Temperature Fluctuations and Current Sheets in Protoplanetary Disks

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Accretion Releases lots of Energy

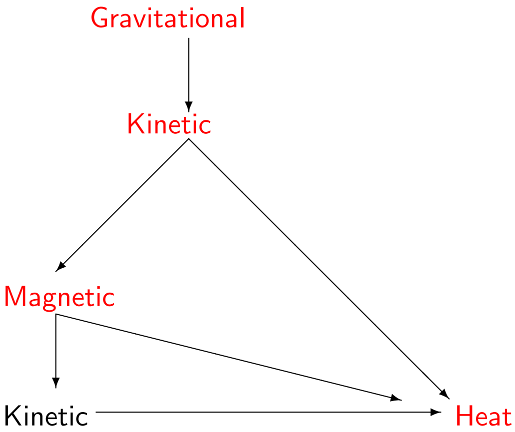
An estimate of energy requirement for thermal processing from chondritic material (King & Pringle 2010):

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

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

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

Follow the Energy



Magnetic Energy

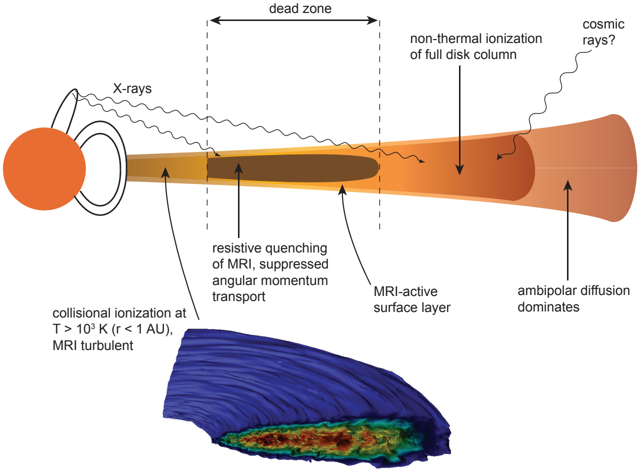
A partial list of proposals for localized heating with magnetic dissipation:

- 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

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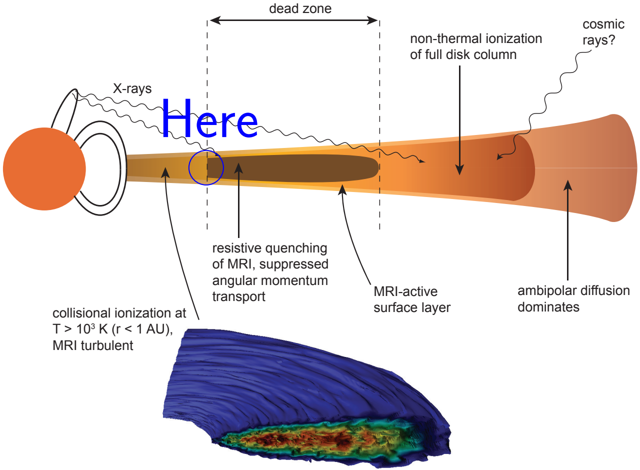


Armitage 2011

An Experiment with Current Sheets

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

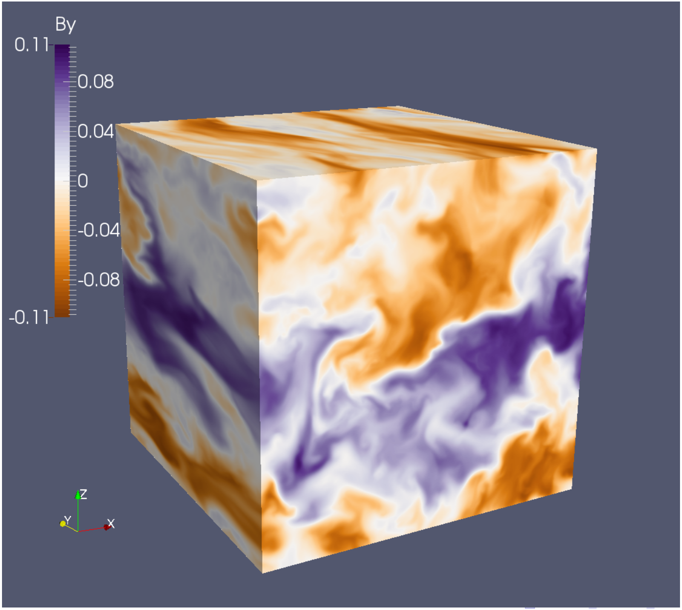
- Optically Thick (Radiative diffusion)
- Unstratified local model (Constant thermal relaxation time)
- Net Vertical Field $\lambda_{\mathrm{MRI}} \sim H$
- Constant Ohmic resistivity (Initial Elsasser number $\Lambda_0 = 0.5$)

And then:

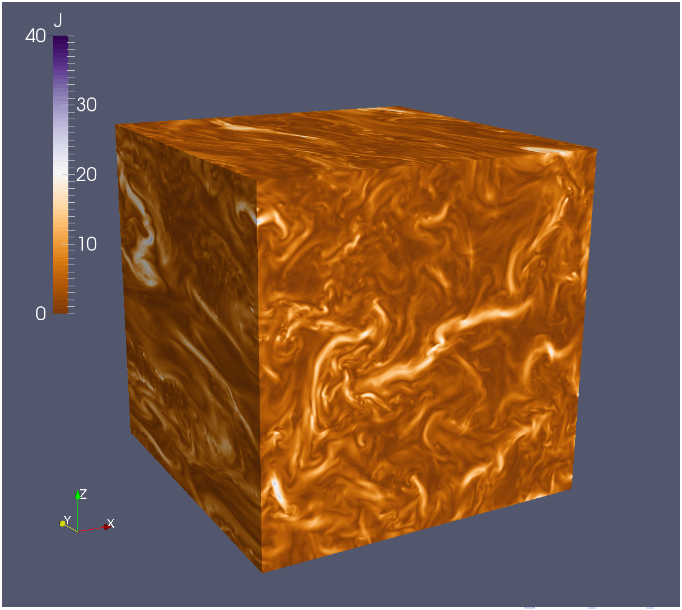
- Use lots of resolution (remesh from 64^3 to 512^3)
- Use different numerical methods (Pencil & Athena)

What does the magnetic dissipation produce?

McNally, Hubbard, Mac Low, Yang, 2014



(A)



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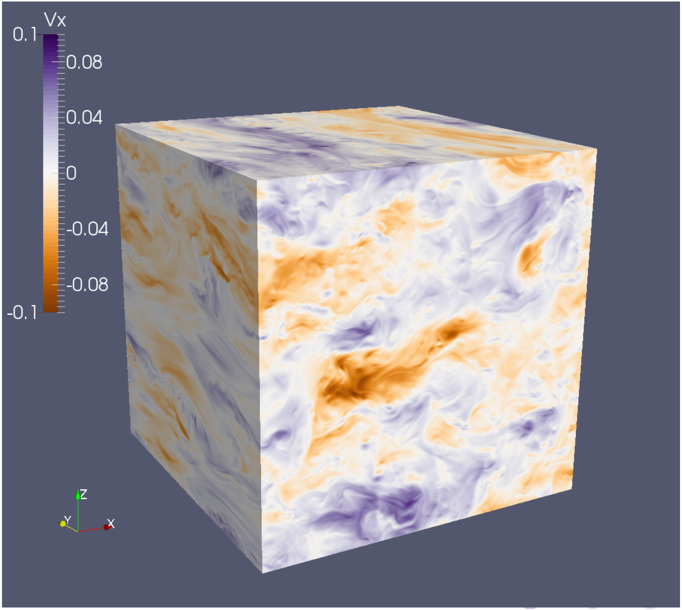

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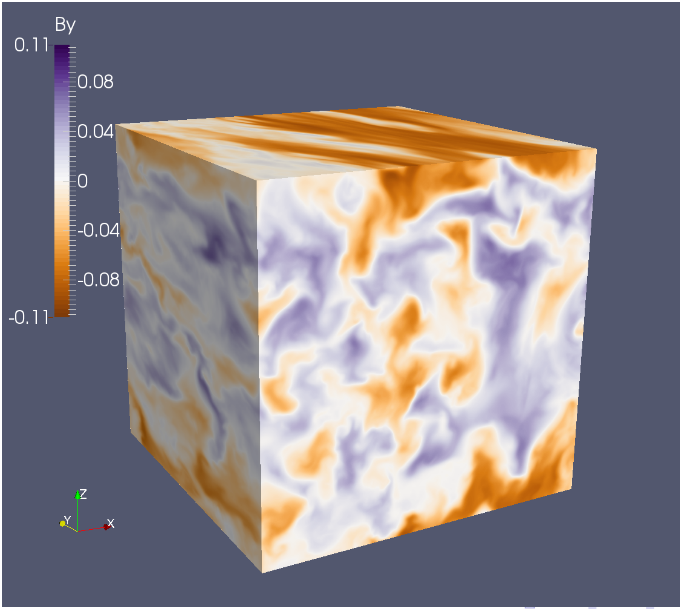
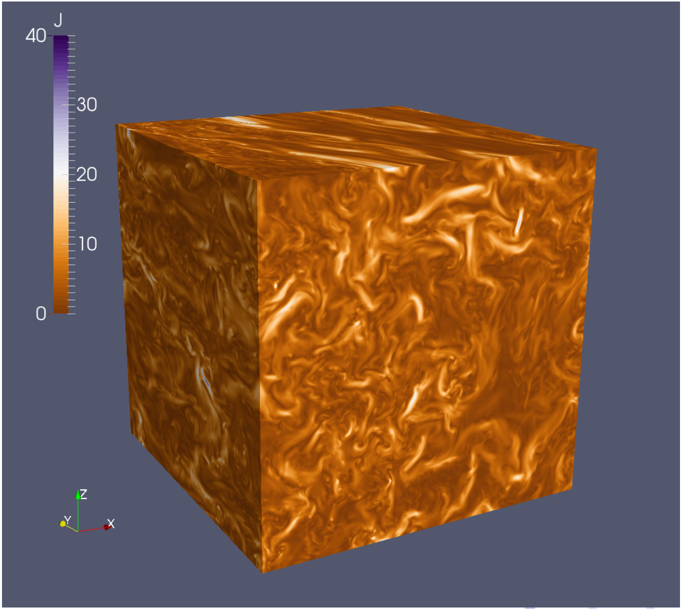


(B)



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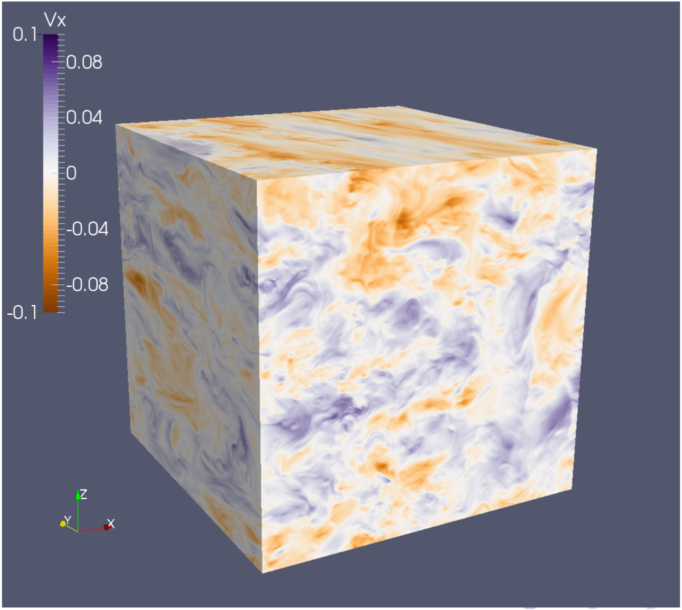

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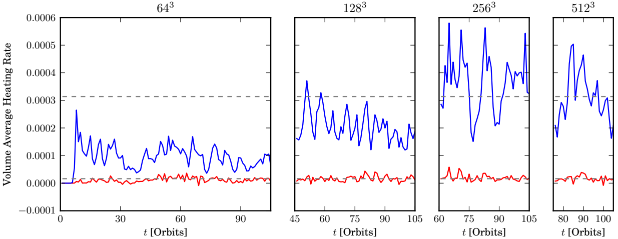
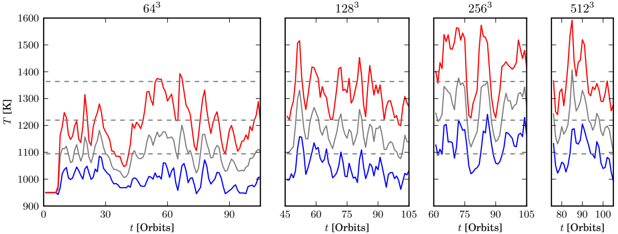
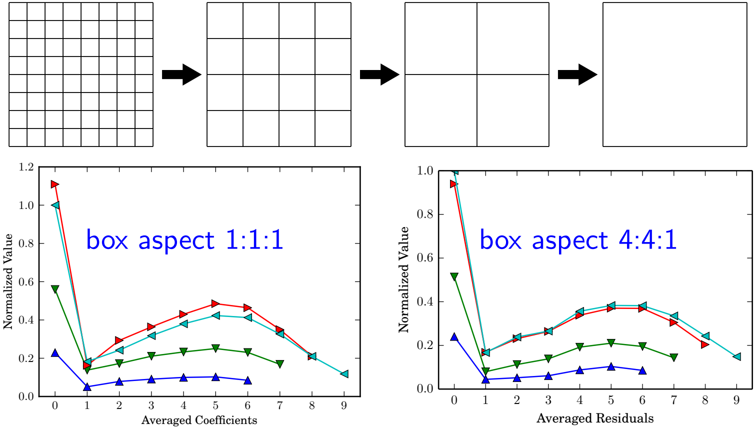


Magnetic Heating dominates Compressive Heating (box 1:1:1)

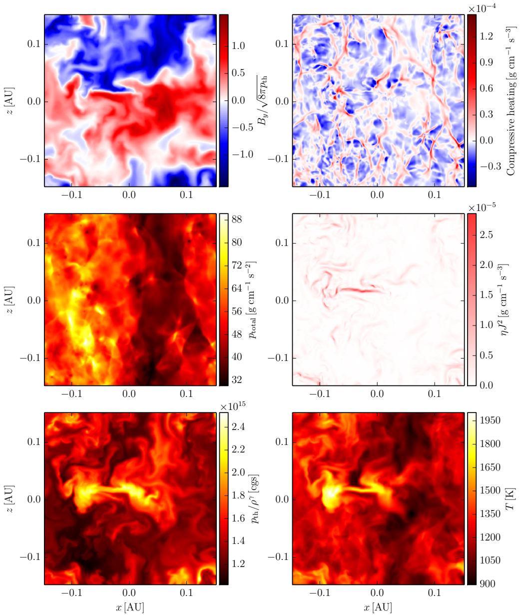


similar conclusion in MHD turbulence and w/ Prandtl number dependence: Brandenburg, ApJ 791, 12 (2014).

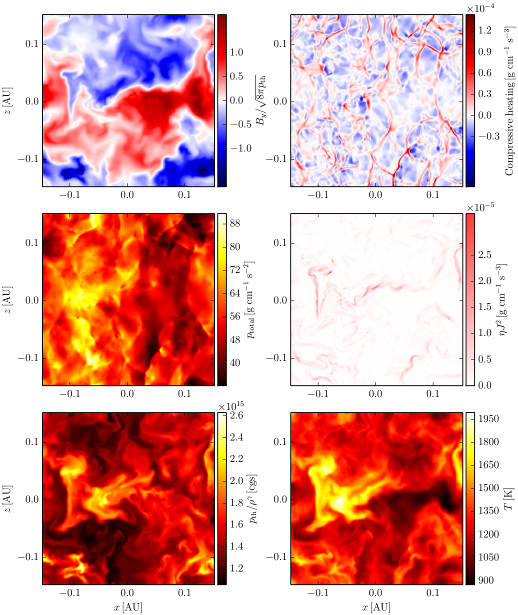
Multiresolution analysis of J^2 reveals convergence



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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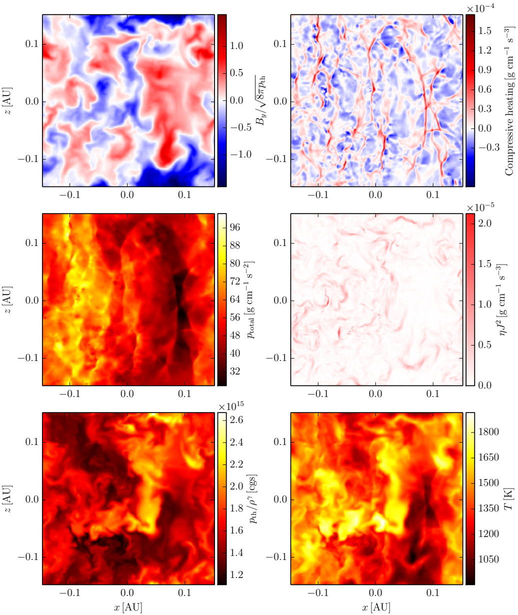

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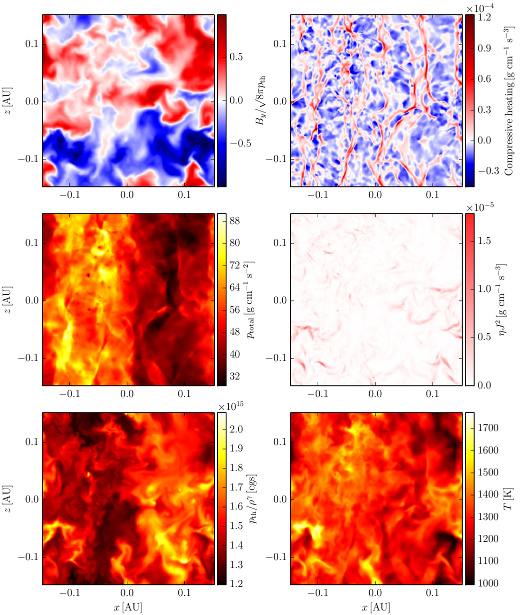

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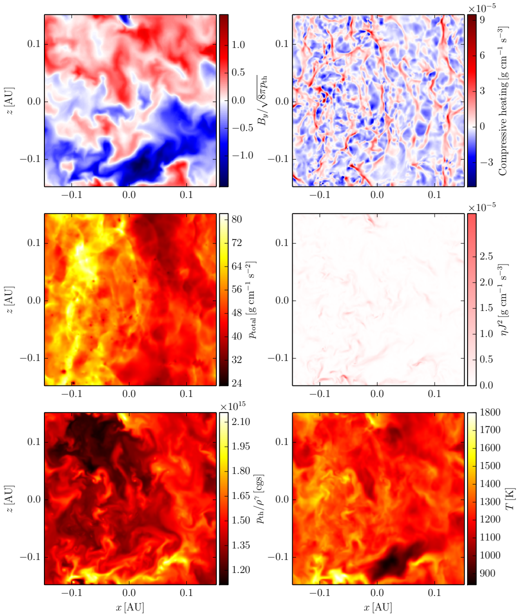

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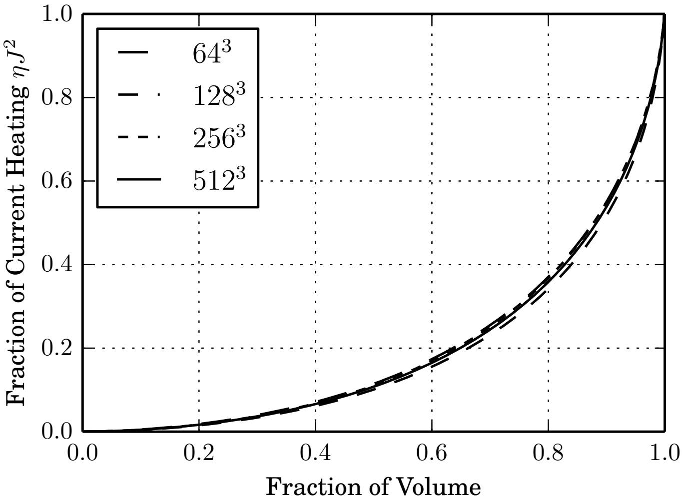
Spatial Intermittency of the Heating



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

Conclusions

McNally, Hubbard, Mac Low, Yang (2014) 2014ApJ...791...62M

- Current sheet heating (Ohmic) is spatially intermittent even in the highly resistive regime
- Current sheets are able to overtake compression as primary driver of temperature fluctuations in protoplanetary disks
- Current sheets can drive significant (order-unity) temperature fluctuations in protoplanetary disks (optically thick region)
- Fluctuations can be large enough that they ought to have consequences for the thermal processing of solids.]

This work motivated by solid processing, but what about gas phase chemistry and emission lines?

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:

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

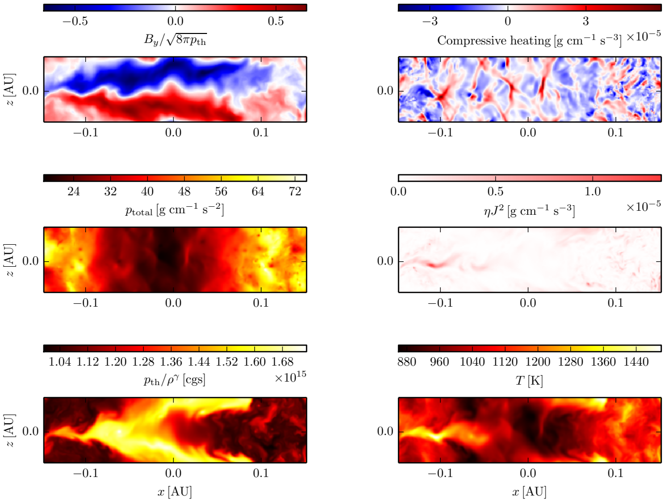
To produce a cooling timescale in between radiative timescale, and orbital timescales, one solution is to use localized heating in the disk.

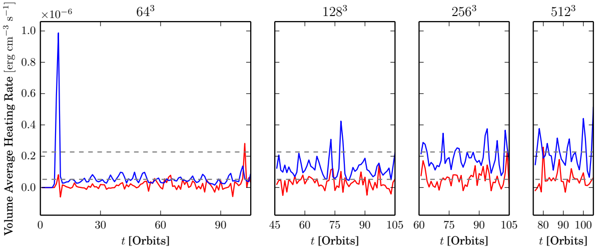
Parameters

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)

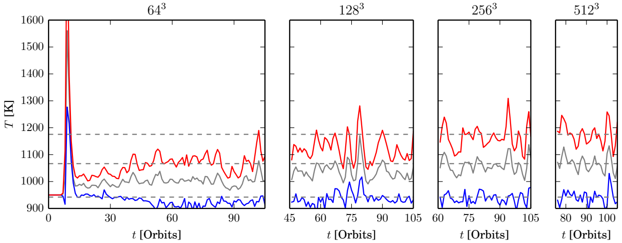
	Parameter	Value
ρ_0	Initial density	10^{-9} g cm^{-3}
T_0	Background temperature	950 K
L_x	Box size in x	0.3 AU
		$4.85H$
Ω_0	Orbital frequency	2π yr^{-1}
r_0	Shearing box position	1 AU
γ	Gas adiabatic Index	1.5
$\bar{m}$	Gas mean particle mass	2.33 amu
η	Ohmic resistivity $c^2/4\pi\sigma$	8.9×10^{14} 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
		$0.92H$

4:4:1 Geometry





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



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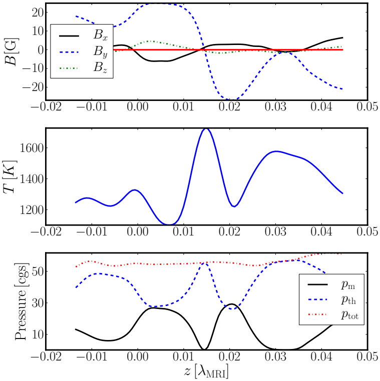
Toy model



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

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

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

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

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 $\delta T_{\max}/T_0 \approx 0.4$

Wishlist:

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