Temperature Fluctuations driven by Magnetorotational Instability in Protoplanetary Disks

Colin Mcnally [1, @] , Alexander Hubbard [2, @] , Chao-Chin Yang [3, @] , Mordecai-Mark Mac Low [2, @]

1 : Niels Bohr Institute (NBI) - ***Website***

Blegdamsvej 17, DK-2100 Copenhagen - Denmark

2 : American Museum of Natural History

79th Street at Central Park West, New York, New York - United States

3 : Lund Univertsity

Lund Observatory, Department of Astronomy and Theoretical Physics, Lund University, Box 43, 22100, Lund, Sweden - Sweden

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The magnetorotational instability (MRI) drives magnetized turbulence in sufficiently ionized regions of protoplanetary disks, leading to mass accretion. The dissipation of the potential energy associated with this accretion is a component of the balance which determines the thermal structure of the disk. This is expected to be most significant in the inner regions, at the midplane inside the inner edge of the dead zone. To model the resulting thermal structure of the disk, it is critical to recognize that magnetized turbulence dissipates its energy intermittently in current sheet structures. I will discuss our recent study of this intermittent energy dissipation using high resolution numerical models including a constant resistivity and radiative thermal diffusion in an optically thick regime. Our models predict that these turbulent current sheets drive order unity temperature variations even where the MRI is damped strongly by Ohmic resistivity (McNally et al. 2014). I will discuss these temperature fluctuations, and the current sheets which drive them.

Subject : : oral
Topics : Astrophysics

Temperature Fluctuations and Current Sheets in Protoplanetary Disks

Colin M^c^Nally

Alexander Hubbard, Mordecai-Mark Mac Low, Chao-Chin Yang, Denton Ebel

The Niels Bohr International Academy

Accretion Releases lots of Energy

An estimate of energy requirement for thermal processing from chondritic material (King & Pringle 2010):

$$E_{req} = 1.2 \times 10^{11} \left(\frac{T}{2000 \text{ K}} \right) \text{ erg g}^{-1} \quad (1)$$

$$E_{kin} = 1.5 \times 10^{12} \left(\frac{M}{M_\odot} \right) \left(\frac{3 \text{ AU}}{R} \right) \text{ erg g}^{-1} \quad (2)$$

- Demands about 8% efficiency at 3 AU.
- Significant, but much looser constraint at smaller radii.

Magnetic Fields

Expect disk dynamo to produce plasma beta $\sim 1 - 50$
Remnant magnetic field measurements indicate Gauss-level magnetic fields were present when some chondrules cooled.

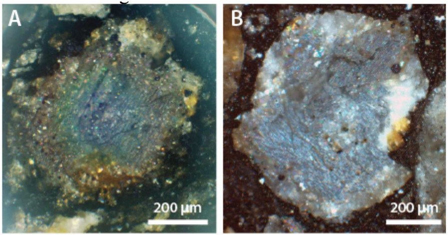


Fig. 1. Crossed-polarized reflected light photomicrographs of two dusty olivine-bearing chondrules measured in this study.

Fu et al. 2014: Semarkona, 0.54 ± 0.21 Gauss imprint from 723 K to 1033 K

Localized Heating and Chondrule Cooling

Chondrule radiative cooling timescale:

$$t_{\rm rad} \sim 10 \text{ s}$$

Chondrule actual cooling timescale:

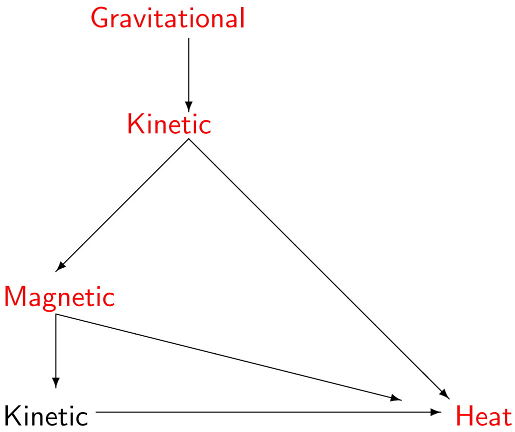
$$t_{\rm cool} \sim 10^5 - 10^6 \text{ s}$$

Orbital timescales:

$$t_{\rm orbit} \sim 10^7 \text{ s}$$

To produce a cooling timescale in between radiative timescale, and orbital timescales, one solution is to use localized heating in the disk.

Follow the Energy



Magnetic Energy

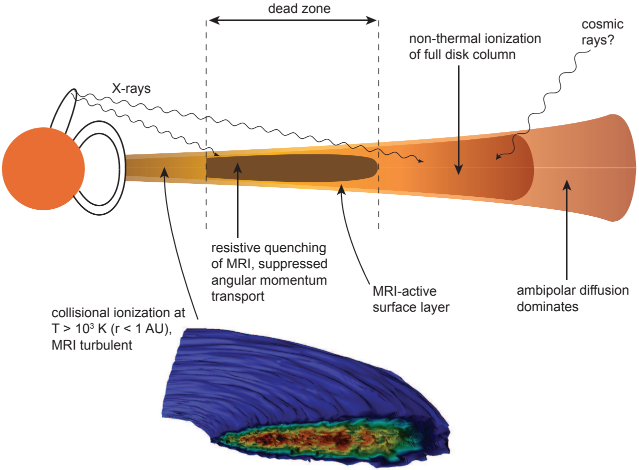
A partial list of proposals for localized heating with magnetic dissipation:

- **Sonnet 1978** heating from relativistic e^- emitted from magnetic reconnection
- **Levy & Araki 1988** magnetic reconnection in disk corona
- **Fleck 1990** magnetic reconnection in the disk midplane
- **King & Pringle 2010** rapid magnetic reconnection driving shocks in the disk midplane
- **Hirose & Turner 2011** 50% heated current sheets in active layer
- **Muranushi, Okuzumi & Inutsuka 2012** MRI-lightning ionization avalanche
- **Hubbard et al. 2012** McNally et al. 2013, "Short-circuit" instability

Questions

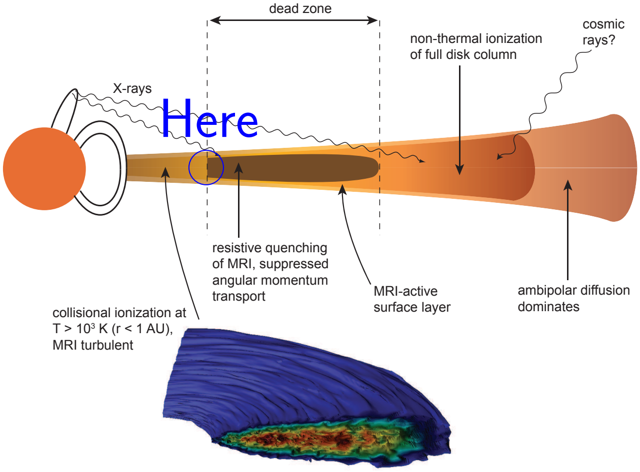
1. Can Ohmic dissipation dominate over shock-heating in disk-like shear flow?
2. What do current sheets in MRI-turbulent disk-like shear flow really look like close up?

Magnetic Field Coupling Regimes



Armitage 2011

Magnetic Field Coupling Regimes



Armitage 2011

An Experiment with Current Sheets

Step back.
Ask a simple question in the simplest physical regime:

- Optically Thick (Radiative diffusion)
- Unstratified local model (Constant thermal relaxation time)
- Net Vertical Field $\lambda_{\mathrm{MRI}} \sim H$
- Constant Ohmic resistivity (Initial Elsasser number $\Lambda_0 = 0.5$)

And then:

- Use lots of resolution (remesh from 64^3 to 512^3)
- Use different numerical methods (Pencil & Athena)

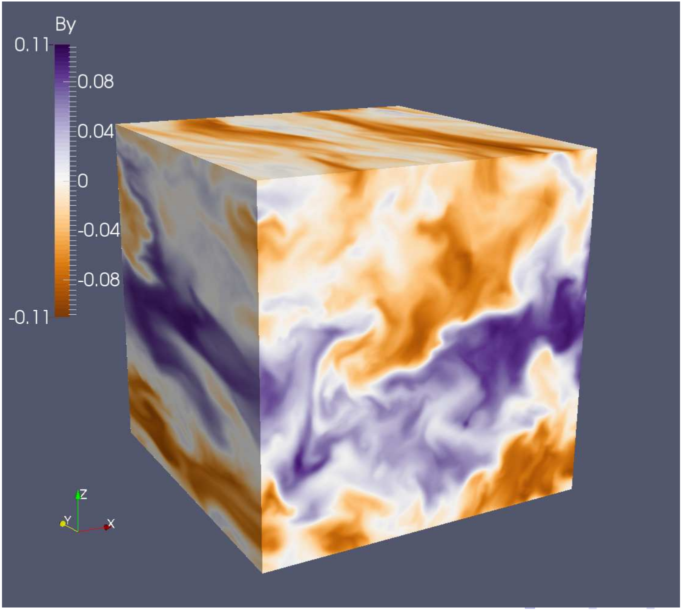
What does the magnetic dissipation produce?

McNally, Hubbard, Mac Low, Yang, 2014

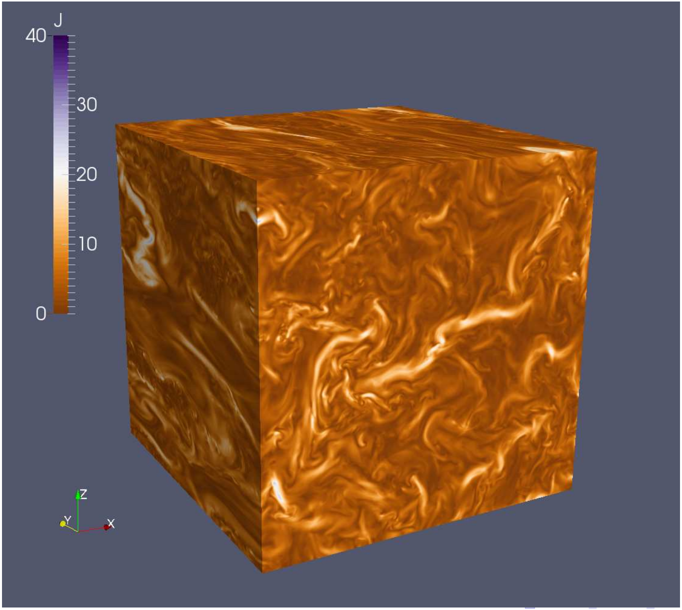
Parameters

Box 1:1:1 - (0.3 AU, 0.3 AU, 0.3 AU) = (4.85H, 4.85H, 4.85H)
Box 4:4:1 - (0.3 AU, 0.3 AU, 0.3 AU) = (4.85H, 4.85H, 1.21H)

	Parameter	Value
ρ_0	Initial density	10^{-9} g cm^{-3}
T_0	Background temperature	950 K
L_x	Box size in x	0.3 AU $4.85H$
Ω_0	Orbital frequency	2π yr^{-1}
r_0	Shearing box position	1 AU
γ	Gas adiabatic Index	1.5
$\bar{m}$	Gas mean particle mass	2.33 amu
η	Ohmic resistivity $c^2/4\pi\sigma$	8.9×10^{14} cm^2 s^{-1} $5.2 \times 10^{-3}\Omega H^2$
β_0	Initial plasma beta	750
v_{A0}	Initial Alfvén speed	9.5×10^3 cm s^{-1} $5.2 \times 10^{-2}\Omega H$
Λ_0	Initial Elsasser number	0.5
κ	Rosseland mean opacity	20 cm^2 g^{-1}
τ_0	Thermal relaxation time	1 yr
$\lambda_{\rm MRI}$	MRI fastest growing mode	5.7×10^{-2} AU $0.92H$



(A)



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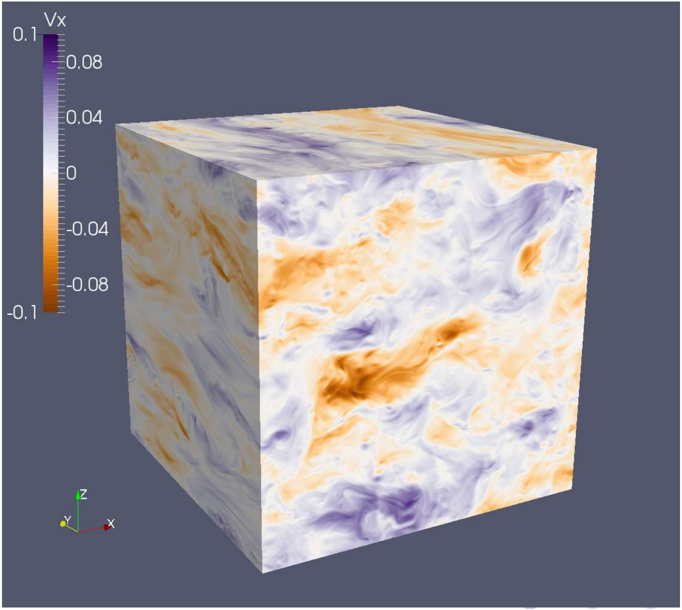

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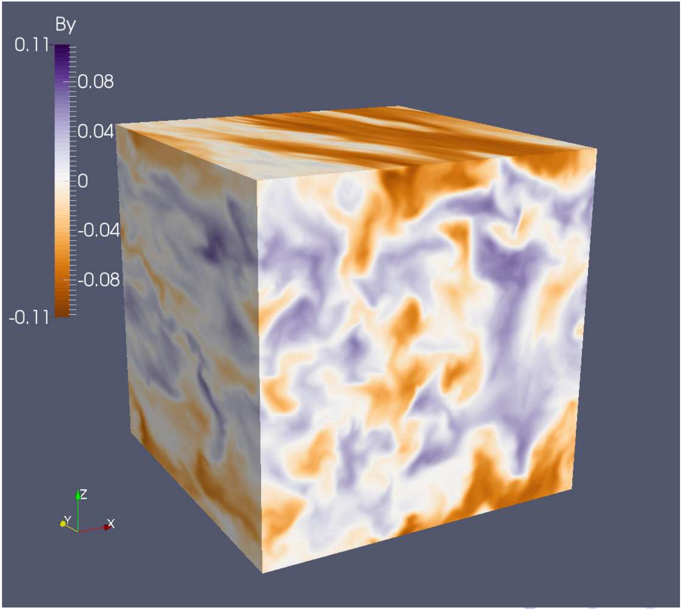

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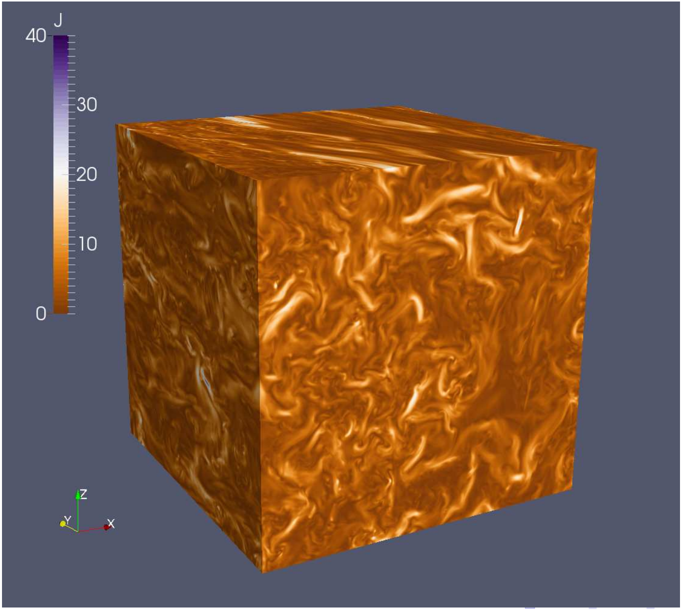

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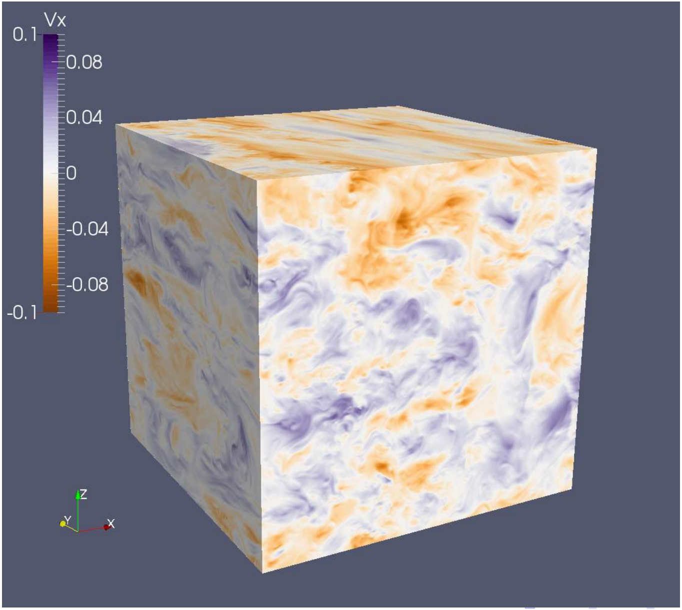

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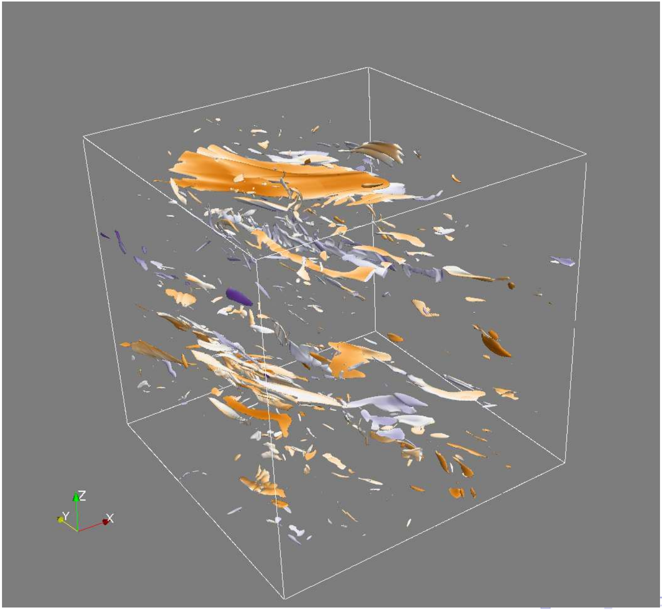
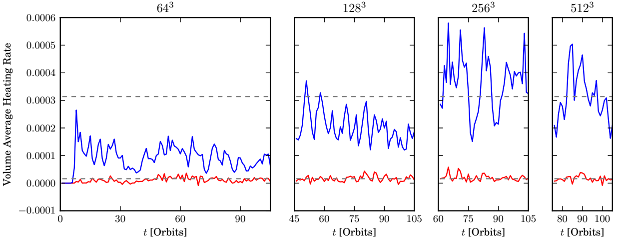
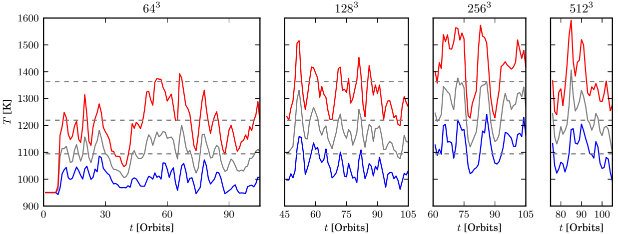
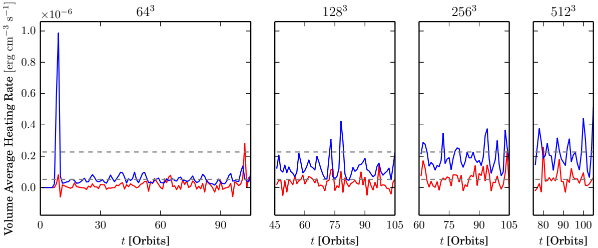

Z
Y
X



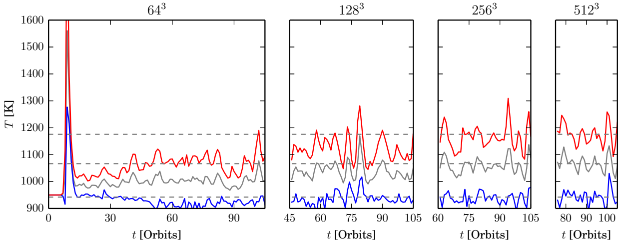
Magnetic Heating dominates Compressive Heating (box 1:1:1)



similar conclusion in MHD turbulence and w/ Prandtl number dependence: Brandenburg, ApJ 791, 12 (2014).

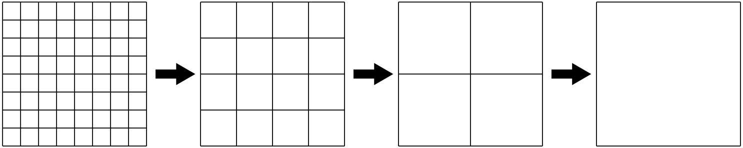


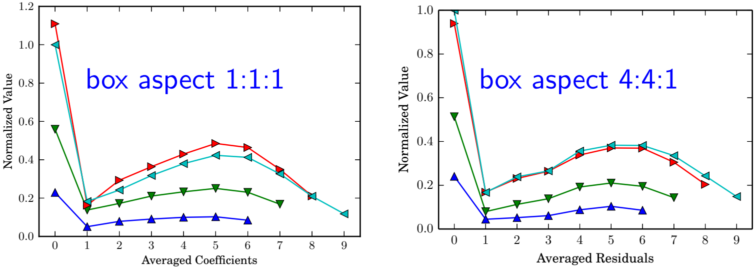
Magnetic Heating dominates Compressive Heating (box 4:4:1)



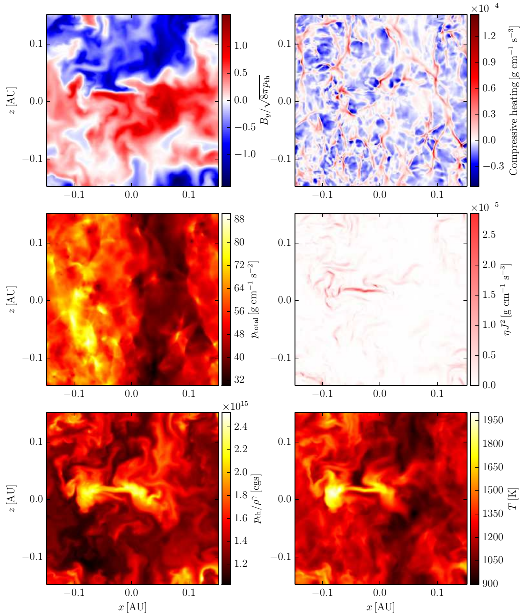
similar conclusion in MHD turbulence and w/ Prandtl number dependence: Brandenburg, ApJ 791, 12 (2014).

Multiresolution analysis of J^2 reveals convergence

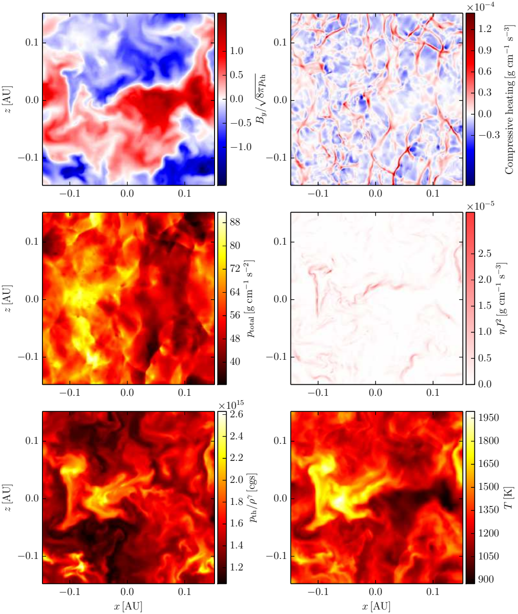




64^3 128^3 256^3 512^3



- Hottest regions are current sheets
- Compressive heating largely reversed by expansion
- Largest current sheet occurs where dominantly azimuthal field reverses
- Current sheets do not stand out in total pressure (thermal + magnetic)



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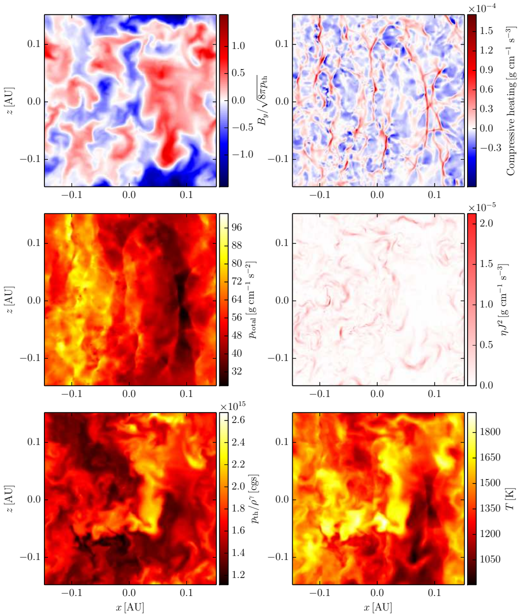

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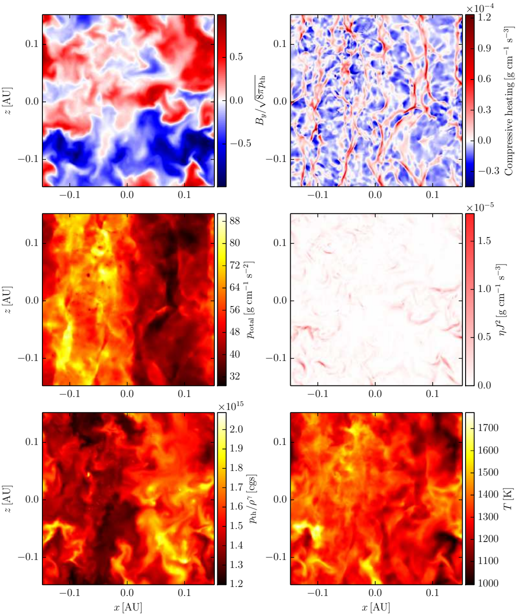

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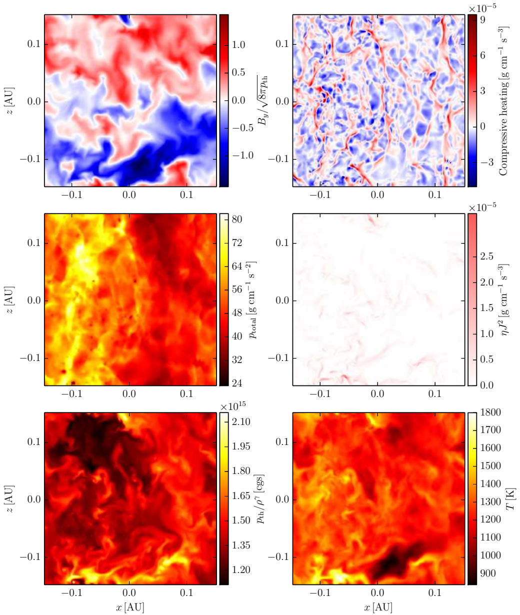

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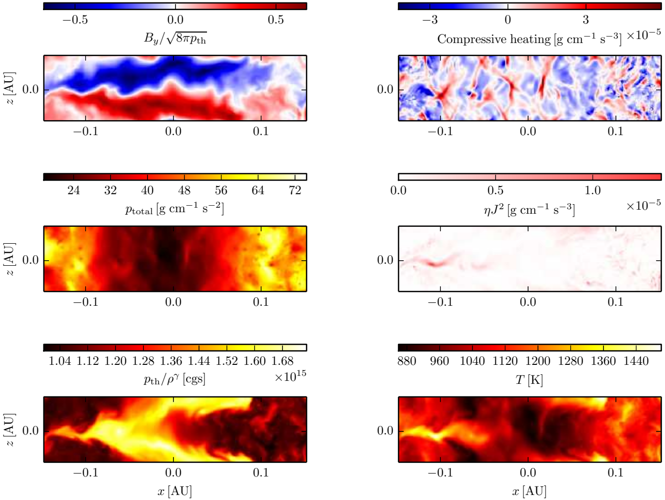
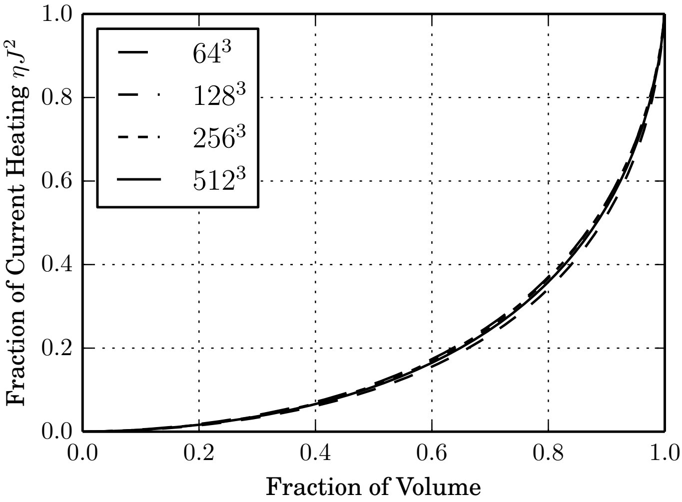
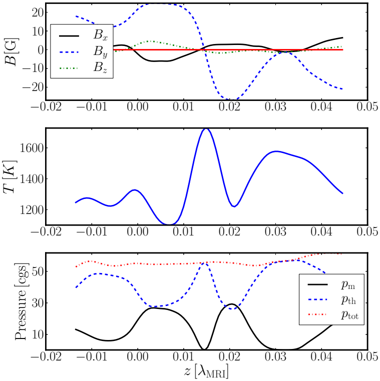
4:4:1 Geometry



Spatial Intermittency of the Heating



Toy model



$$\frac{\partial B_x}{\partial t} = \eta \frac{\partial^2 B_x}{\partial z^2}$$

$$\frac{\partial B_y}{\partial t} = -\frac{3\Omega_0}{2} B_x + \eta \frac{\partial^2 B_y}{\partial z^2}$$

$$B_x(t) = B_0 \exp(-t/\tau) \sin(kz)$$

$$B_y(t) = -B_0 \left(\frac{3\Omega_0 t}{2}\right) \exp(-t/\tau) \sin(kz)$$

If τ_E(Thermal diffusion timescale) $= \tau/2$ then

$$\delta T_{\max} = \frac{9(\gamma - 1)}{4 \exp(1) \beta_p} T_0$$

In simulation, gives $\delta T_{\max}/T_0 \approx 0.4$

Subconclusions

Caveats

- Unstratified, zero net flux, optically thick approach is limited
- Radially local approach cannot track the movement of the edge of dead zone regime (Faure, Fromang, Latter 2014)
- No variation of η and κ - should respond to thermal ionization and grain destruction

Other Conclusions

- Required ~ 50 zones per scale height with Pencil (6th order in space) to resolve current sheets even with maximal resistivity
- Remelting of compact CAIs could occur in a regime like the one modeled (Stolper & Paque 1986, Scott & Krot 2005)
- Temperature fluctuations would broaden ice lines
  - if $T \propto R^{-1/2}$ then radial variation $= 2\times$ temperature variation

Short Circuit Instability - Hubbard et al. 2012

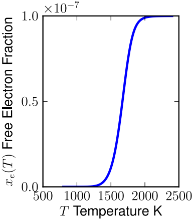
Ingredients in a Short-Circuit:

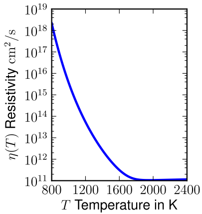
Induction Equation: $$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}) - \nabla \times (\eta(T)\mathbf{J})$$

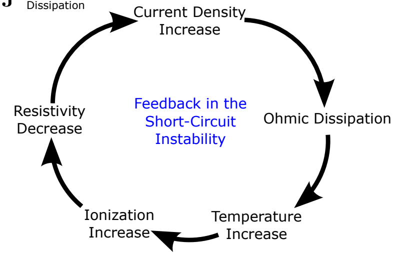
Energy Equation: $$\frac{\partial T}{\partial t} = -\nabla \cdot (T\mathbf{v}) - c_T P \nabla \cdot \mathbf{v} + \frac{c_T \eta}{4\pi\rho}\mathbf{J}^2$$

(Ohmic Dissipation)

Resistivity dependence on temperature:







How Fast?

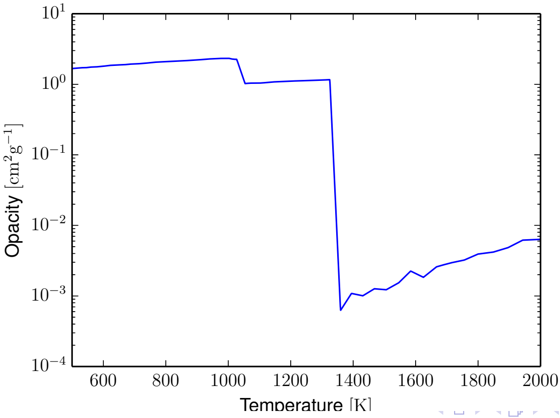
$$\partial_t \mathbf{B} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B} - \nabla(\nabla\eta \cdot \mathbf{B}) + (\mathbf{B} \cdot \nabla)\nabla\eta - (-\nabla\eta \cdot \nabla)\mathbf{B}$$

- $-\nabla\eta$ behaves like an anti-diffusion
- Thermal ionization of alkali metals (K, Na) has exponential T dependence
- in 1D runs, see $-\nabla\eta \sim 10^4$ cm/s

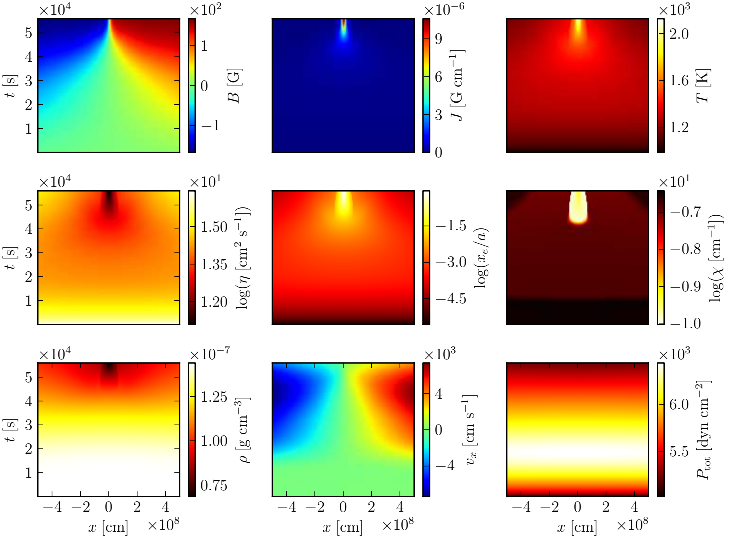
(What about if η increases in the current sheet?)

What limits the instability?

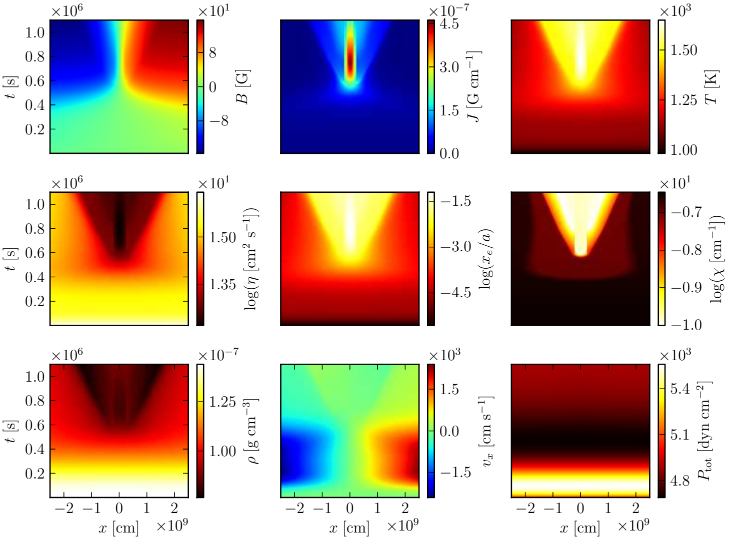
Presence of temperature gradient dependent on opacity, which is in turn strongly temperature dependent. (D'Alessio 2001)



Not Limited by Cooling McNally et al. 2013



Limited by Cooling (silicate grain destruction) McNally et al. 2013



Conclusions

- Current sheets can drive significant (order-unity) temperature fluctuations in protoplanetary disks (optically thick region).
- The local variations of conductivities and opacities can both enhance and limit the heating in current sheets.
- Fluctuations can be large enough that they ought to have consequences for thermal processing of solids.
- Functional dependence and form of η and κ can be critical.

Wishlist:

- Zero net flux current sheet study
- Stratified current sheet study
- Track particles though the current sheets
- Follow current sheets later in time