities in particular seem to be important. First, the intensities of the remanence-specific magnetic moments seem typically to be larger for small components of the meteorites (e.g., chondrules and inclusions) than for the aggregate rocks. Second, the small, intensely magnetized components are frequently disordered and oriented in random directions.

The inferred *model* magnetizing intensities for "whole rock" samples tend to fall in the range of 0.1—1 Gauss (Nagata and Suguira 1977; Nagata 1979). The connection of this "model" magnetizing intensity to a real physical magnetic field depends to some extent on the way in which the meteorite accumulated and subsequently evolved in the presence of a magnetic field, as well as on the prior magnetic history of the individual components. More provocatively, the inferred magnetizing fields for individual small components of meteorites (for example, chondrules) range to the order of 10 Gauss (Lanoix *et al.* 1978; Suguira *et al.* 1979; Suguira and Strangway 1983). Probably even these inferences, although based on measurements of some of the physically simplest and least heterogeneous of meteorite material, should be regarded as tentative, pending wider-ranging and deeper studies of the processes involved in the acquisition of meteorite remanence.

One interpretation of the measurements is that the meteorite parent bodies were assembled out of small components that were already intensely magnetized as individual, free objects *before* they were incorporated into larger assemblages (Suguira and Strangway 1985). This interpretation, while simple and consistent with the measurements, is probably not unique.

One might imagine, for example, that the randomization of the small components occurred after magnetization, from an internally generated field on a larger object, during the subsequent churning of a regolith. However, for the present we will accept as a tentative inference that magnetizing fields as high as 10 Gauss might have occurred in the protoplanetary nebula. Inasmuch as the meteorites seem to have formed at several astronomical units, of the order of three, from the Sun, this 10 Gauss magnetic field also seems likely to have existed at that distance, although other possibilities are not strictly ruled out.

THE POSSIBLE ORIGIN OF A NEBULAR MAGNETIC FIELD

Assuming the presence of such a nebular magnetic field, there are several ways, in principle, that it could have arisen. One possibility is that the field could have been generated in the Sun; another possibility is that the field could have been a manifestation of the interstellar magnetic field compressed by the collapse of the protosolar gas (Safronov and Ruzmaikina 1985). Consider, however, the possibility that the nebular magnetic field was rooted in the early Sun. This possibility is largely attractive in the case that the nebula itself was too poor an electrical conductor to have its own magnetohydrodynamic character. In that case, the solar magnetic field must fall off at least as fast as r^{-3} in the electrically nonconducting space outside of the Sun. (In fact, if there is some ionized gas outflow from the Sun, even outside of the disk, the field might fall off somewhat less rapidly with distance, but probably not so differently as to alter the general conclusion here.) Then for a 10 Gauss magnetic field at 5×10^{13} cm from a 10^{11} cm radius Sun, the solar surface magnetic field would have had to have been about 10^{9} Gauss. Such a situation would have had a profound influence on the Sun, especially with respect to the dynamical equilibrium and stability of the system, since the energy associated with such a field would have been comparable to the gravitational binding energy of the Sun. Clearly, there are many other aspects of this that could be considered. However, the purpose here is not to rule out completely the possibility of an important nebular field arising from the Sun; rather it is to indicate that such an assumption does not lead to an easy and obvious solution of the problem of a nebular magnetic field.

Here we will presume a turbulent nebula in which the short mixing times and low electrical conductivity, and the consequent rapid dissipation of magnetic fields, quickly erase any memory of the nebular fluid's previous magnetization. In this case, if the nebula is to carry a large-scale magnetic field, then it must be contemporaneously generated, most likely by some sort of dynamo process (Parker 1979; Zel'dovich and Ruzmaikin 1987). The possible existence of conditions in the nebula that could have allowed the generation of such a magnetic field raises substantial physical questions. However, in the spirit of the present discussion, we will assume whatever is necessary and come back to the implications in the end.

The ability of a fluid flow to generate a magnetic field through hydromagnetic dynamo action can, in simple cases, be parameterized by a dimensionless number called the dynamo number, N, where

$$N = \frac{\gamma \Gamma \delta^3}{\eta^2}. \tag{1}$$

Γ is a measure of the helical part of the convection while γ measures the strength of the fluid shear, and η is the magnetic diffusivity, $c^2/4\pi\sigma$, with electrical conductivity σ; δ is the scale length of the magnetic field. Following a simple analysis for accretion disks (Levy 1978; Levy and Sonett 1978),

$$\gamma \equiv \frac{\partial V_\phi}{\partial r} - \frac{V_\phi}{r} \approx \frac{3}{2}\Omega. \tag{2}$$

In a Keplerian disk, $\Omega = (GM_\odot/r^3)^{1/2}$, and to order of magnitude, $\Gamma \approx \ell\Omega$, where ℓ is the large scale of the turbulence. Numerically then, $\gamma \sim 1.7 \times 10^{13} r^{-3/2}$ sec^{-1} and, $\Gamma \sim 1.1 \times 10^{13} \ell r^{-3/2}$ cm sec^{-1}. Now, taking both the scale of the largest eddies, l, and the scale of the magnetic field, δ, to be of the order of the scale height of the disk gas, $\sim 5 \times 10^{12}$ cm, we find that $N \sim 1.3 \times 10^{35}\ \eta^{-2}$, when $r \sim 3$ AU. Recent detailed numerical calculations of magnetic field generation in Keplerian disks indicate (Stepinski and Levy 1988) that magnetic field generation occurs at $N \approx 10^2$. Putting these results together, we find that a regenerative dynamo can be expected to be effective in such a disk if the electrical conductivity exceeds about 500 sec^{-1}. We will return to this question in the end.

Now consider the strength that such a magnetic field might attain. Inasmuch as the essential regenerative character of a dynamo fluid motion is associated with the cyclonic or helical component of the motion, which results from the action of the Coriolis force, then one estimate of the possible maximum amplitude of a dynamo magnetic can be derived from balancing the Coriolis force and the Lorentz stress:

$$\rho V \Omega \sim \frac{< B_p B_\phi >}{4\pi\delta}. \tag{3}$$

B_p and B_ϕ represent the poloidal and toroidal parts of the magnetic field respectively. Taking $\rho \sim 10^{-9}$ gm cm^{-3} and $V \sim 0.1$ kilometers per second, then with the other values as above, we find $< B_p B_\phi >^{1/2} \sim 10$ Gauss, as a measure of the maximum magnetic field strength that might be produced in such a nebula. Other processes also can act to limit the strength of the magnetic field. For example, with the low ionization level indicated above for the action of a nebular dynamo, the strength of the magnetic field can be limited by the differential motion of the neutral and ionized components of the gas: a phenomenon sometimes called ambipolar diffusion. Consideration of this dynamical constraint (Levy 1978) yields a limit on the magnetic field strength similar to the one just derived.

It is provocative that this estimate of the magnetic field strength possible in a protoplanetary nebula dynamo agrees so closely with the inferred intensity of the magnetizing fields to which primitive meteorites were exposed. At this point, the general estimates are sufficiently crude, and other questions sufficiently open, that this coincidence probably cannot be considered more than provocative.

THE POSSIBILITY OF MAGNETIC FLARES

One of the most intriguing puzzles posed by meteorites is the evidence that some components were exposed to very large and very rapid transient excursions away from thermodynamic equilibrium. Specifically, meteorite chondrules are millimeter-scale marbles of rock, which apparently were quickly melted by having their temperatures transiently raised to some 1700K and then quickly cooled. While there is some uncertainty about the time scales involved, the evidence suggests time scales of minutes to hours, though some workers have suggested even shorter melting events, of the order of seconds. Although a number of possible scenarios have been suggested for the chondrule-melting events, none seem to have been established in a convincing way (King 1983; Grossman 1988; Levy 1988). Here we will focus on the possibility that chondrules melted as a result of being exposed to energetic particles from magnetic nebular flares (Levy and Araki 1988).

In astrophysical systems, explosive restructuring of magnetic fields, associated with instabilities that relax the ideal hydromagnetic constraints and allow changes in field topology, seems to be among the most prevalent of phenomena responsible for energetic transient events. Such events are well studied in the Earth's magnetosphere (where they are involved in the dissipative interaction between the solar wind and the geomagnetic field and in geomagnetic activity) and in the solar corona (where they produce solar flares and other transient manifestations). It is thought that many other explosive outbursts in cosmical systems result from similar mechanisms.

To summarize the analysis given in Levy and Araki (1988), following the simple and basic analysis given by Petschek (1964), the energy emerging from a flare event is estimated at

$$F \sim \frac{B^3}{8\pi\sqrt{4\pi\rho}} \text{ erg cm}^{-2} s^{-1}. \tag{4}$$

Physically, this corresponds to an energy density equivalent to the energy of the magnetic field flowing at the Alfvén speed. Levy and Araki conclude that, in order to deliver energy to nebular dust accumulations at a rate sufficient to melt to the silicate rock, the flares must occur in the disk's tenuous corona, with local mass density in the range of 10^{-18} gm cm^{-3}, and with a magnetic field intensity in the range of about 5 Gauss. Under these conditions, they estimate that much of the flare energy is likely to emerge in the form of 1 MeV particles, which are channeled down along the magnetic field; in much the same way that geomagnetic-tail-flare particles are channeled to the Earth's auroral ovals. Under these conditions, Levy and Araki find that the value to which a particle's temperature can be raised is given by

$$T = \left(T_o^4 + \frac{B^3}{16\pi^{5/2}\sigma\sqrt{\rho}}\right)^{1/4}, \tag{5}$$

where T_o is the ambient temperature into which the particle radiates, and which has no substantial influence on the result. From equation (5) it is found that the above cited conditions in the flare site, $\rho \sim 10^{-18}$ gm cm^{-3} and B ~ 5-7 Gauss, yield flare energy outflows sufficient to melt chondrules; substantially weaker magnetic fields or higher ambient mass densities yield energy fluxes too low to account for chondrule melting. It is easy to see that the time scale constraints for rapid chondrule formation are easily met. At the equilibrium temperature given by equation (5), the rate of energy inflow is balanced by radiative energy loss. Thus the heating time scale is of the order of the radiative cooling time scale, second to minutes, depending on the physical structure of the precursor dust accumulation, and the temperature variation of the chondrule closely tracks the variation of the energy inflow.

The conclusion from this exploration is that chondrules might plausibly have been melted from magnetic flare energy in the protoplanetary nebula. Apparently, the most reasonable conditions under which flares could have accomplished this occur for flares in a low-density corona of the disk and with magnetic fields having intensities of around 5 Gauss or somewhat greater. It is provocative that these conditions are entirely consistent with inferences about the possible character of nebular magnetic fields that were summarized in the previous two sections.

If chondrules were made in this way, it is also necessary that the locale of chondrule formation was at moderately high altitudes above the nebular midplane: below the locale of the flares, but still high enough that the matter intervening between the flare site and the chondrule-formation site was sufficiently tenuous to allow the passage of MeV protons. This implies that the dust accumulations would have to have been melted at an altitude of about one astronomical unit above the midplane. It is conceivable that dust accumulations might have been melted into chondrules during their inward travel from interstellar cloud to the nebula. It is perhaps more likely that dust accumulations were lofted from the nebula to high altitudes by gas motions. This latter possibility requires that the precursor dust assemblages were very loose, fluffy, fairy-castle-like structures, somewhat like the dust balls that accumulate under beds (Levy and Araki 1988). However, this is perhaps the most likely physical state of early dust assemblages in the protoplanetary nebula.

Because the energetic particles associated with the flares described here are likely to have had energies in the range of an MeV, it is possible that nuclear reactions might also be induced that could account for some isotopic anomalies measured in meteorites. However, this possibility requires further investigation.

EXTERNAL MANIFESTATIONS

It is especially instructive to estimate the gross energetics of the flares described in the previous section. Again, following Levy and Araki (1988), consider that the time scale of the flare is of the order of the heating time of the chondrules, somewhere in the range of 10^2 to 10^4 seconds. Crudely, the flare energy is derived from the collapse of a magnetic structure of some spatial scale L_f in a time τ_f. The rate of such collapse is expected to occur at a fraction of the Alfvén speed, say $\sim 0.1\ V_A$, so that $L_f \sim 0.1\ V_A \tau_f$; the volume of involved magnetic field is then about $(0.1\ V_A \tau_f)^3$. Thus the total flare energy should be of the order of

$$\epsilon_f \sim 10^{-3} \frac{B^5}{64\pi^{5/2}\rho^{3/2}} \tau_f^3 . \qquad (6)$$

Taking $B \sim 5$ Gauss and $\rho \sim 10^{-18}$ gm cm^{-3}, then ϵ_f ranges from some 3×10^{30} to 3×10^{36} ergs per flare, as the flare time scale ranges from 100 to 10,000 seconds. For a flare time scale of one hour, equation (6) gives an energy of 1.3×10^{35} ergs. The total flare energy given by equation (6) is an especially sensitive function of the magnetic field strength: a 10 Gauss magnetic field would multiply all of the above energies by a factor of 32.

Now it is interesting to compare these results with the observations of flaring T Tauri stars. Such stars show diverse flaring activities over a range of time scales and intensities (Kuan 1976). Worden *et al.* (1981) suggest that 10-minute flares on T Tauri stars release at least 10^{34} ergs per event. This is in the range of flare energies given in the previous paragraph. Although there is considerable uncertainty in the numbers and in the physical conditions, it is conceivable that at least some of the flares observed on T Tauri stars are the same phenomenon that we have described here as a possible energy source for chondrule melting.

In a possibly related development, Strelnitskij (1987) has interpreted observed linear-polarization rotation angles, in an H_2O maser around a "young star," to require the presence of an approximately 10 Gauss magnetic field at distances of 10 and more astronomical units from the central star. It is not clear whether this surprising result has any connection to the problems discussed here, but the observation is surely provocative in terms of our understanding of the environments of young stars and protostars.

DYNAMICAL EFFECTS OF THE MAGNETIC FIELD

A nebular magnetic field having the strength and distribution discussed in this paper would have had substantial effects on the structure and dynamical evolution of the system. The main effects would be of two kinds, deriving from pressure of the magnetic field and the ability of the field to transport angular momentum.

Consider that a 5 Gauss magnetic field exerts a pressure of just about 1 dyne/cm^2. Compare this with the nebular gas pressure, which, for the mass density $\rho \sim 10^{-9}$ gm/cm^2 and the gas temperature T $\sim$ 300K, is about 10 dynes/cm^2. Thus the magnetic pressure is about 10% of the gas pressure. Although a 10% change in the effective gas pressure seems like a relatively small effect, within the context of the ideas discussed here, the overall effect of the magnetic field will be, in fact, much larger. The magnetic field constitutes a net expansive stress on the system, all of which must be confined in equilibrium by the gravity acting on the gas. This can be seen in a straightforward way from the magnetohydrodynamic virial theorem. To the extent that the low-mass-density corona also is permeated by a significant magnetic field, the expansive stress associated with the coronal fields must also be confined by the disk mass. Thus, to make a crude estimate, if the volume of coronal space filled with disk-generated magnetic field is, say, five times larger than the volume of the disk itself, suggested as a possibility in this discussion, then the effective expansive stress communicated to the disk gas is some five times larger. In that case the magnetic field becomes a major factor in the structure and dynamical balance of the disk, especially with respect to the vertical direction. Because the magnetic field acts much like a bouyant, zero-mass gas, the dynamical behavior of the gas and disk system would be expected to have similarities to what we observe in the solar photosphere-corona magnetic coupling. This is exactly the situation envisioned above in the speculative picture of nebula-corona flares. In that case, the nebula would also be expected to exhibit behaviors similar to those described by Parker (1966) for the galactic disk.

The magnetic contribution to angular momentum transport could have similarly important effects with a magnetic field such as that considered in this paper. Consider the torque transmitted across a cylindrical surface aligned with disk axis and cutting the disk at a radius R:

$$T = \frac{< B_p B_\phi >}{4\pi} 2\pi R^2 (2\Lambda), \tag{7}$$

where we have included the torque between z = $\pm\Lambda$ Let τ_L be the time scale for angular momentum transport, then $\tau_L \sim L/T$, where L is a characteristic angular momentum of the system. Taking $L \sim \pi \mathrm{R}^2 (2\Lambda) \rho \mathrm{R}^2 \Omega$ we find that

$$\tau_L \sim \frac{2\pi\rho\sqrt{GMR}}{< B_p B_\phi >}. \tag{8}$$

Taking $\sqrt{< B_p B_\phi >}$ ~1-10 Gauss results in an evolutionary time scale for angular momentum transport of 10^2-10^4 years. Thus, the presence of such a nebular magnetic field would have a substantial impact on the angular momentum transport and on the radial evolution of the system.

This angular momentum transport rate is large in comparison with the time scales generally believed to characterize nebular evolution. In that respect, it is worth noting effects that could alter the simplest relationships between the 1-10 Gauss field strengths and the overall evolution time scale. First, we note that MHD dynamo modes in a disk are spatially localized (Stepinski and Levy 1988), so that such fast angular momentum transport may extend over only limited portions of the nebula at any one time. Second, detailed observations of the Sun show us that intense magnetic fields may be confined to thin flux ropes, with the intervening field strength being much weaker. Such a situation in the nebula, with a spatially intermittent magnetic field, might admit the most intense magnetic fields inferred from meteorite magnetization, while still producing an overall rate of angular momentum transfer much lower than that estimated above. Finally, angular momentum transport at the fast rate suggested in the previous paragraph might be expected to produce sporadic, temporally *intermittent* evolutionary behavior in the nebula over short time scales. One might imagine that the $10^2 - 10^4$ years magnetic timescale could represent rapidly fluctuating local *weather* episodes during the slower, long-term, large-scale evolution of the nebula.

THE PROBLEM OF IONIZATION

Perhaps the most difficult barrier to understanding the possible presence of a substantial magnetic field in the protoplanetary nebula is the question of electrical conductivity. Except near its very center, the nebula was a relatively high-density, dusty gas at relatively low temperatures. Under such conditions, the thermally induced ionization fraction and the electrical conductivity are very low. Significant levels of electrical conductivity require some nonthermal ionization source to produce mobile electrons. Consolmagno and Jokipii (1978) point out that ionization resulting from the decay of short-lived radioisotopes might have raised the electron fraction to the point at which the nebula gas was coupled to the magnetic field. Based on their preliminary analysis, Consolmagno and Jokipii suggested that an electron density of perhaps a few per cm^3 would have been produced with the then prevalent ideas about the abundance of ^{26}Al in the nebula. This is sufficient to produce the behaviors described above. Thus, although more complete calculations of nebular electrical conductivity are needed (and are underway) in light of new information about the cosmic abundance of ^{26}Al (Mahoney *et al.* 1984) and new information about the dominant ion reactions, it is at least possible that the nebula was a sufficiently good conductor of electricity to constitute a hydromagnetic system.

SUMMARY AND CONCLUSIONS

A coherent picture can be drawn of the possible magnetohydrodynamic character of the protoplanetary nebula. This picture is based on a mixture of evidence and speculation. From this picture emerges a reasonable explanation of meteorite magnetization, a possible source of transient energetic events to account for chondrule formation, a plausible picture of dynamo magnetic field generation and field strength in the nebula, and a possible connection to energetic outbursts observed in association with protostars. This picture has potentially significant implications for our understanding of the dynamical behavior and evolution of the protoplanetary nebula because a magnetic field having the implied strength and character discussed here would have exerted considerable stress on the system.

The primary unresolved question involves the electrical conductivity of the nebular gas. In order for the described picture to be real, the nebular gas must conduct electricity well enough to become a hydromagnetic fluid; this requires a nonthermal source of ionization. However, other questions also press at us. What is the real nature and genesis of meteorite magnetization? Are the present, simplest interpretations correct, or is something eluding us? Clearly important work remains to be done in this area. What were the natures and histories of meteorite parent bodies? Could a magnetizing field have been internally generated? We are seriously in need of *in situ* investigation (with sample return) of comets and asteroids. What is the nature of protoplanetary environments? Astronomical studies are needed to ascertain the small-scale environments associated with star formation and protoplanetary disks.

From a broader point of view, it is possible that many things begin to fall into place if one presumes that the protoplanetary nebula did, in fact, have the characteristics described here. The protosolar system then takes on the aspect of a typical astrophysical system, which of course it was, with dynamical behaviors thought to be common in many such systems. In this case, it seems that a considerable conceptual gap separates the relatively simple and well-behaved nebula that emerges from our planetary system-based theoretical fantasies, and the energetic, violently active systems that we associate with protostars in the astrophysical sky. Some considerable work—theoretical, observational, and experimental—remains in order to close that gap.

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REFERENCES

Consolmagno, G.J., and J.R. Jokipii. 1978. ^{26}Al and the partial ionization of the solar nebula. The Moon and Planets 19:253.

Grossman, J.N. 1988. Formation of chondrules. Page 680. In: Kerridge, J.F., and M.S. Matthews (eds.). Meteorites and the Early Solar System. University of Arizona Press, Tucson.

King, E.A. 1983. (ed.). Chondrules and their Origins. Lunar and Planetary Institute, Houston.

Kuan, P. 1976. Photometric variations of T Tauri stars. Astrophysical Journal 210:129.

Lanoix, M., D.W. Strangway, and C.W. Pearce. 1978. The primordial magnetic field preserved in chondrules of the Allende meteorite. Geophysical Research Letters 5:73.

Levy, E.H. 1978. Magnetic field in the early solar system. Nature 276:481.

Levy, E.H. 1988. Energetics of chondrule formation. Page 697. In: Kerridge, J.F., and M.S. Matthews (eds.). Meteorites and the Early Solar System. University of Arizona Press, Tucson.

Levy, E.H., and S. Araki. 1988. Magnetic reconnection flares in the protoplanetary nebula and the possible origin of meteorite chondrules. Icarus, 81:74-91.

Levy, E.H., and C.P. Sonett. 1978. Meteorite magnetism and early solar system magnetic fields. Page 516. In: T. Gehrels (ed.). Protostars and Planets. University of Arizona Press, Tucson.

Mahoney, W.A., J.C. Ling, W.A. Wheaton, and A.S. Jacobson. 1984. HEAO-3 Discovery of ^{26}Al in the interstellar medium. Astrophys. J. 286:578-585.

Nagata, T. 1979. Meteorite magnetism and the early solar system magnetic field. Physics of the Earth and Planetary Interiors 20:324.

Nagata, T., and N. Suguira. 1977. Paleomagnetic field intensity derived from meteorite magnetization. Physics of the Earth and Planetary Interiors 13:373.

Parker, E.N. 1966. The dynamical state of the interstellar gas and field. Astrophysical Journal 145:811.

Parker, E.N. 1979. Cosmical Magnetic Fields. Their Origin and their Activity. Clarendon Press, Oxford.

Petschek, H.E. 1964. Magnetic field annihilation. Page 425-439. In: Hess, W.N. (ed.). NASA SP-50: AAS-NASA Symposium on the Physics of Solar Flares. NASA, Washington, D.C.

Safronov, V.S., and T.V. Ruzmaikina. 1985. Formation of the solar nebula and the planets. Page 959. In: Black, D.C., and M.S. Matthews (eds.). Protostars and Planets II. University of Arizona Press, Tucson.

Strelnitskij, V.S. 1987. On magnetic field strength in H_2O masers. Astronomical Circular 1490:4.

Stepinski, T., and E.H. Levy. 1988. Generation of dynamo magnetic fields in protoplanetary and other astrophysical accretion disks. Astrophysical Journal 331:416.

Suguira, N., and D.W. Strangway. 1983. A paleomagnetic conglomerate test using the Abee E4 meteorite. Earth and Planetary Science Letters 62:169.

Suguira, N., M. Lanoix, and D.W. Strangway. 1979. Magnetic fields of the solar nebula as recorded in chondrules from the Allende meteorite. Physics of the Earth and Planetary Interiors 20:342.

Suguira, N., and D.W. Strangway. 1985. NRM directions around a centimeter-sized dark inclusion in Allende. Proceedings of the 15th Lunar and Planetary Science Conference. Journal of Geophysical Research 90:C729.

Suguira, N., and D.W. Strangway. 1988. Magnetic studies of meteorites. Page 595. In: Kerridge, J.F. (ed.). Meteorites and the Early Solar System. University of Arizona Press, Tucson.

Wasilewski, P. 1987. Magnetic record in chondrite meteorites–microstructure, magnetism, and the FeNi phase diagram. Proceedings of the Meteoritical Society 50:183.

Worden, S.P., T.J. Schneeberger, J.R. Kuhn, and J.L. Africano. 1981. Flare activity on T Tauri stars. Astrophysical Journal 244:520.

Zel'dovich, Ya.B., and A.A. Ruzmaikin. 1987. The hydromagnetic dynamo as a source of planetary, solar, and galactic magnetism. Soviet Physics Uspekhi 30:494.