Convection Modifies MHD Turbulence in Accretion Disks

Matthew Coleman

Ph.D. Candidate
University of California, Santa Barbara
Department of Physics
`mcoleman@physics.ucsb.edu`

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KITP

Disks, Dynamos, and Data:
Confronting MHD Accretion Theory with Observations

Collaborators:

Omer Blaes	Iwona Kotko	Greg Salvesen
Shigenobu Hirose	Julian Krolik	Takayoshi Sano
Yan-Fei Jiang	Jean-Pierre Lasota	Evan Yerger

Outline

1. Context
    - Accretion Disk Theory
    - Dwarf Novae
2. Convective Accretion Disks
    - Convection Enhances α
    - Convection Quenches Magnetic Field Reversals
3. Observational Implications (Lightcurves)
4. Summary

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α-Disk Model

Shakura & Sunyaev (1973)

$$\alpha \equiv \frac{\langle \text{stress} \rangle_z}{\langle \text{pressure} \rangle_z} = \frac{\int_{-\infty}^{\infty} w_{r\phi}\, dz}{\int_{-\infty}^{\infty} p\, dz} \equiv \frac{W_{r\phi}}{\int_{-\infty}^{\infty} p\, dz}$$

- Prescription to estimate turbulent stresses
  - Turbulent stresses can also be thought of as an effective viscosity

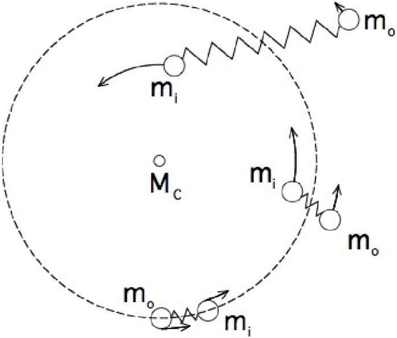
$$\bar{\nu}_{\mathrm{eff}} = \frac{2}{3}\frac{W_{r\phi}}{\Sigma\Omega} = \frac{2}{3}\alpha\frac{\int_{-\infty}^{\infty} p\, dz}{\Sigma\Omega}$$

- Allows us to approximate the structure of disks

Source of Stress

$$w_{\mathrm{r}\phi} = -\frac{B_\mathrm{r} B_\phi}{4\pi} + \rho v_\mathrm{r} \delta v_\phi$$

- Magnetorotational Instability (MRI)
  - Generates turbulent stress
  - Can be simulated



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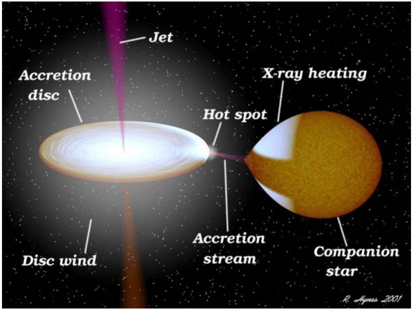
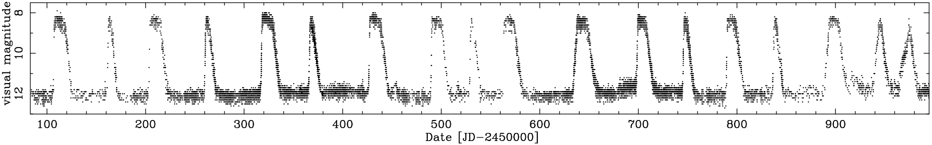
Dwarf Novae

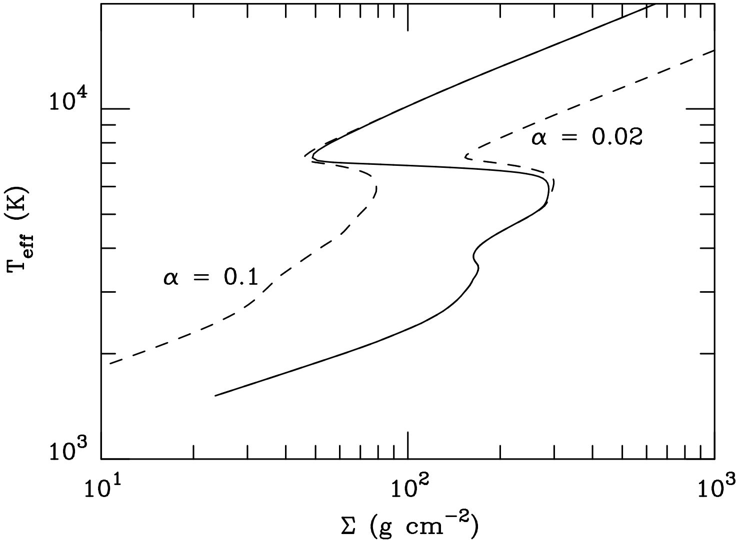
- DNe are white dwarfs in binaries (Cataclysmic variables)
- Powered by thermal instability in the accretion disk
- Extremely well studied
    - SS Cygni was discovered in 1896





SS Cygni (Wheatley et al., 2003)

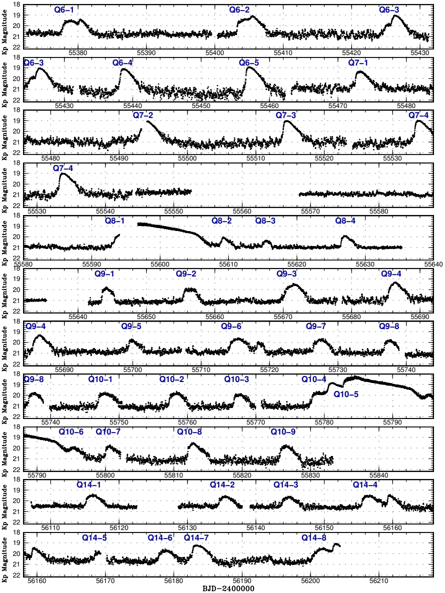
S-curve



Lasota (2001)

Dwarf Novae can Illuminate the Underlying Physics

- Wealth of data
    - Kepler data
- Properties of steady state disks are insensitive to α
    - Time variations give α
- The mechanism which determines α is not well understood
- Previous accretion disk simulations give $\alpha \sim 0.01$
    - These lay outside the dwarf nova regime



Kato & Osaki (2013)

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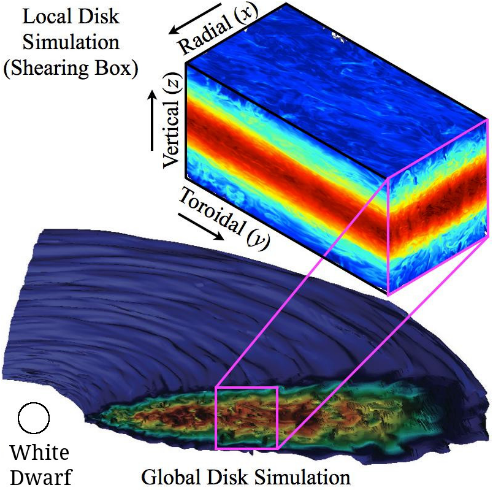
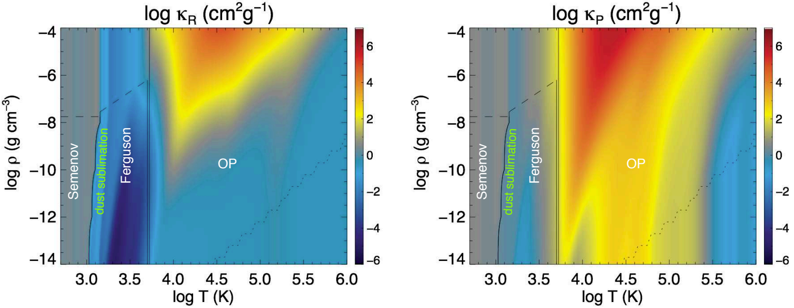
Simulations Methods

- Modified ZEUS code
- Ideal MHD
- Flux limited diffusion
- Stratified shearing box geometry
- Initial conditions based on 1D model
- Realistic dust free opacity
- Realistic equation of state

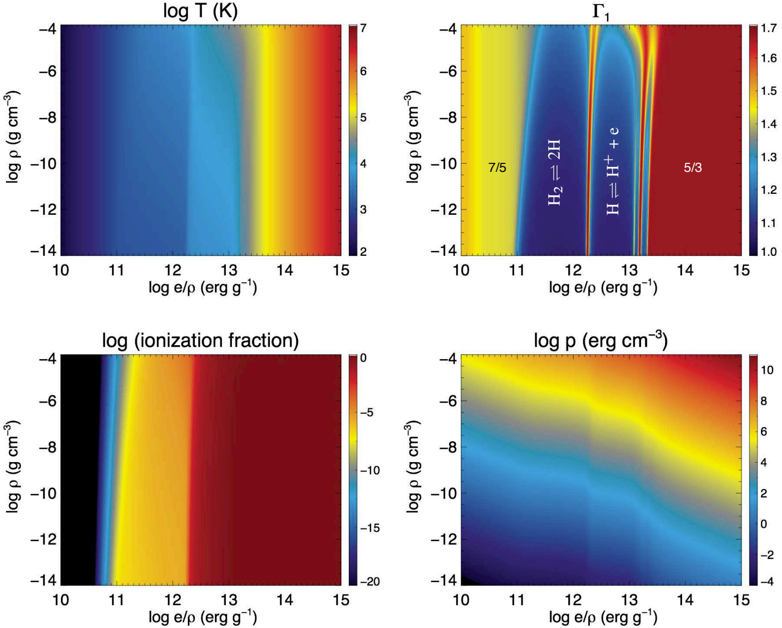


Opacity Tables

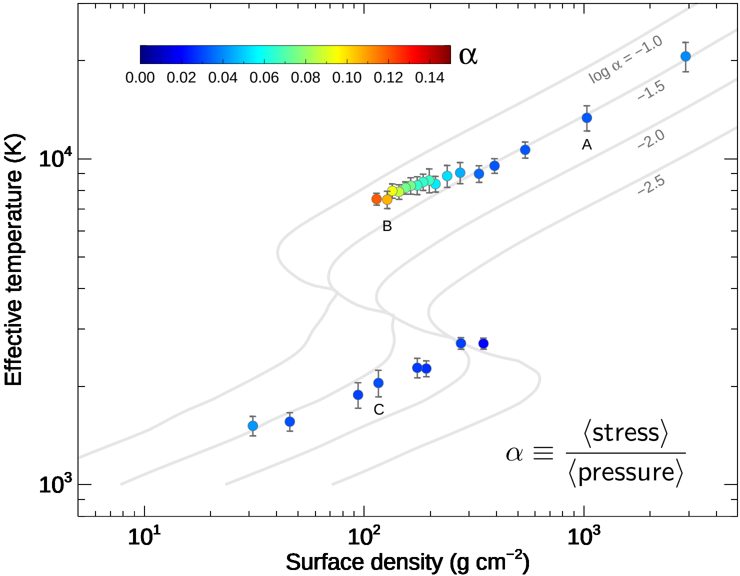


Mean opacities combining three published opacity tables by Semenov et al. (2003), Ferguson et al. (2005) and the Opacity Project (OPCD_3.3).

Equation of State



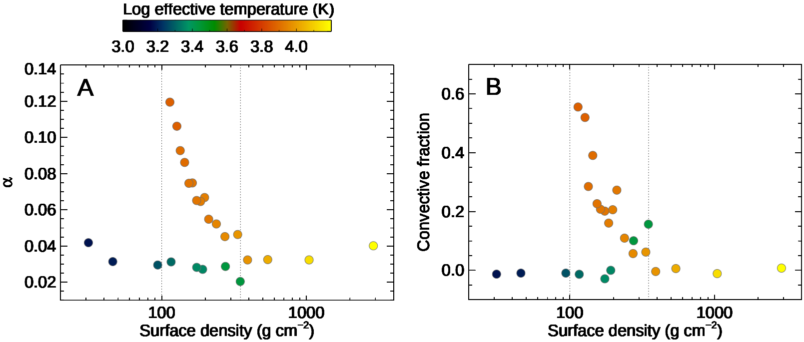
Simulation S-curve



$$\alpha \equiv \frac{\langle \text{stress} \rangle}{\langle \text{pressure} \rangle}$$

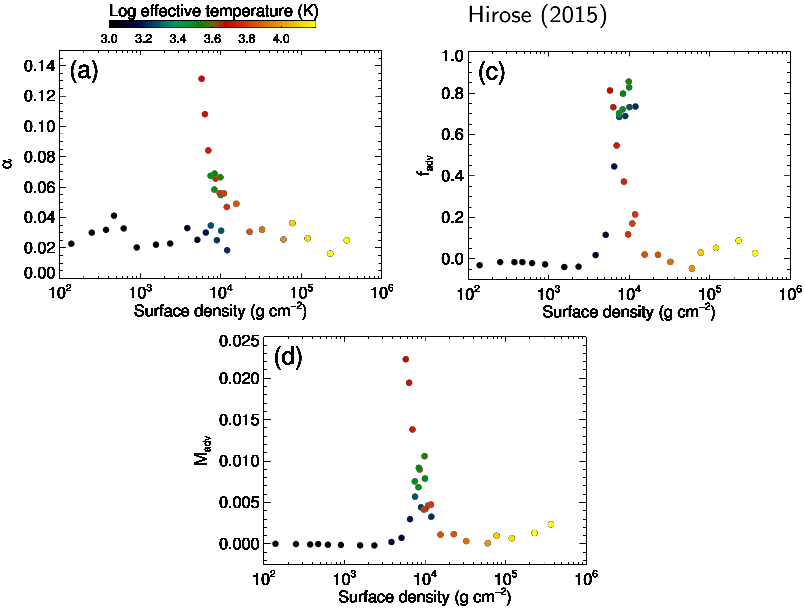
Hirose et al. (2014)

Convection Enhances α



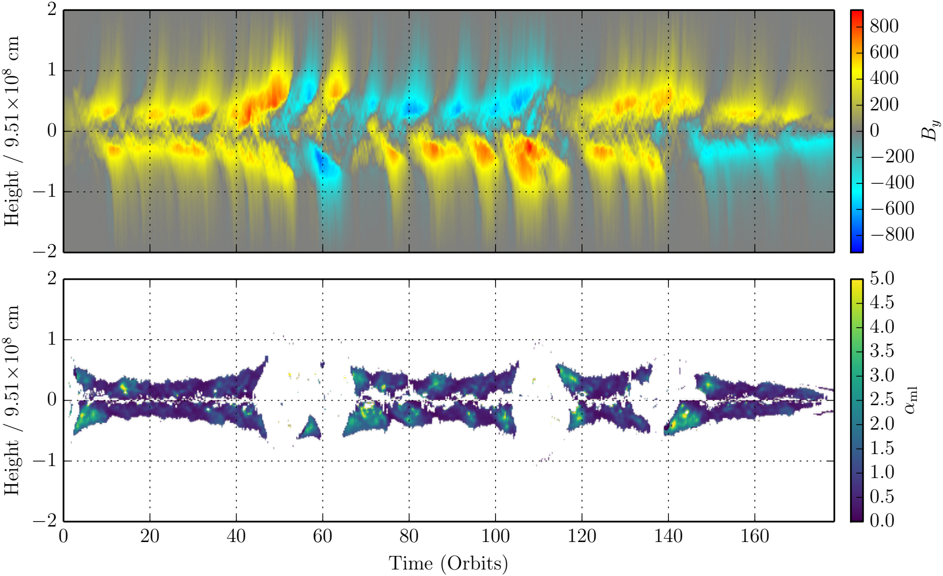
Hirose et al. (2014)

Convection Enhances α in FU Ori

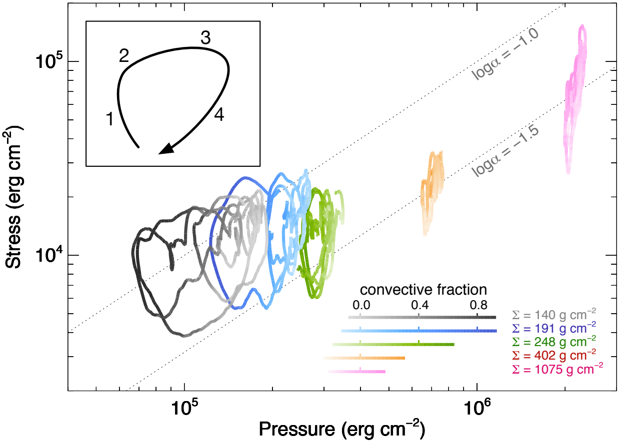


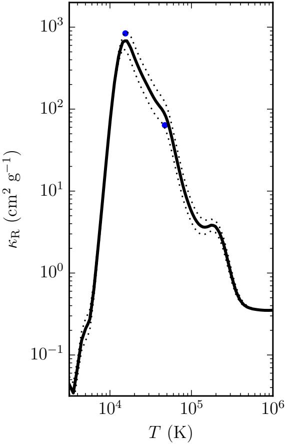
Hirose (2015)

Intermittent Convection



Convective Limit Cycle





Hirose et al. (2014)

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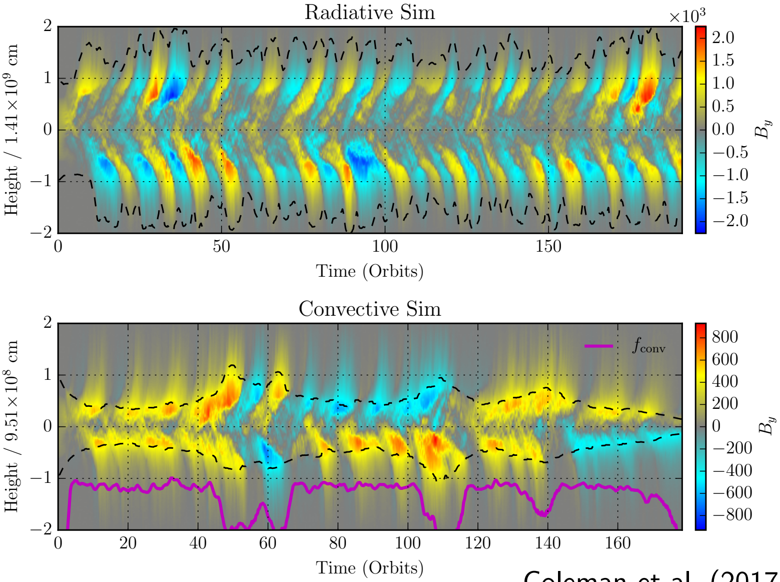
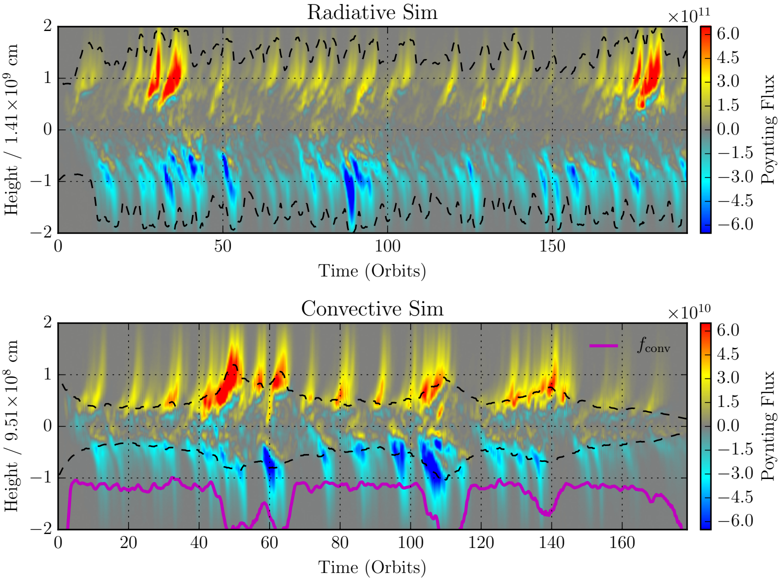
Magnetic Dynamos and the Butterfly Diagram

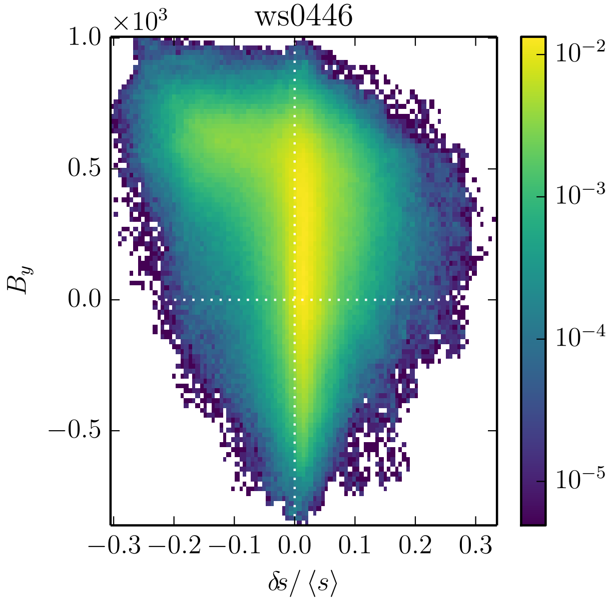


Coleman et al. (2017)

Poynting Flux



Convection Drags Magnetic Field



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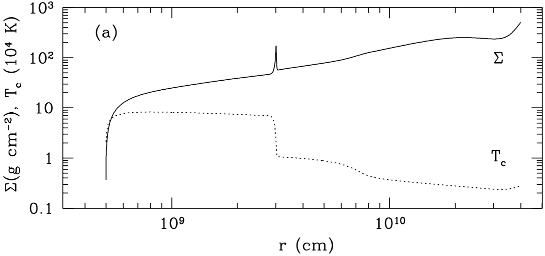
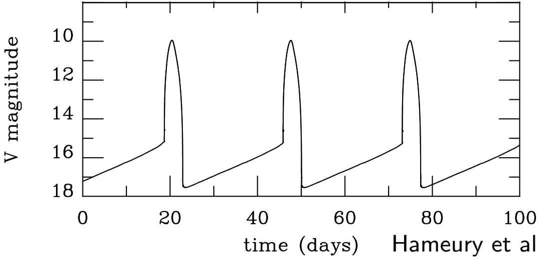
Disk Instability Model

- Developed by Jean-Marie Hameury and Guillaume Dubus
- Uses library of equilibrium vertical structures to determine how adjacent annuli in the disk communicate.





Hameury et al. (1998)

Improving Vertical Structures

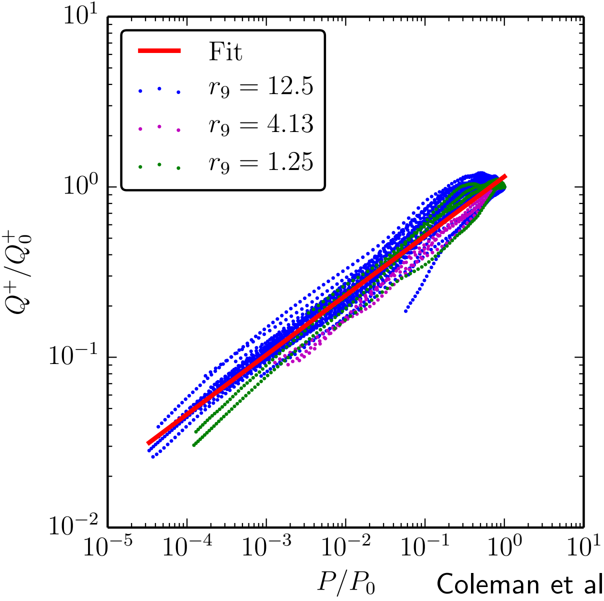
Existing Models

- $Q^{+}(z) = \frac{3}{2}\alpha\Omega P(z)$
- Lack description of magnetic pressure
- $\alpha\left(T_0\right) \approx \begin{cases} \alpha_{\rm hot} & T_0 > T_{\rm c} \\ \alpha_{\rm cold} & T_0 < T_{\rm c} \end{cases}$
- Mixing length based on Sun

Modified Models

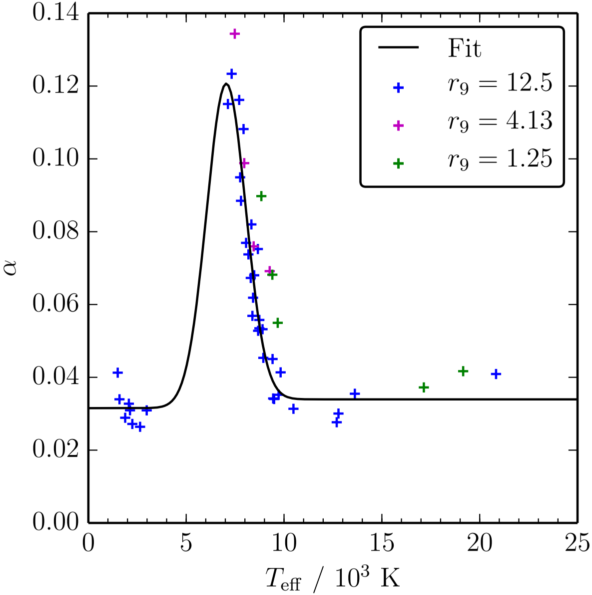
- $Q^{+}(z) \propto P(z)^{\beta}$
  - $\beta \approx 0.35$
- Still lacks magnetic pressure
- $\alpha\left(T_{\rm eff}\right) = \alpha_{\rm sim}\left(T_{\rm eff}\right)$
- Mixing length based on time-averaged DN simulations ($\alpha_{ml} = 6$)

Simulation Profile data

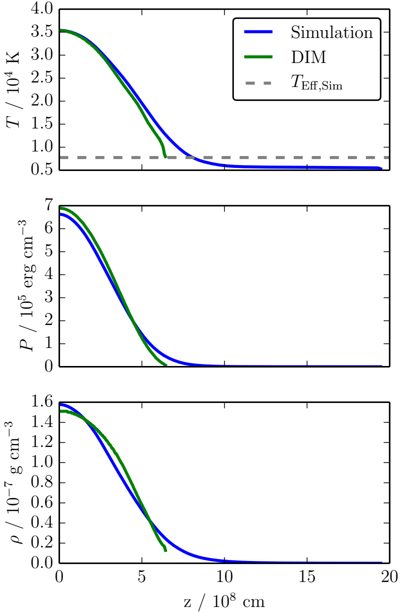


Coleman et al. (2016)

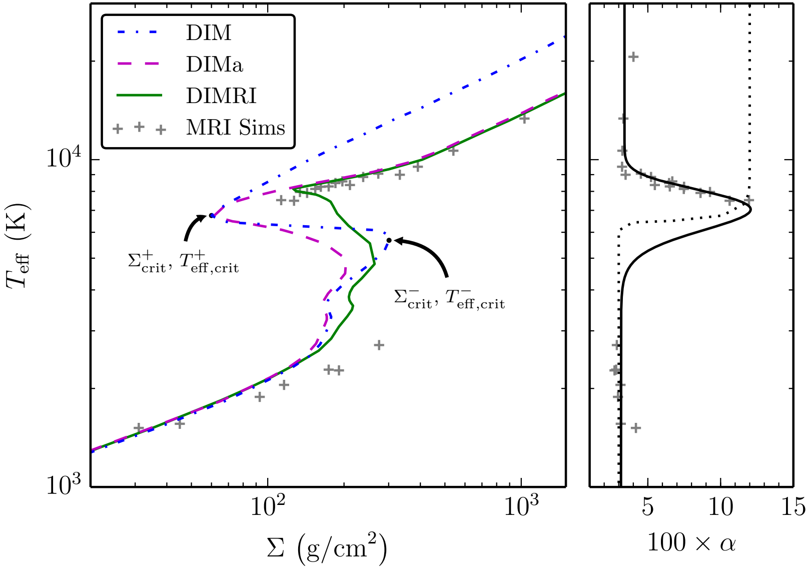
α from Simulations is Well Behaved



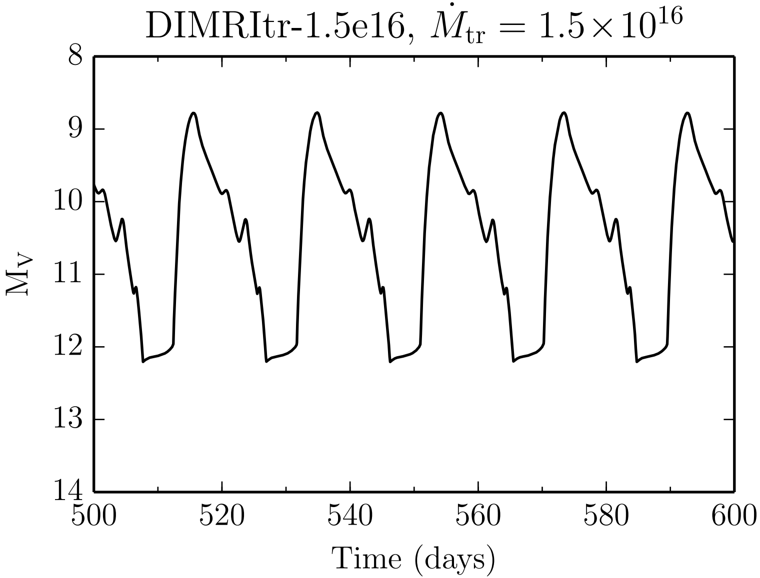
Vertical Structure Comparison



S-curves


DIM
DIMa
DIMRI
MRI Sims
$\Sigma^+_{\rm crit}$, $T^+_{\rm eff,crit}$
$\Sigma^-_{\rm crit}$, $T^-_{\rm eff,crit}$
10^4
10^3
$T_{\rm eff}$ (K)
10^2
10^3
Σ (g/cm^2)
5
10
15
$100 \times \alpha$

Light Curve


DIMRItr-1.5e16, $\dot{M}_{\rm tr} = 1.5\times10^{16}$
M_V
8
9
10
11
12
13
14
500
520
540
560
580
600
Time (days)

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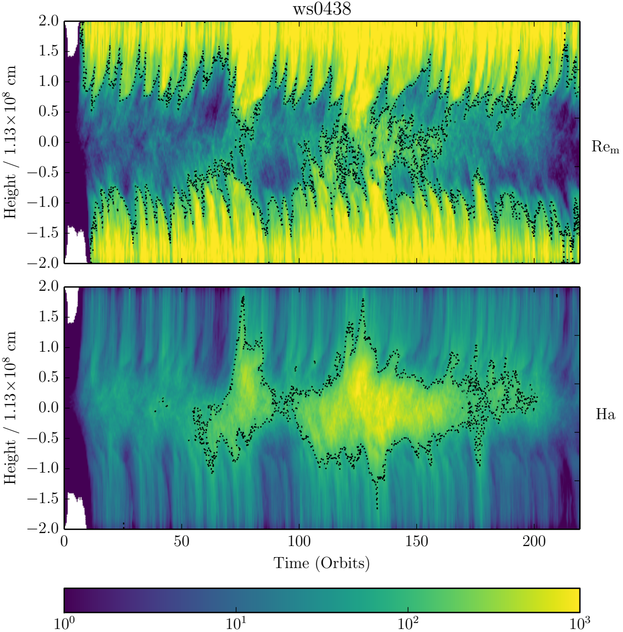
Summary

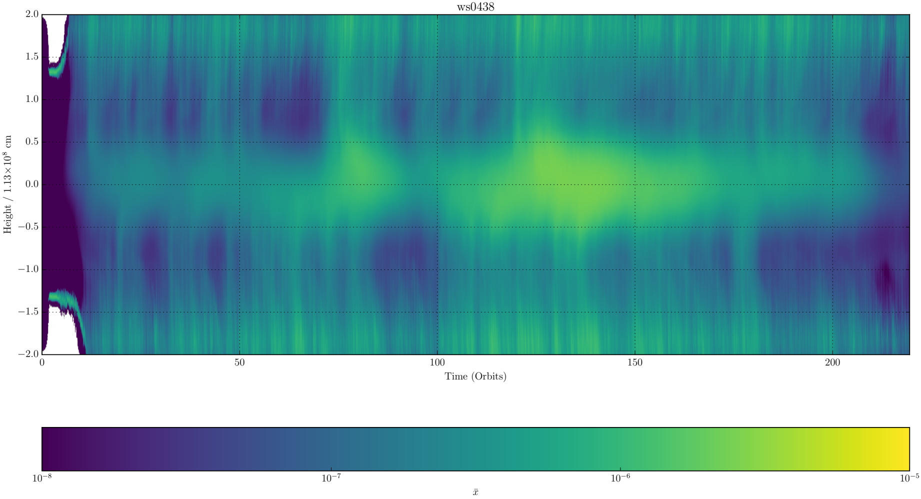
- DNe provide insight into accretion disks
    - Time variation
    - Well studied
- Convective accretion disks
    - α varies with $\alpha \sim .1$ at the tip of the upper branch
    - α highly correlated with convection
    - Convection Quenches Field Reversals
- Generated lightcurves
    - Modified DIM to incorporate local simulation data
    - Gives lightcurves (mostly) consistent with observations
    - Puts enhancement of α on stronger theoretical grounds
- Global simulations to come (Future work with Yan-Fei Jiang)
- Featured work
    - Coleman, M. S. B., Yerger, E., Blaes, O., Salvesen, G., & Hirose, S., 2017, MNRAS (in press), arXiv:1701.08177
    - Coleman, M. S. B., Kotko, I., Blaes, O., Lasota, J.-P., & Hirose, S., 2016, MNRAS, 462, 3710
    - Hirose, S. 2015, MNRAS, 448, 3105
    - Hirose, S., Blaes, O., Krolik, J. H., Coleman, M. S. B., & Sano, T., 2014, ApJ, 787, 1

Bonus Slides!

Non-ideal MHD

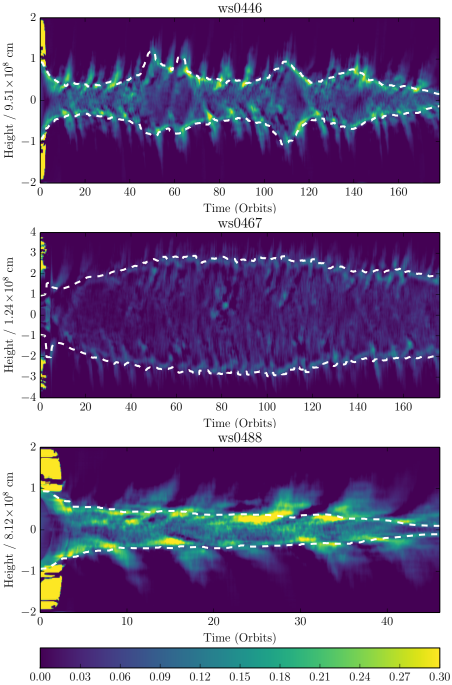


Ionization Fraction

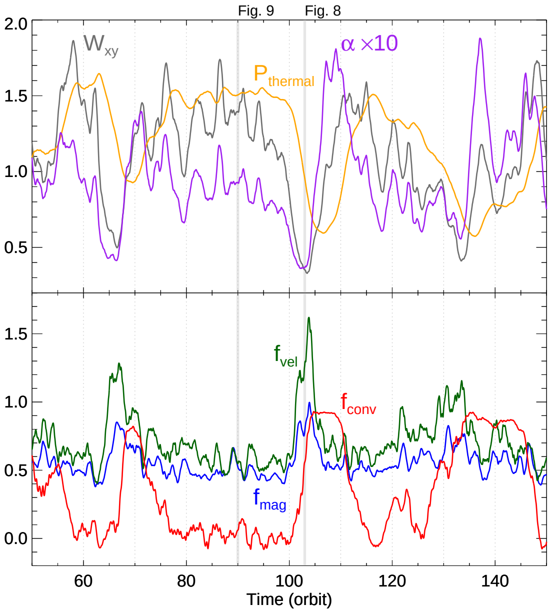


Non-Equilibrium

$$\alpha_{\mathrm{eff}}(z,t) \equiv \frac{2}{3}\frac{1}{\Omega P_0}\frac{\partial F_z}{\partial z}\left(\frac{P_0}{P}\right)^{\delta}$$



Time Variation



$$f_{\rm mag} \equiv \frac{\int \left[\left\langle B_z^2 \right\rangle\right] \left[\langle p_{\rm gas}\rangle\right] dz}{\int \left[\langle B_r^2 \rangle\right] \left[\langle p_{\rm gas}\rangle\right] dz}$$

$$f_{\rm vel} \equiv \frac{\int \left[\left\langle v_z^2 \right\rangle\right] \left[\langle p_{\rm gas}\rangle\right] dz}{\int \left[\langle v_r^2 \rangle\right] \left[\langle p_{\rm gas}\rangle\right] dz}$$

Hirose et al. (2014)

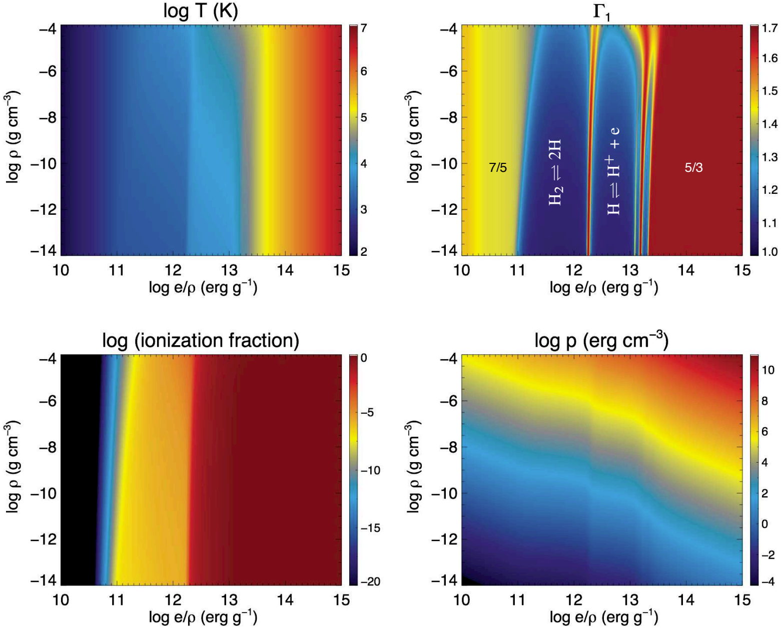
Equation of State

We wrote our own equation of state (EOS) code.
Preexisting codes lack alkali metals which ionize easily.

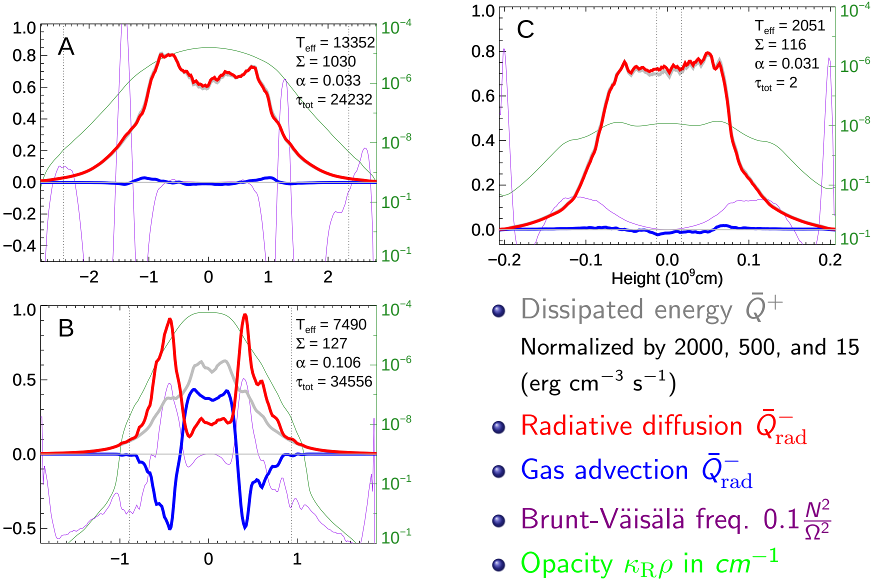
EOS properties

- Local thermal equilibrium
- Independent variables are density (ρ) and specific internal energy (e/ρ)
- Hydrogen species: H^-, H, H^+, H_2, H_2^+
- Helium species: He, He^+, He^{++}
- Metals (neutral and singly ionized only): C, N, O, Ne, Na, Mg, Al, Si, P, S, Cl, Ar, K, Ca, Cr, Mn, Fe, Ni
- Solar metallicity

Equation of State Cont.



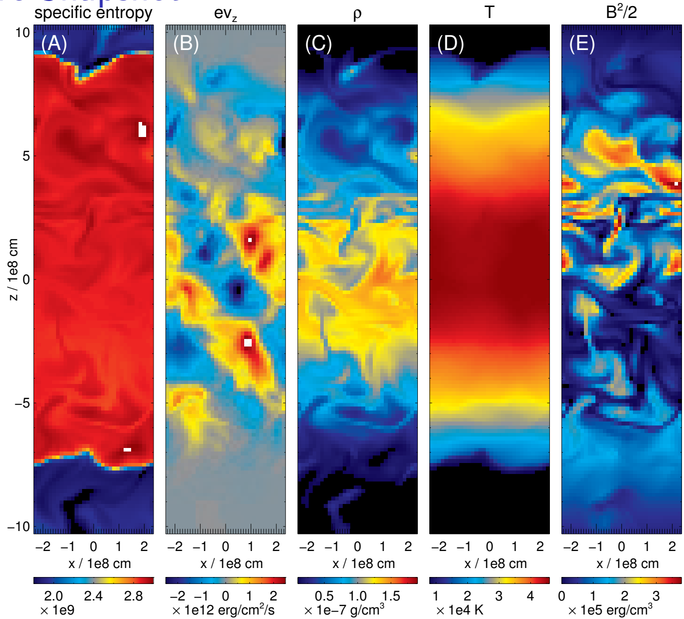
Evidence for True Thermal Convection



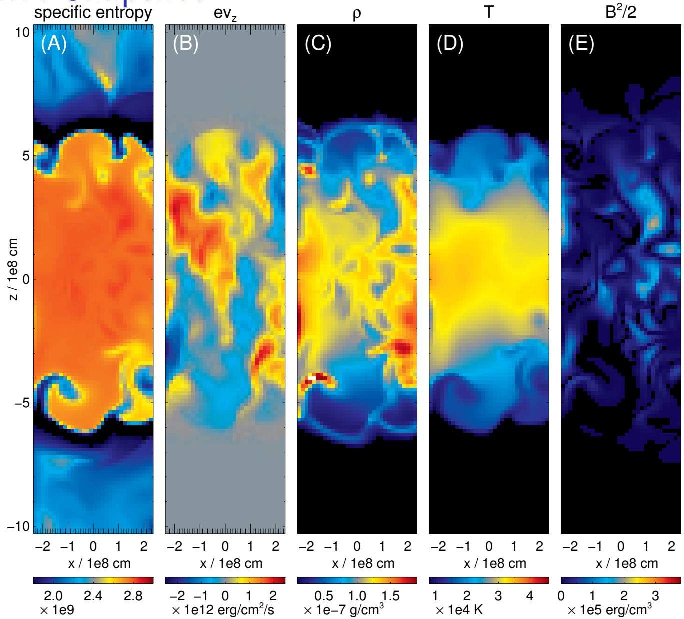
- Dissipated energy $\bar{Q}^+$

  Normalized by 2000, 500, and 15 (erg cm^{-3} s^{-1})
- Radiative diffusion $\bar{Q}^-_{\text{rad}}$
- Gas advection $\bar{Q}^-_{\text{rad}}$
- Brunt-Väisälä freq. $0.1\frac{N^2}{\Omega^2}$
- Opacity $\kappa_{\text{R}}\rho$ in cm^{-1}

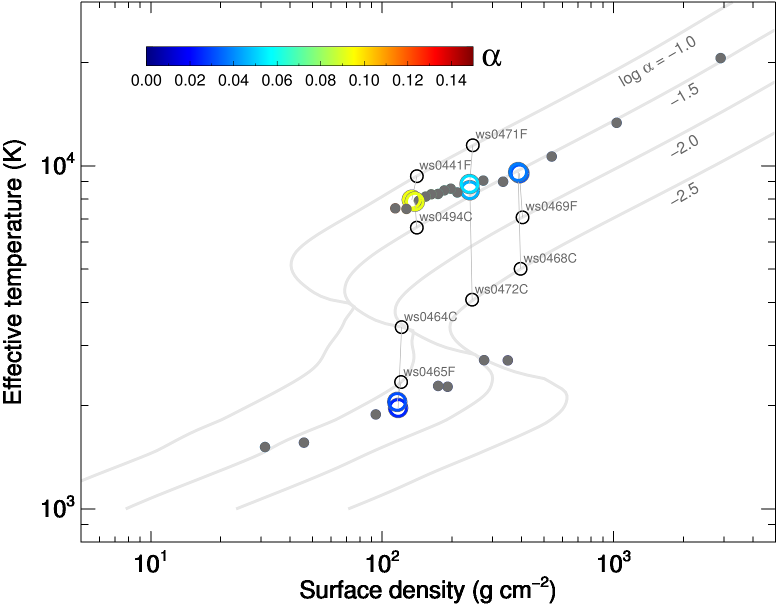
Radiative Snapshot



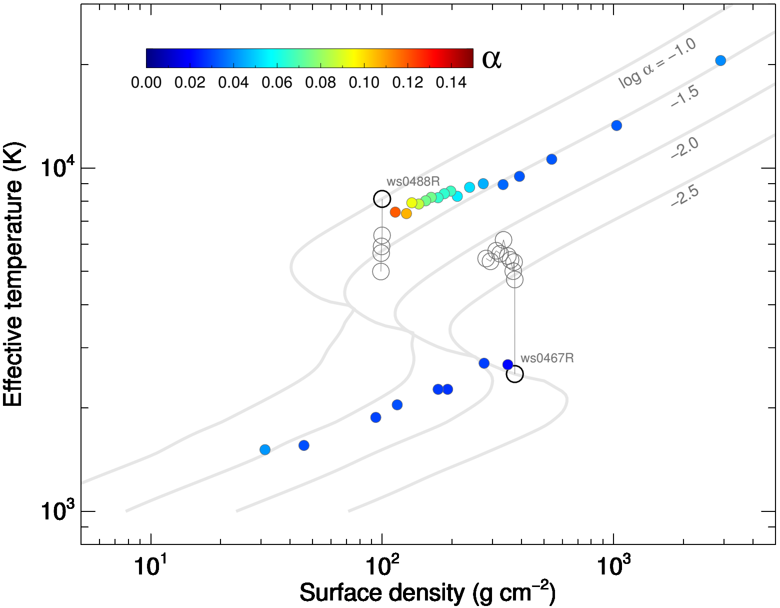
Convective Snapshot



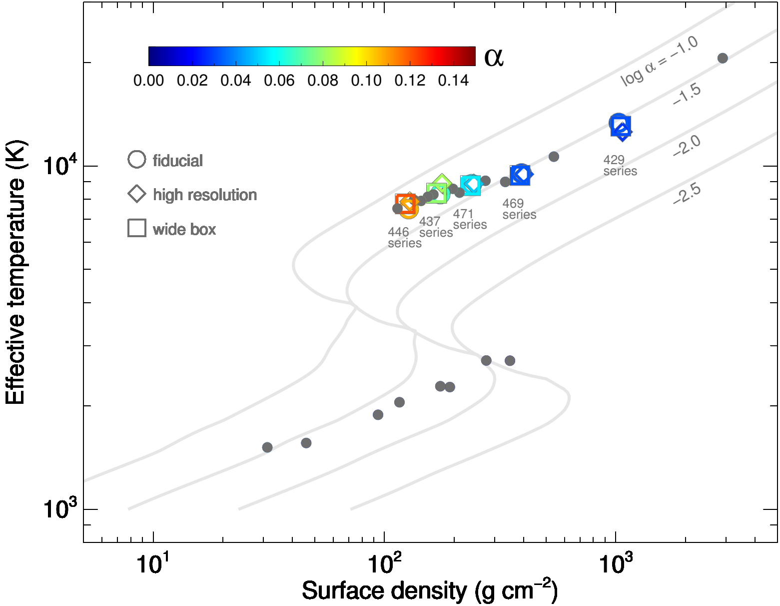
Branches are Attractors



Branches have Ends



Equilibria are Robust to Numerics



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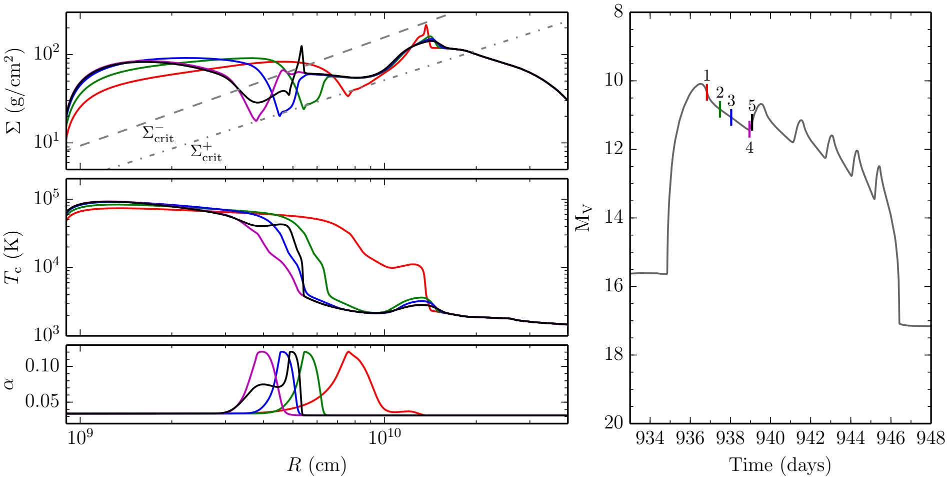
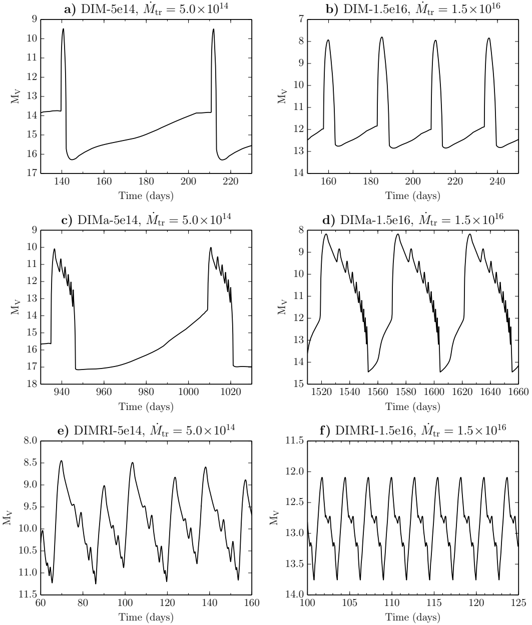
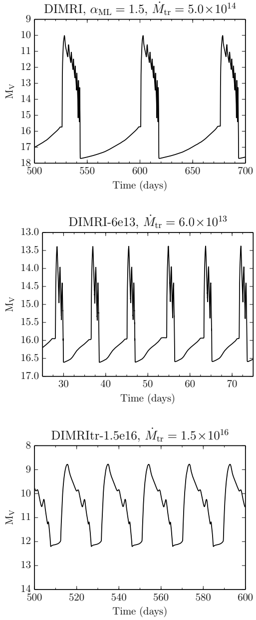

Σ (g/cm^2)
10^2
10^1
$\Sigma^-_{\rm crit}$
$\Sigma^+_{\rm crit}$
$T_{\rm c}$ (K)
10^5
10^4
10^3
α
0.10
0.05
10^9
10^{10}
R (cm)
$\rm M_V$
8
10
12
14
16
18
20
1
2
3
4
5
934
936
938
940
942
944
946
948
Time (days)

Light Curves Continued





Work Cited

Coleman, M. S. B., Kotko, I., Blaes, O., Lasota, J.-P., & Hirose, S. 2016, MNRAS, 462, 3710

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Hameury, J.-M., Menou, K., Dubus, G., Lasota, J.-P., & Hure, J.-M. 1998, MNRAS, 298, 1048

Hirose, S. 2015, MNRAS, 448, 3105

Hirose, S., Blaes, O., Krolik, J. H., Coleman, M. S. B., & Sano, T. 2014, ApJ, 787, 1

Kato, T., & Osaki, Y. 2013, PASJ, 65, 97

Lasota, J.-P. 2001, NewAR, 45, 449

Shakura, N. I., & Sunyaev, R. A. 1973, , 24, 337

Wheatley, P. J., Mauche, C. W., & Mattei, J. A. 2003, MNRAS, 345, 49