CHONDRULE FORMATION BY CURRENT SHEETS IN PROTOPLANETARY DISKS. D. S. Ebel¹, M. K. R. Joung²,³, and M.-M. Mac Low²,³. ¹Dept. of Earth and Planetary Sciences (debel@amnh.org), ²Dept. of Astrophysics, American Museum of Natural History, Central Park West at 79th St., New York, NY 10024 (mordecai@amnh.org), ³Dept. 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 10⁶ years [1]. With only molecular (frictional) viscosity, accretion takes 10⁹ 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, magnetorotational 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] of thickness l_e~10⁵ 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 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 10⁴ 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_e drops, for example: off the midplane, late in the disk lifetime as the disk thins (e.g. to order ~10⁴ km), during solar wind blow-off of the disk, or during planetary gap formation.

that \( \chi_i \geq \chi_{crit} \) in (1) the inner disk (<~0.3AU) where \( T_{gas} \geq 2000K \) 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_e~10⁵ 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.

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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 $10^{-5}$ K per hour
* evaporate or destroy grains <0.1 mm.

We find that current sheets that meet these criteria have: 1) low gas density ($n_g \lesssim 10^{12}$ cm$^{-3}$), for a high heating rate, 2) high chondrule and dust densities ($n_d > 1$ cm$^{-3}$), so infrared heating times are 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 $\zeta \approx 50$ (italic labels), $T_{dust} = 50$ halts when grains evaporate.

**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.


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