CHONDRULE FORMATION BY CURRENT SHEETS IN PROTOPLANETARY DISKS. D. S. Ebel[1], M. K. R. Joung[2,3], and M.-M. Mac Low[2,3]. [1]Dept. of Earth and Planetary Sciences (debel@amnh.org), [2]Dept. of Astrophysics, American Museum of Natural History, Central Park West at 79th St., New York, NY 10024 (mordecai@amnh.org), [3]Dept. of Astronomy, Columbia University, 550 West 120th St., New York, NY, 10027 (moo@astro.columbia.edu).

Introduction: Theories of protoplanetary disk evolution require that the viscosity of the differentially rotating disk (the resistance of the disk to shear forces) be sufficient for stellar accretion on timescales of 10^6 years [1]. With only molecular (frictional) viscosity, accretion takes 10^3 times longer. Vertical turbulent convection cannot provide the needed viscosity [2]. The leading mechanisms for disk viscosity are (a) gravitational instability, which would drive density waves in the disk [3,4], and (b) coupling of the disk rotation to its magnetic field [5].

In cold disk regions with a high mass density, gravitational instabilities could occur, and drive chondrule-forming shocks [6, 7]. Alternatively, magneto-rotational instability (MRI) is predicted to occur in regions of the disk where the gas is ionized enough to couple to magnetic fields [8]. Like spiral density waves, MRI effectively transfers angular momentum outward in the disk. The MRI also produces magnetic field gradients. In weakly ionized regions where neutral particles can slip through ions (*i.e.*-where ambipolar diffusion occurs), magnetic field gradients are predicted to grow steeper with time, producing sheets of strong electrical current [9, 10]. We propose that these current sheets could melt chondrule precursors.

Unlike mechanisms involving accumulation and dissipation of charge (nebular 'lightning', *e.g.*-[11]), the MRI is driven by the abundant energy of the differential rotation of the disk itself. Furthermore, current sheets are predicted to occur in different regions over the lifetime of the disk.

Which disk regions make current sheets, when, and where might they form chondrules? Because current sheet thermal profiles are qualitatively similar to those of shocks, our results are testable against meteoritic evidence by techniques analogous to those used by [6].

Technique: We assume the simple minimum-mass solar nebula of [12, 13], and magnetic field strengths (β_{max}) like those recorded in meteorites [refs. in 6]. We then estimate the importance of ion-neutral drift (ambipolar diffusion) for coupling of magnetic fields to the disk. The ionization fraction of the gas (χ_i) is a critical determinant of which disk regions will be turbulent due to MRI. If the gas exceeds the critical ionization fraction (χ_{crit}) every neutral particle collides with an ion at least once per orbit, the MRI remains active. Although protoplanetary disks are relatively cold and dense astrophysical systems, [14, 15] showed that $\chi_i >> \chi_{\mathrm{crit}}$ in (1) the inner disk (<~0.3AU) where $T_{\mathrm{gas}} \geq 2000$K causing ionization, (2) surface layers at radii R< 10 AU, from local and cosmic radiation, and (3) the entire disk at R>10 AU, also from radiation.

The fastest growing perturbation wavelength of the MRI (*i.e.*-the mode where it is most unstable) has a length scale of 0.001 - 0.1AU. At MRI-produced gradients in the magnetic field, magnetic pressure acts on ions by ambipolar diffusion, to steepen the gradient, which ultimately sharpens to a singularity that produces a sheet of high electric current [9] of thickness l_{cs}~10^2 km. We ignore the time evolution of the current sheets, and assume steady-state flow, following [9]. However, a major caveat to our work is that heating and ionization in current sheets could blow them apart, producing local shocks.

Micron-sized dust heated by collisions with ions in the current sheets radiates in the infrared, heating chondrule precursors. Numerical solutions of this process are found using of the radiation transfer equations [16] that describe the radiative heating of chondrule precursors by this infrared radiation. The resulting chondrule temperature (T) histories are then compared to experimental constraints on chondrule formation [*e.g.*-17,18]. Gas and dust are assumed to travel with velocities of order the Alfvén velocity (1 km/s) through the current sheet. We compute the thermodynamics and radiative transfer in this flow using a grid of 10^3 1 km thick zones in a one-dimensional slab geometry [16]. In future work we plan to use a dynamical model to study how dust grains actually move through current sheets as the sheets evolve. We assume a bimodal dust size distribution (10μm + 1 mm) with equal masses in each size fraction, a simplification from the likely power law size distribution that is justified because smaller grains radiate in the infrared most efficiently near their melting temperature, so their thermal evolution drives the thermal evolution of the chondrule precursors.

Results: In current sheets, neutral particles are heated primarily by friction during ion-neutral diffusion, as well as by Ohmic (resistive) dissipation. The peak heating rate rises as gas density n_g drops, for example: off the midplane, late in the disk lifetime as the disk thins (*e.g.*-to order ~10^4 km), during solar wind blow-off of the disk, or during planetary gap formation.

In order to match experimental [17,18] and theoretical [19,20] constraints on chondrule formation, we sought conditions where current sheets:

* partially or fully melt 1 mm grains for a few minutes.
* cool grains by 10^2-10^3 K per hour
* evaporate or destroy grains <0.1 mm.

We find that current sheets that meet these criteria have: 1) low gas density ($n_g \leq 10^{12}$ cm^{-3}), for a high heating rate, 2) high chondrule and dust densities ($n_d >$ 1 cm^{-3}), so infrared heating times are only a few minutes, and 3) very small dust grains ($a_d \sim 1\mu$m), so dust heats rapidly. To satisfy all three conditions simultaneously requires a very large dust-to-gas mass ratio ($\zeta \sim 50$). In a standard nebula model with $\zeta \cong 0.01$ (*i.e.*-solar), current sheet heating is ineffective. Late in disk evolution, however, much of the dust is expected to settle into a thin, dense layer [21]. Near the ionized surface of the turbulent midplane, we preict that thin ($\sim 10^2$ km), hot (T>1600 K) current sheets will form. Fig. 1 shows that some dust/gas mass ratio, $5<\zeta<50$, exists that favors chondrule formation for a particular set of conditions in this region.

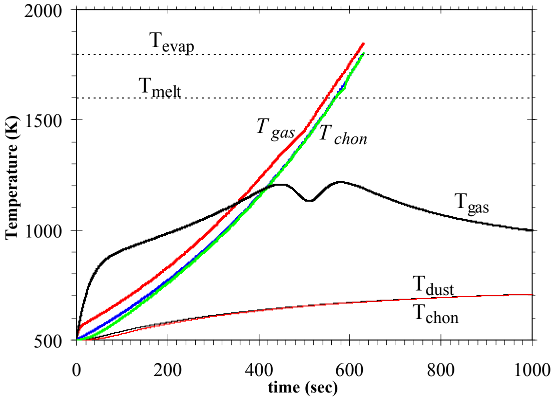

Fig 1: Time evolution of gas, dust and chondrule temperature (T) at a fixed position in space for n_g=10^{12}/cm^3, B_{max}=3G, and ζ=5 (bold labels), and ζ=50 (italic labels). $T_{dust} \cong T_{chon}$ in both cases. Run ζ=50 halts when grains evaporate.

Discussion: We are exploring the transition between the MHD regime, when the magnetic field is fully coupled to conducting disk gas, and the gas dynamical regime, in which neutral particle collisional mechanics dominate and magnetic fields decouple from the flow. The disk location of these regimes has been explored by [15], who found that if grains grow to micron size and sediment to the midplane, then MRI occurs in most regions outside the midplane. For example, MRI does not occur inside r_{crit}~20 AU for grain abundances like those in molecular clouds (f_g=1), but if f_g falls to 10^{-4} outside the midplane, then r_{crit}~1.4 AU, and MRI occurs throughout most of the disk. To melt significant amounts of midplane dust, turbulent motion must bring grains into the MRI-active surface of the midplane. Following [21], we estimate that the average dust grain experiences a current sheet each 3x10^4 yrs. The prediction of small grain evaporation and chondrule melting only for high dust-to-gas mass ratio ζ is consistent with chondrule oxidation states above that in a gas of canonical solar composition [20], and the lack of isotopic evaporation signatures in chondrules [22].

Conclusions: Magnetorotational instability (MRI) is a well-studied mechanism driving disk accretion by outward transfer of angular momentum. Current sheets due to MRI are predicted to form in mostly neutral regions of protoplanetary disks. Our first order approach shows that dust passing through current sheets, particularly late in disk evolution, could be processed into chondrules [23].

We are modeling processes that occur over large time and length scales, involving tightly coupled pressure imbalances, ionization, temperature evolution, and magnetic fields. Incorporating dynamical evolution of current sheets, and a power-law dust size distribution are the next steps in more rigorously modeling these processes. We are currently taking these steps.

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