MAGNETIC FIELDS IN THE CHONDRULE-FORMING REGION OF A PLANETARY BOW SHOCK.
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Introduction: Magnetic forces drive protoplanetary disks' accretion and evolution. Important mechanisms for disk evolution such as the magnetorotational instability (MRI) and launching of magnetocentrifugal winds, depend on the strength of the background magnetic field. Direct knowledge of the background magnetic field in the solar nebula is lacking, but recent laboratory measurements [1,2] of the remanent magnetization of chondrules might be able to offer new clues to the ancient magnetic fields in the chondrule-forming region and, with modeling, in the solar nebula.

Chondrules are predominantly ferromagnesian silicates that often contain small amounts of metallic Fe-Ni (kamacite and tetrataenite), etc. The thermal histories of chondrules indicate that their precursors were "flash heated" to above the liquidus, melted, became free-floating droplets, and were cooled down slowly to crystallize. The metallic minerals, if present in those droplets, could be permanently magnetized while in the solar nebula as chondrules cooled down to the Curie point of kamacite (around 1038 K). These remanent magnetizations in chondrules have been found and measured due to laboratory advances. [1] found that around 10% of chondrules in the Semarkona L3.0 chondrite have olivine phenocrysts (dusty olivines) which contain iron-nickel metal inclusions that retain magnetizations. Within a chondrule the magnetizations are unidirectional, but they vary in direction from one chondrule to another, indicating that chondrules must have acquired magnetizations before they were assembled into the chondrite parent body. The study by [1] shows the chondrules were magnetized by a magnetic field 0.54±0.21 G. [2] indicates chondrules in CR chondrite LAP02342 are magnetized by a background field weaker than 0.15 G.

Whether these magnetizations reflect the solar nebula background field or a magnetic field specific to the chondrule-forming region requires modeling of chondrule formation and the diffusion of the magnetic field during chondrule formation. In that sense, the measurements of chondrule magnetizations can also serve as a strong constraint on chondrule formation hypotheses. Theorists have developed various chondrule formation models. Experimental constraints favor the hypothesis that the majority of chondrules appear to have been melted by passage through shock waves in the solar nebula [3]. Shock waves amplify the magnetic field as they compress the gas. They could be 1D nebula shocks [4, 5], in which the postshock magnetic field strength is proportional to the gas density (assuming the shock propagates perpendicular to the B field), regardless of the details of magnetic diffusion. Chondrule precursors could also be melted by bow shocks caused by large planetary embryos on eccentric orbits [6, 7]. These shocks are decidedly not 1D. This small scale bow shock geometry can result in complicated distributions of physical properties, including the magnetic diffusivity. It is uncertain what the magnetic field evolution timescale is, and therefore what magnetization the chondrules can acquire.

In this work we explore how much the magnetic field diffuses behind the bow shock around a planetary embryo, and relate the magnetic field strength recorded by chondrules to the background magnetic field strength of the solar nebula.

The Bow Shock Model: We model the 3D bow shock using Boxzy Hydro [7]. We assume a planet with radius R = 3000 km moving at 7 km/s through nebular gas with density $\rho = 10^{-9}$ g cm^{-3} and temperature $T = 300$ K. An adiabatic equation of state is assumed. The simulation is evolved for around 10^6 s until a steady state is achieved. Major outputs include pressure, temperature, gas density and velocity distribution. The temperature ranges from 300 to 1200 K and is most enhanced in front of and behind the embryo.

Gas Ionization State: The ionization state of gas determines the magnetic diffusivity and diffusion rate. Here we consider gas-phase collisional ionization of potassium atoms. In regions with $T < 800$ K, the thermionic emission of electrons and ions from solids becomes important [8]; the Saha equation is only valid at high temperature. We calculate the ionization state using the code and formulism in [9]. We construct a lookup table for the densities of electrons and K^+ ions as a function of gas density and temperature. In the relevant regime, adsorption and emission of charges from the surfaces of dust grains and chondrules will dominate over gas phase reactions, and the ionization state is insensitive to the surface area of particles. We assume a solids/gas mass ratio of 0.01, a grain radius 1 μm, and a particle work function of 5 eV.

The Magnetic Diffusivities: Magnetic fields diffuse at different rates in different directions due to different processes. We calculate the rates of Ohmic dissipation and ambipolar diffusion, and thus the rates of magnetic diffusion parallel ($D_{\parallel}$) and perpendicular ($D_{\perp}$) to the field. [9] indicates that the diffusion coefficient $D_{\parallel}$ is associated only with Ohmic dissipation, while $D_{\perp}$ is associated with the combined actions of Ohmic dissipation and ambipolar diffusion. $D_{AD} = D_{\perp} - D_{\parallel}$ scales as B^2, meaning that strong fields can enhance ambipolar magnetic diffusion. We assume a background field B=0.5 G. We calculate the perpendicular magnetic diffusion rate using standard formulas in [9] to relate electron and ion densities to electrical conductivities, combining these with gyro-frequencies and collision timescales of individual species. We use the momentum transfer rates in [10].

Results: Figure 1 shows the calculated values of $D_{\parallel}$ and $D_{\perp}$ around the bow shock. In general, because of thermal ionizations, $D_{\parallel}$ decreases with rising temperature, being as low as 10^{10} cm^2 s^{-1} in the hottest gas in front of the planet, remaining below 3×10^{13} cm^2 s^{-1} within a cylinder with radius around 3000 km behind the planet, attaining much higher values farther from the planet. For this diffusion coefficient, the timescale for the field to diffuse laterally significantly is $t_{diff} \sim \frac{R^2}{D_{\parallel}} \sim \frac{(3000\ km)^2}{3\times10^{13}\ cm^2 s^{-1}} \sim 3\times10^3 s$, which is comparable to the dynamical timescale of the postshock gas $t_{dyn} \sim \frac{R}{V} \sim \frac{(3000\ km)}{(1\ km/s)} \sim 3\times10^3 s$. We conclude that with Ohmic dissipation alone, the magnetic field is frozen into the gas and can remain amplified *only* in the cylinder with radius around 3000 km behind the planet. Outside of this cylinder, the magnetic field quickly drops to the background field strength ~ 0.5 G. We also find that the diffusion of the field perpendicular to the magnetic field, described by $D_{\perp}$, is an order of magnitude higher than $D_{\parallel}$ at B =0.5 G, and would be even higher at larger B. Due to ambipolar diffusion, the radius of the low-diffusivity cylinder as defined above shrinks to around 2000 km.

Discussion: Simulated chondrule precursors' trajectories are compared with the above results ($D_{\parallel}$ only) in Fig. 2. For now, we simply draw the conclusion that the majority of chondrules that pass through the bow shock do not enter the low-diffusivity zone behind the planetary embro. Including ambipolar diffusion, the low-diffusivity zone is even smaller, and chondrules are not likely to be magnetized by the enhanced magnetic field. Therefore, it is highly possible that the field value inferred by the sample in Semarkona represents the typical background nebula magnetic field (0.5 G), which aligns with previous studies (e.g. [13]) indicating the background field strength should be 0.1 ~ 1 G. The weak field recorded by LAP02342 may also be the background field strength, probably in a different location and time in the protoplanetary disk.

References: [1] Fu, R.R. et al. 2014, Science 346, 1089. [2] Fu, R.R., Weiss, B.P. & Schrader, D.L. 2015, LPSC 46, 1587. [3] Desch, S.J., et al. 2012, MAPS 47, 1139. [4] Desch, S.J. & Connolly, Jr., H.C. 2002, MAPS 37, 183. [5] Morris, MA. & Desch, S.J. 2010, ApJ 722, 1474. [6] Morris, M.A., et al. 2012, ApJ 752, 27. [7] Boley, A.C., Morris, M.A. & Desch, S.J. 2013, ApJ 776, 101. [8] Desch, S.J. & Turner, N.J. 2015, ApJ 811, 156. [9] Desch, S.J. & Mouschovias, T.Ch. 2001, ApJ 550, 314. [10] Pinto, C. & Galli, D. 2008, A&A 484, 17.

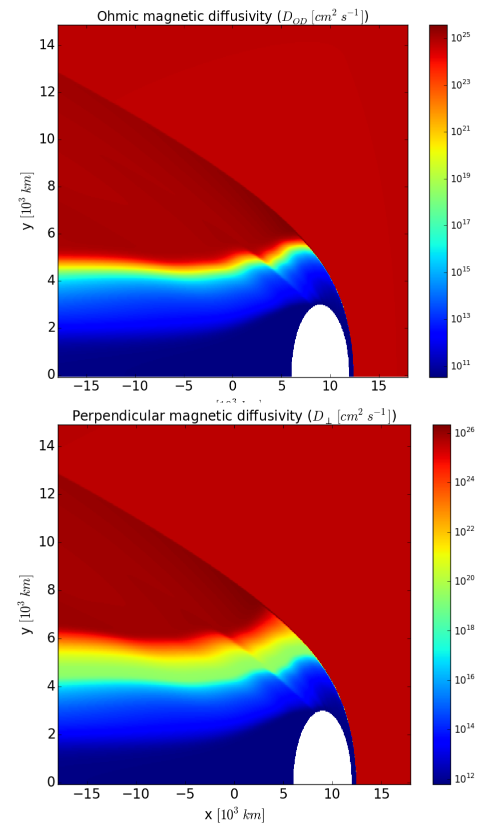

Fig. 1 Magnetic diffusivity distribution: top ($D_{\parallel}$), bottom ($D_{\perp}$).

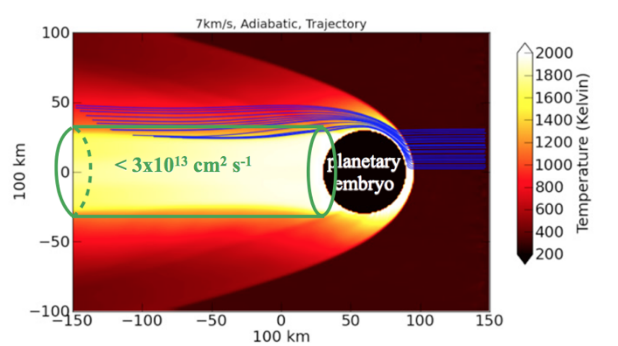

Fig. 2 Comparison of chondrule trajectories with low-diffusivity zone.