Thermal Processing of Solids through the Short Circuit Instability

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Papers: Hubbard, McNally & Mac Low, ApJ 761, 58, 2012
McNally, Hubbard, Mac Low, Ebel & D'Alessio, ApJ 761, L2, 2013

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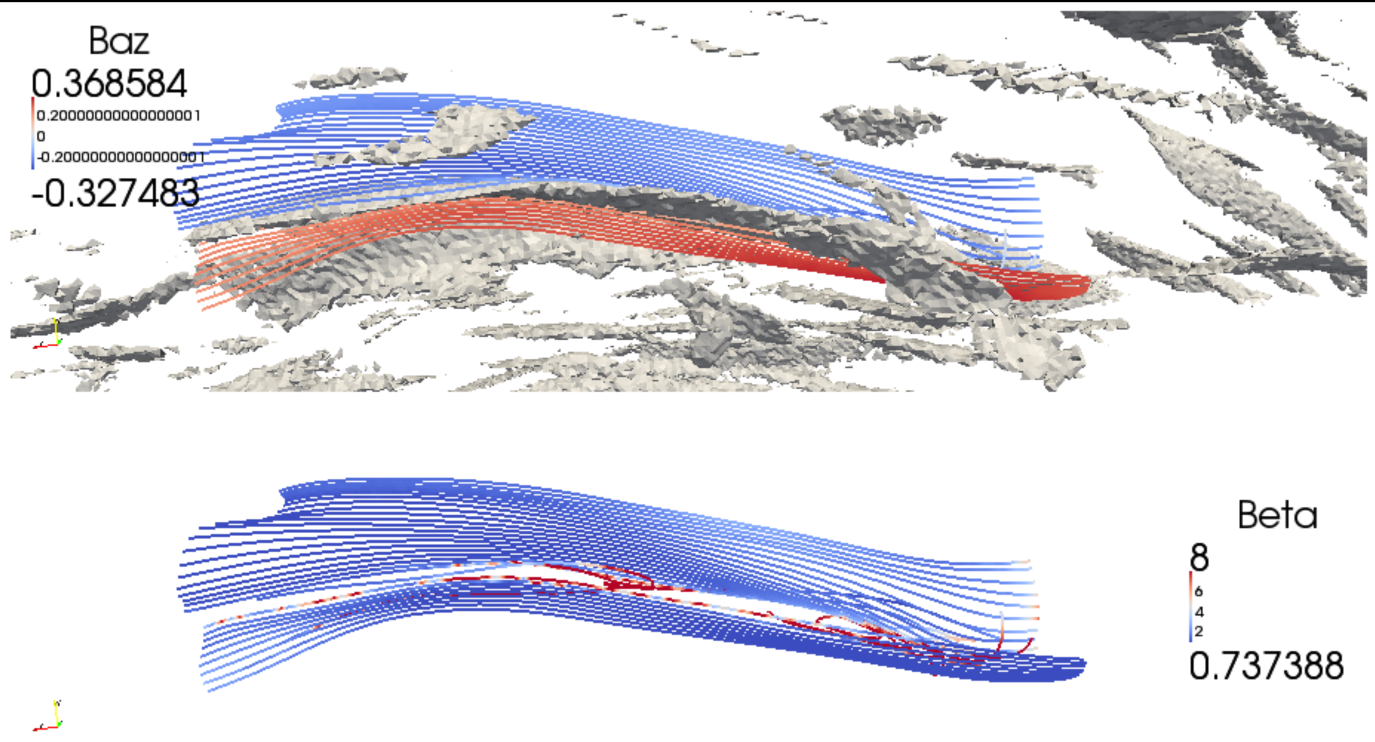
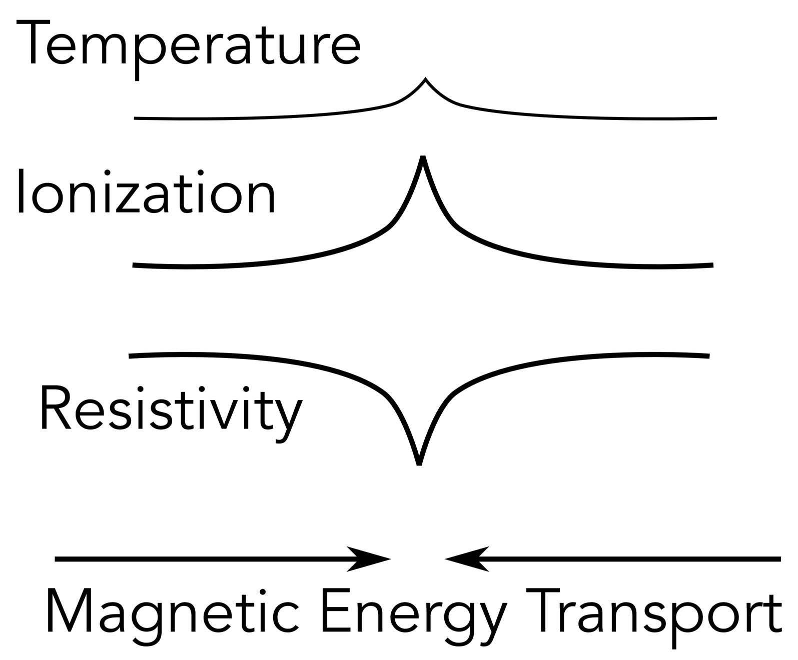


The short-circuit instability focuses current sheets to produce very high temperatures. Current sheets are a ubiquitous feature of magnetized turbulence. The short-circuit instability occurs when current sheets form in a plasma with strongly temperature dependent ionization, such as the thermally ionized regions of a protoplanetary disk. The figure (above, upper panel) shows an example current sheet in a MRI-turbulent simulation. The gray isosurface shows regions with high current density, and the magnetic field lines are colored by azimuthal field in the upper panel. In the lower panel, the same field lines are colored by plasma beta (the ratio of magnetic pressure to gas pressure).



As the current flows, it dissipates energy, (Ohmic dissipation) heating the gas and raising the temperature in the current sheet.

In the coolest thermally ionized regions of a protoplanetary disk, even a small increase in the temperature will increase the ionization dramatically (Saha ionization equilibrium).

As the ionization is increased, the resistivity of the plasma decreases.

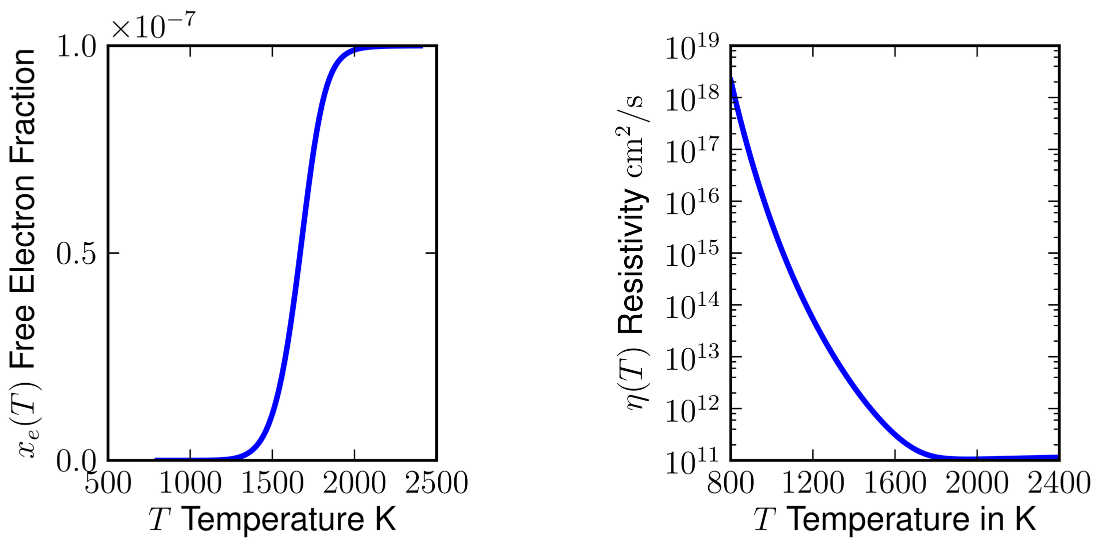
The resulting strong gradients of resistivity dominate the evolution of the current sheet.

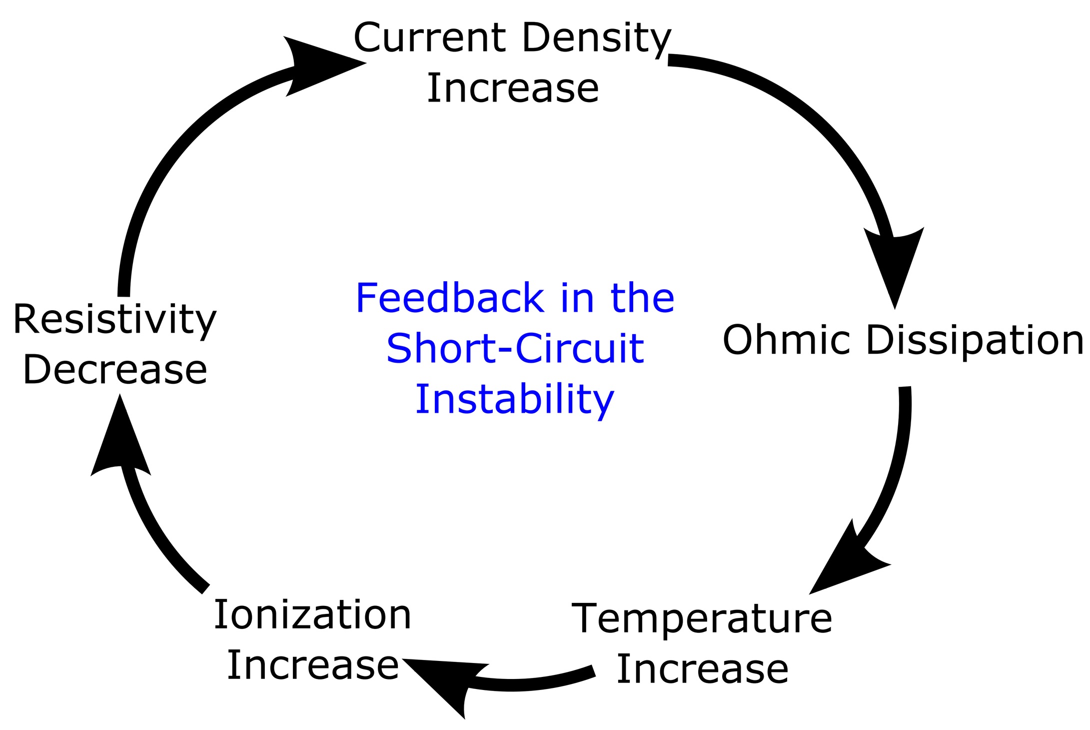
Ingredients in a Short-Circuit:

Induction Equation:
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}) - \nabla \times (\eta(T)\mathbf{J})$$

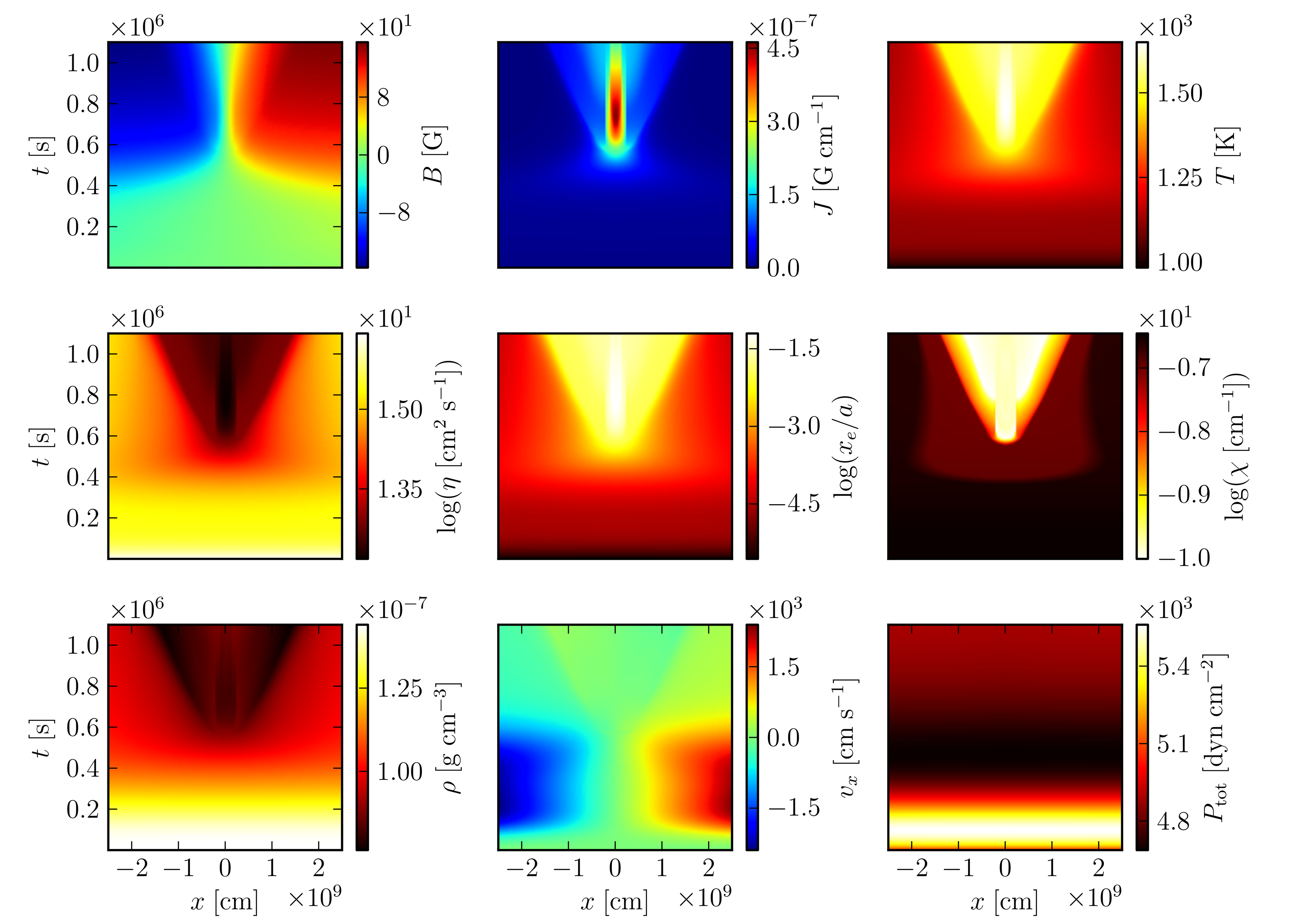
Energy Equation:
$$\frac{\partial T}{\partial t} = -\nabla \cdot (T\mathbf{v}) - c_T P \nabla \cdot \mathbf{v} + \frac{c_T \eta}{4\pi\rho}\mathbf{J}^2$$
(Ohmic Dissipation)

Resistivity dependence on temperature:





In the thermally ionized regions of the disk, the short-circuit instability is capable of heating to the temperatures required for thermal processing of chondrules and CAIs.



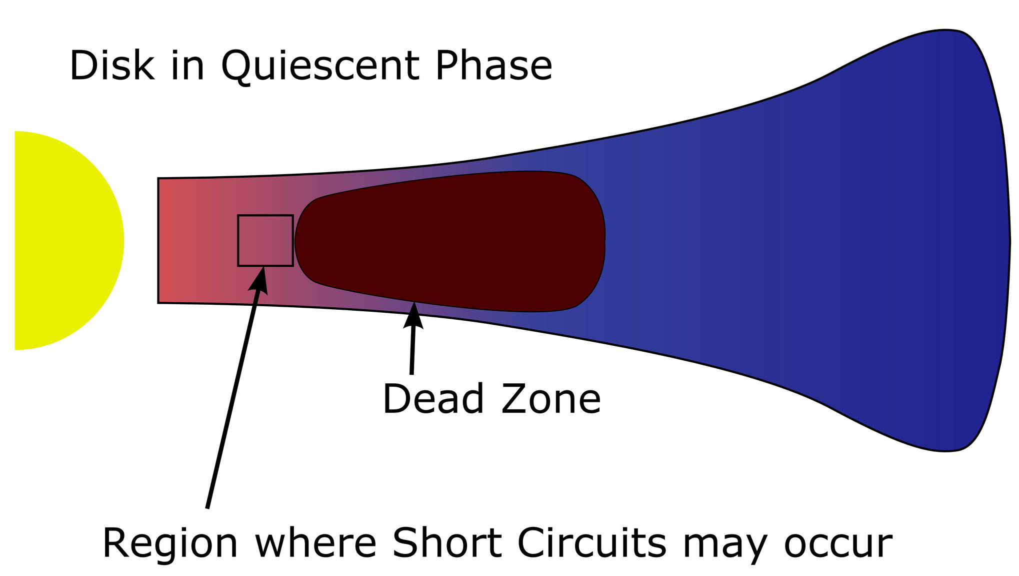
Above: Space-time plots of a short circuit event.

Plot Symbols:

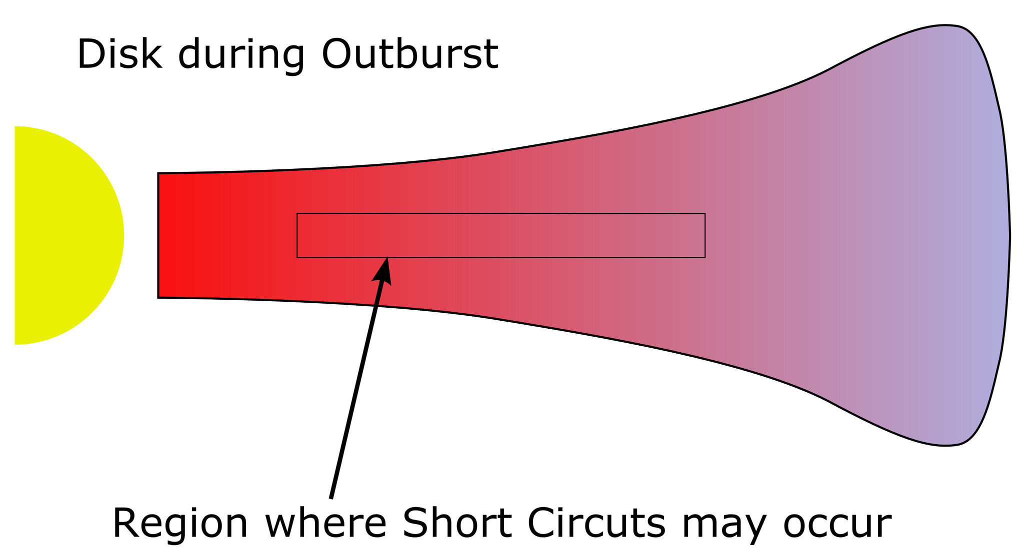
B	Magnetic Field
β_0	Background plasma beta
J	Current Density $\nabla \times \mathbf{B}$
T	Temperature
t	Time
x	Distance perpendicular to the current sheet
ρ	Density
v_x	x-velocity
x_e/a	Fraction of potassium ionized
χ	Photon mean free path
P_{tot}	Total of gas + magnetic pressure

When including cooling of the gas by radiation, and using realistic opacity tables for the temperature dependence of opacity two classes of short circuit heating event are seen. In this case, the decrease in opacity corresponding to the destruction of silicate grains increases the cooling and quenches the instability before reaching full ionization of potassium. These plots show only the central region of the short - the initial current sheet has a half-width of 5×10^{10} cm. A slightly narrower initial current sheet will heat to ~2100 K.

The areas of the disk most susceptible to the Short Circuit instability are magnetically active regions where the temperature of current sheets can be sufficient to trigger significant ionization of potassium (>850 K). For the bulk of the disk lifetime, the most favorable region is just radially inward of the dead zone, near the midplane.



During an FU Ori event or other outburst, the disk may become much hotter, leading to bursts of wide-spread short-circuit activity over wider regions of the disk.



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