MINERAL PROCESSING BY SHORT CIRCUITS IN PROTOPLANETARY DISKS.

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Introduction: Chondrules provide evidence of rapid heating to temperatures in excess of 1800 K followed by cooling that is slow compared with free radiation to background, but fast compared to protoplanetary disk thermal and dynamical times [1,2]. Complementarity in major [3] and minor [4] element composition for the combination of chondrules and matrix, combined with the lack of thermal processing of matrix material [5,6,7] mandate a localized heating process. This process must be intermittent, but not vanishingly rare either in space or time as witnessed by multiple igneous rims on chondrules [8,9].

Several mechanisms have been proposed to explain the origin of chondrules, including planetesimal bowshocks [10] and the now discredited X-wind model [11]. While the former can explain intermittency, it is not clear how one generates planetesimals at the appropriate stage of Solar System formation. An alternative energy source for the heating is the gravitational potential energy released by the accretion flow of the protoplanetary disk. The difficulty there lies in releasing the energy in an adequately localized manner.

The accretion flow is thought to be mediated by the magneto-rotational instability (MRI [12]) which drives magnetized turbulence that dissipates the gravitational energy into heat. MHD turbulence quite generally generates spatially isolated current sheets where the energy is dissipated [13]. However, at the magnetic energy densities expected (similar to but below equipartition with the gas thermal energy density), these current sheets will not straightforwardly generate chondrule processing temperatures.

Short Circuits: We proposed an instability in the current sheets associated with magnetized turbulence in solar composition gas at temperatures around and above 850 K [14]. This instability can be compared to both electrical short circuits and lightning [15]: at temperatures above 1000 K, thermal ionization of alkali metals (mainly potassium) replaces non-thermal ionization as the dominant source of charge carriers to carry the currents in the current sheets. At that temperature and at densities associated with protoplanetary disks, the resistivity then becomes a very steep function of temperature (halving with every 30 K rise). As magnetic energy is dissipated into heat, the temperature of the current sheet rises from temperatures below this switch and the increased number of free electrons drops the resistivity in the warmer portions of the current sheet itself. The system evolves to concentrate the current in the thin, hot, lower resistivity central layer of the current sheet, locally increasing the Ohmic dissipation and heating the system further, similarly to an electrical short. This leads to a runaway instability where the current sheet narrows and heats until either all the potassium is ionized or radiative cooling stabilizes the instability. This can also be compared to lightning, with the key differences that the ionization occurs thermally, rather than through a strong electric field, and the magnetic field is a current source rather than a voltage source.

This instability naturally generates hot gas on small length scales, as the initial current sheet narrows. MHD turbulence creates volume filling, temporally intermittent current sheets, so this instability can explain the localized heating combined with neighboring low temperatures regions demanded by consideration of complementarity. Further, the necessary rapid heating followed by measured cooling is explained by the chondrule precursors entering the narrowed sheet, being processed, and exiting to cool in a warm, radiatively heated sheath around the current sheet proper.

Technique: We have examined this instability numerically in the presence of radiative cooling using a detailed opacity model [16] for the dust found in protoplanetary disks. The radiation transport is treated through a ray-tracing method rather than flux-limited diffusion. We have studied the evolution of a 1-dimensional current sheet for an initial magnetic pressure of 2/3 of the gas thermal pressure, background temperature of 850 K, background gas densities of 10^{-7} g cm^{-3} and initial current sheet widths of 10^{10} cm and wider. Our free electrons (and hence resistivity) are provided by a background non-thermal ionization rate and the thermal ionization of (only) potassium. We avoid consideration of the boundaries by using a logarithmic grid that pushes them toward infinity. Due to the extreme spatial and temporal variability of the resistivity and opacity we used an implicit method to evolve our system, and we implemented a relaxation equation for the opacity with relaxation times under an hour.

Results: We show that for different initial current sheet configurations, we can achieve a variety of significant final temperatures. For our thinnest current sheets (initial width 10^{10} cm), the short circuit instability runs until all the potassium is ionized, resulting in final temperatures above 2000 K, adequate to produce barred olivine textures [17] or melt Type B CAIs [18].

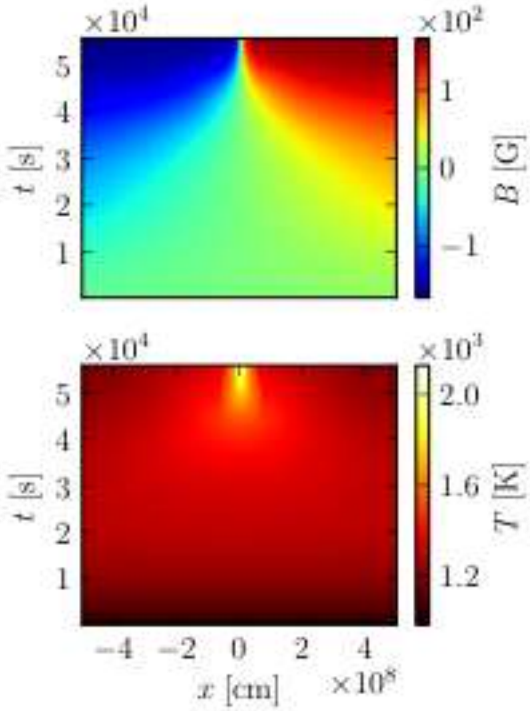

Fig 1: Time evolution (y-axis) of the magnetic field and temperature across the 1-dimensional current sheet (x-axis) for our narrow initial current sheet. Radiative cooling does not halt the short circuit before all the potassium is ionized.

Broader initial current sheets ($5x10^{10}$ cm) result in a weaker instability that halts once the silicate melting temperature (1500 K) is reached, which leads to a sudden drop in the opacity and a corresponding increase in the radiative cooling rate. This leads to final temperatures of the order of 1650 K.

Even broader initial current sheets lead to short circuits that saturate at the opacity drop that occurs once organic compounds melt, at around 1200 K. This produces temperatures below the melting point of silicates which would be ideal for quickly annealing amorphous silicate dust into crystalline silicates [19]. Such transitions are observed in extrasolar protoplanetary disks [20].

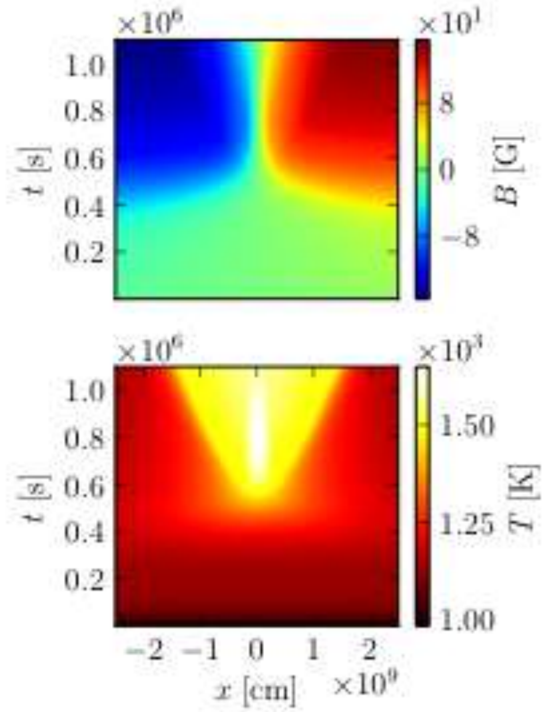

Fig 2: As Fig 1, for a broader initial current sheet. Radiative cooling halts the short circuit shortly after the silicate solids are destroyed.

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References: [1] Connolly HC et al (1998) *GCA 62*, 2725-2735 [2] Alexander et al (2001) *Science 293*, 64-68 [3] Hezel DC & Palme H (2008) *EPSL 265*, 716-625 [4] Bland PA et al (2005) *Proc. Nat. Acad. Sci. 102*, 13755-13760 [5] Alexander et al (1998) *MaPS 33*, 603-622 [6] Huss GR & Lewis RS (1994) *MaPS 29*, 811 [7] Mendybaev et al. (2002) *GCA 66*, 661-682 [8] Krot AN & Wasson JT (1995) *GCA 59*, 4951-4966 [9] Ebel et al (2008) *MaPS 43*, 1725-1740 [10] Ciesla FJ et al (2004) *MaPS 39*, 1809-1821 [11] Desch et al (2010) *ApJ 725*, 692-711 [12] Balbus SA & Hawley JF (1991) *ApJ 376*, 214-233 [13] Cowley SC et al (1997) *Physics Reports 283*, 227-251 [14] Hubbard A et al (2012) *ApJ 761* [15] Horanyi M et al (1995) *Icarus 114, 174-185* [16] D'Alessio et al (2001) *ApJ 553, 321-334* [17] Connolly HC et al (2006) in *Meteorites and the Early Solar System II, (Tuscon, U of Arizona),* 383 [18] Grossman L et al (2000) *GCA 16*, 2879-2894 [19] McNally et al (2013) arXiv:astro-ph [20] Sargent B et al (2009) *ApJS 182*, 477-508.