New MHD Simulations of radiation-dominated accretion

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We solve equations of radiation MHD

Euler equations + Maxwell's equations + moment equations.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v} + P + B^2/2 - \mathbf{B}\mathbf{B}) = -\mathbb{P}\mathbf{S_M}$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E+P)\mathbf{v} + (B^2/2)\mathbf{v} - \mathbf{B}(\mathbf{B}\cdot\mathbf{v})] = -\mathbb{P}\mathbb{C}S_E$$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) = 0$$

$$\frac{\partial E_r}{\partial t} + \mathbb{C}\nabla \cdot \mathbf{F}_r = \mathbb{C}S_E$$

$$\frac{\partial \mathbf{F}_r}{\partial t} + \mathbb{C}\nabla \cdot \mathsf{P}_r = \mathbb{C}\mathbf{S_M}$$

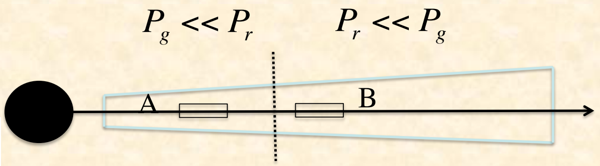
E_r, F_r, P_r are radiation energy density, flux, pressure in Eulerian frame. Source terms are O(v/c) expansion of material-radiation interaction terms in fluid frame (Lowrie et al 1999).

Numerical Methods

- Compute closure relation **P=fE** directly
  - Variable Eddington tensor (VET) **f** calculated from "snap-shot" solution of time-independent transfer equation using short characteristics.
- Source terms can be very stiff
  - Use modified Godunov method for stability
- Wide range of timescales associated with v, C_s, c
  - Requires fully implicit (backward Euler) differencing of radiation moment equations

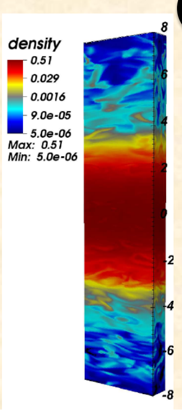
Each of these three ingredients are implemented in a new radiation module in the Athena MHD code. Davis, Stone, & Jiang 2012
Jiang, Stone, & Davis 2012

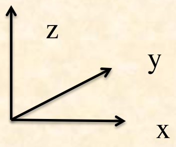
Local shearing-box simulations of radiation dominated accretion disks



Electron scattering dominates.

Free-free absorption dominates.





Shearing box

Box size: Hx4Hx16H
Resolution: 32/H – 64/H

Parameters

Turner 2004; Hirose et al 2009

Radiation pressure dominated regime

Table 1:: Location A

Parameters	Value	Comment
M	$6.62 M_\odot$	Mass of Central Black Hole
r	$30\,(GM/c^2)$	Radius
ρ_0	5.66×10^{-2} g cm^{-3}	Initial Mid-plane density
T_0	2.45×10^7 K	Initial Mid-plane temperature
τ	3.514×10^4	Total Electron Scattering Optical Depth

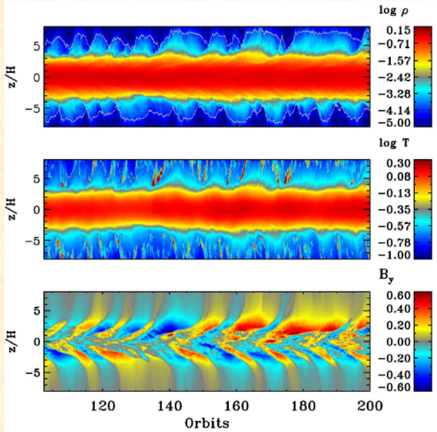
Gas pressure dominated regime

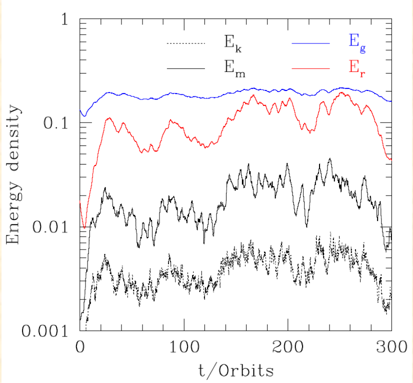
Table 2:: Location B

Parameters	Value	Comment
M	$6.62 M_\odot$	Mass of Central Black Hole
r	$300\,(GM/c^2)$	Radius
ρ_0	1.12×10^{-2} g cm^{-3}	Initial Mid-plane density
T_0	2.89×10^6 K	Initial Mid-plane temperature
τ	1.06×10^4	Total Electron Scattering Optical Depth

A: gas pressure dominated case

Space-time diagram

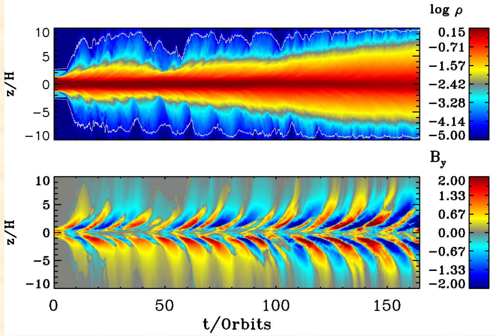


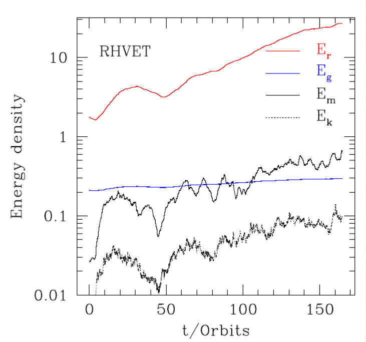


Stable solution

B: radiation dominated case ($P_{rad}/P_{gas} = 4.13$)

Space-time diagram

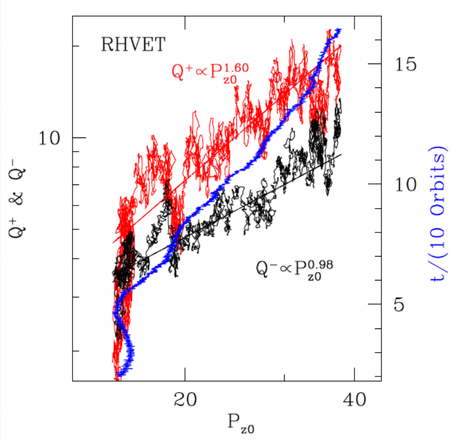




Thermal runaway: energy increases with time.

Stop calculation when photosphere hits boundary.
Restart with taller box and energy continues to increase…

Heating and Cooling Rates



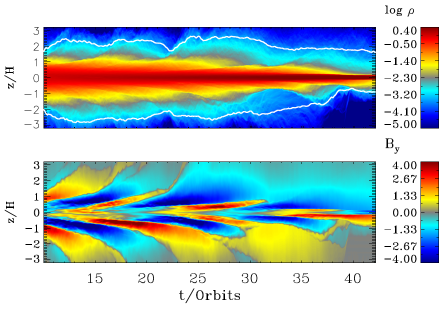
Instability criterion:

$$\left.\frac{\partial \log Q^+}{\partial \log P_t}\right|_\Sigma > \left.\frac{\partial \log Q^-}{\partial \log P_t}\right|_\Sigma$$

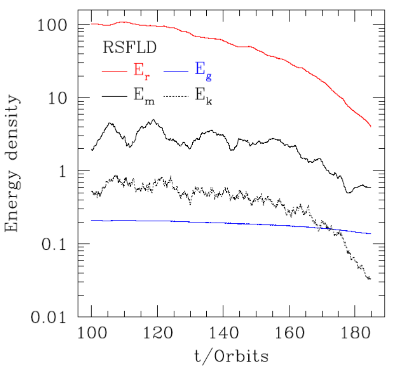
Instability criterion satisfied, however the exact scaling differs from standard α model.

Lower surface density (P_{rad}/P_{gas}=206)

Space-time diagram



Calculation with VET:
Thermal runaway; disk collapses



Calculation with FLD in Athena:
Thermal runaway; disk collapses

Must stop both calculations when disk is too thin to be resolved.

Is this the SS76 thermal instability?

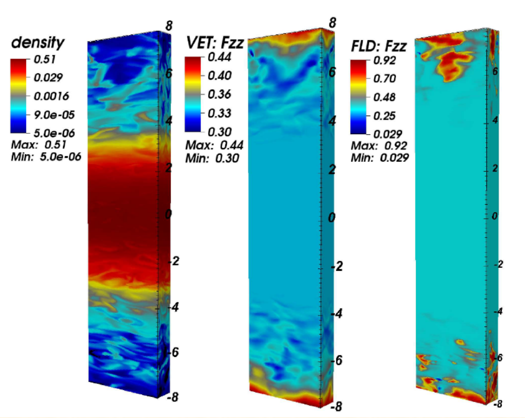
- None of the assumptions in the SS76 model apply
  - Disk is turbulent: linear analysis cannot be applied
  - No exponential runaway
  - Stress not directly proportional to midplane pressure
  - Vertical distribution of dissipation not proportional to density
  - Advective flux of radiation non-negligible in many cases

Physics of runaway is different than SS76 model.

Why do our results differ from those of Hirose et al. (2006; 2009) computed using FLD?

There seems to be two differences:

(1) Radiative transfer algorithm does matter.

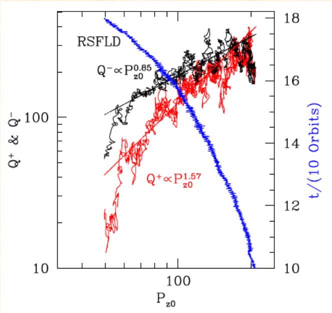


Get different profiles for Eddington tensor using FLD versus VET

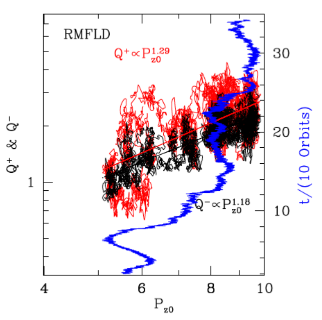
Why do our results differ from those of Hirose et al. (2006; 2009) computed using FLD?

There seems to be two differences:

(2) Small domains make evolution with FLD stable.



FLD in large domain
(H x 4H x 16H): *collapse*



FLD in small domain
(H/2 x 2H x 16H): *stable*

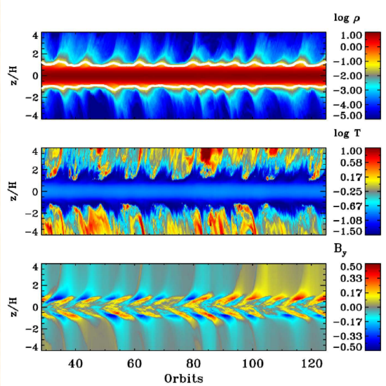
Accretion disk coronae

With MRI turbulence, dissipation decreases more slowly with vertical height than density.

- Dissipation can occur above the photosphere, leading to hot corona

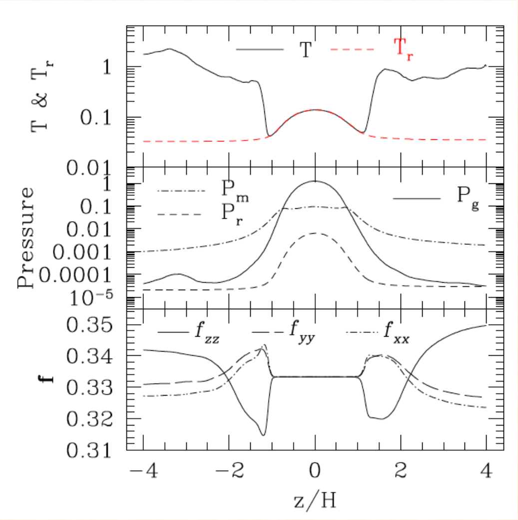
Low surface density, gas pressure dominated disk.

Total optical depth = 286



See also Blaes et al. (2006); Hirose et al. (2009)

Vertical profiles: hot coronae



Summary

- Developed a new algorithm for radiation MHD that does not adopt an arbitrary closure, but instead is based on a formal solution of the transfer equation.
- We find radiation dominated disks always undergo thermal runaway.
- Physics of runaway is different than SS76.
- Global simulations are *absolutely essential* to understand outcome of runaway.