Convection Affects Magnetic Turbulence in White Dwarf Accretion Disks

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Overview

Dwarf Novae (DNe):

- Accreting white dwarfs in binaries
- Outbursts last ~ 1 week with recurrence times ~ 1 month
- Outbursts triggered by H ionization instability in the accretion disk

AM CVn:

- Similar to DNe, but accreting He rich, H poor material

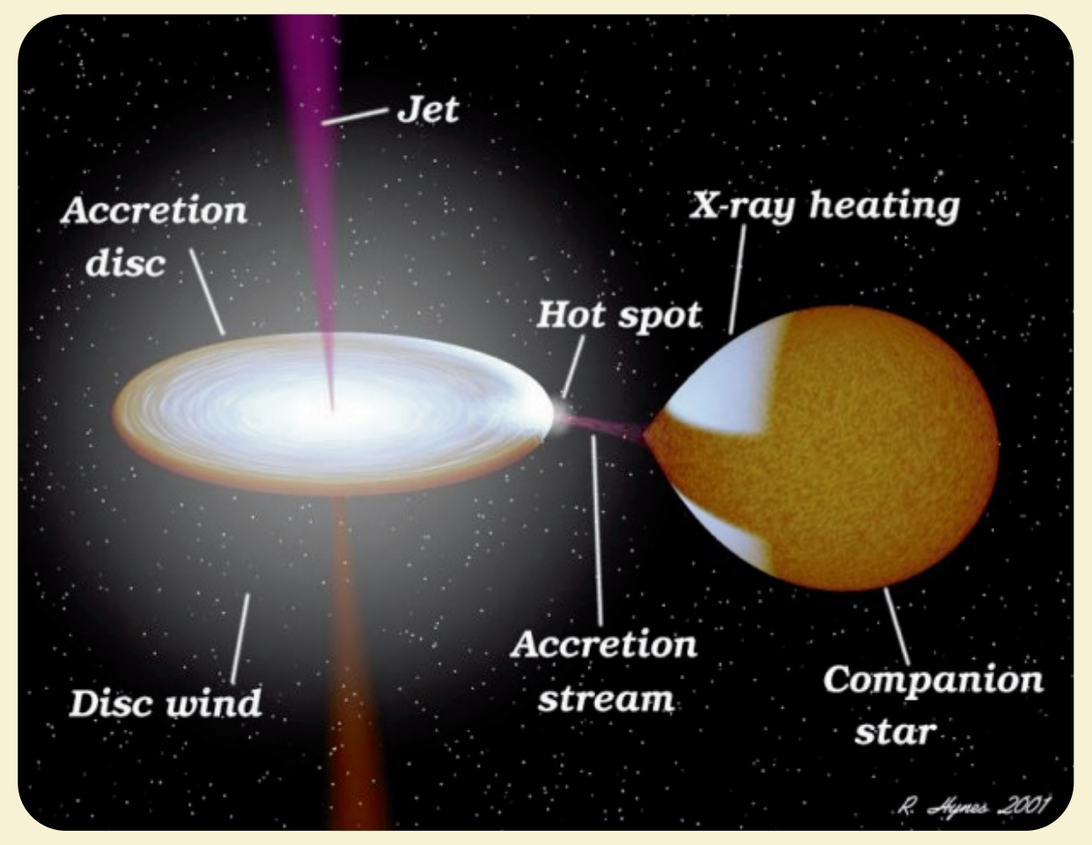


Fig 1: Dwarf nova schematic. The jet emanating from the white dwarf is only observable in radio.

SS Cygni Lightcurve

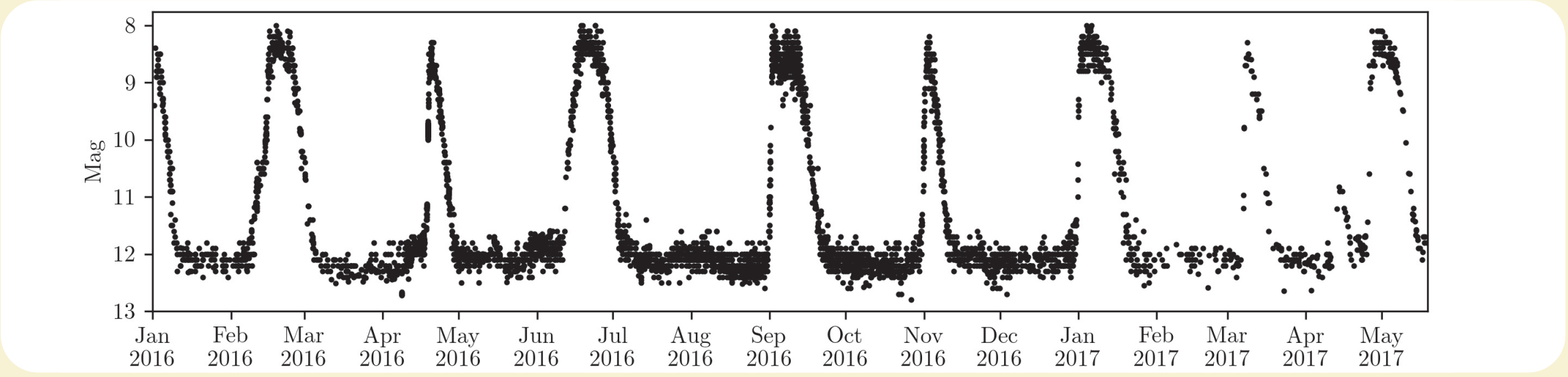


Fig 2: Visual lightcurve of the dwarf nova SS Cygni from AAVSO

Motivation:

- Properties of steady state disks are insensitive to the stress to pressure ratio/viscosity parameter α
- Time variations of DN and AM CVn outbursts probe α
  - The relative durations of quiescence and outburst implies that α is larger in outburst
- What roll does convection play in determining α?
- Values of α measured from magnetohydrodynamic (MHD) simulations tend to be inconsistent with the values inferred from observations.
  - Can convection fix this?
- Test compositional dependance

Methods:

- 3D radiation-MHD local disk simulations using Zeus
  - Realistic opacities and equation of state
- Modified disk instability model incorporating simulation results

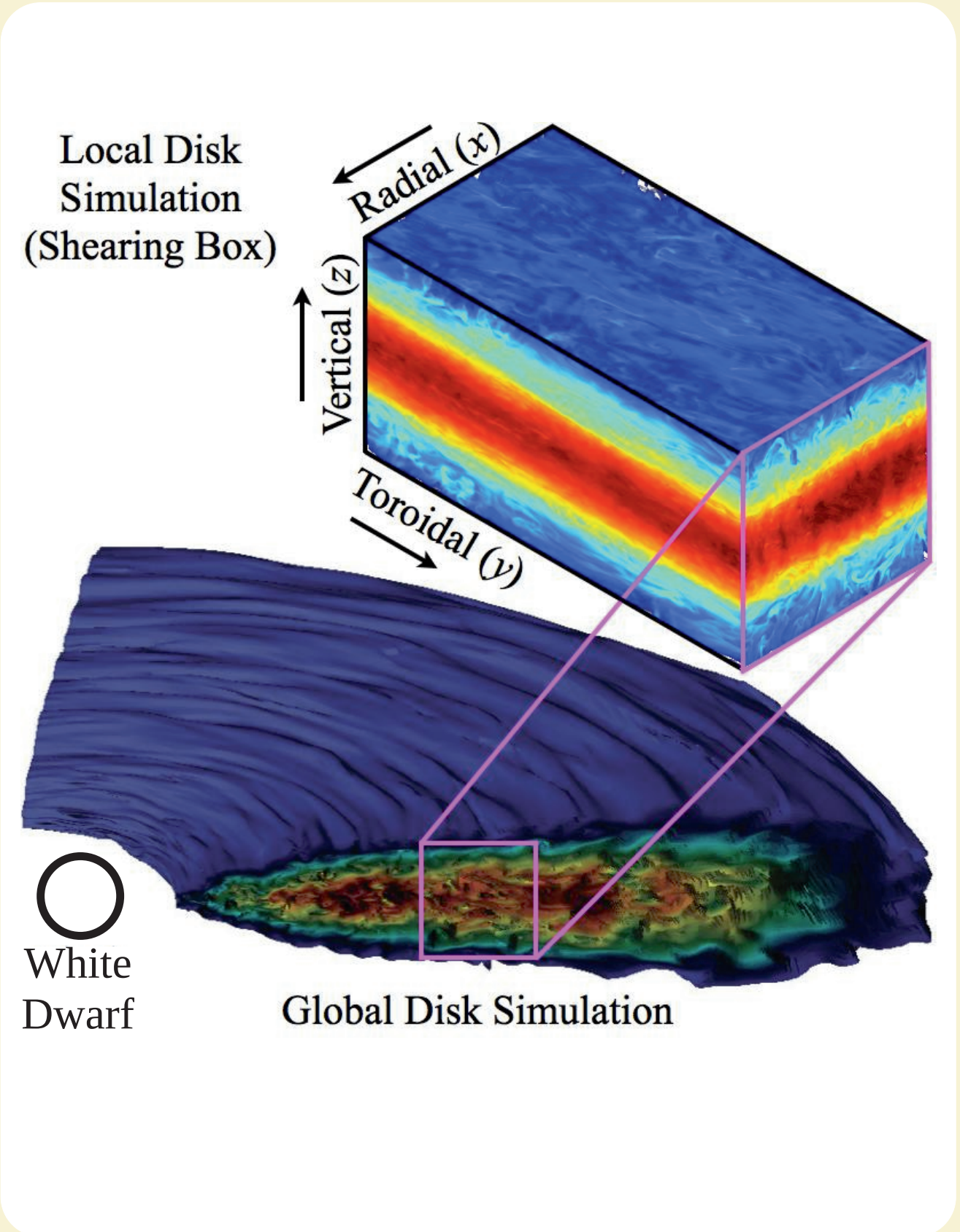


Fig 3: We use the local shearing box approximation in our MHD simulations.

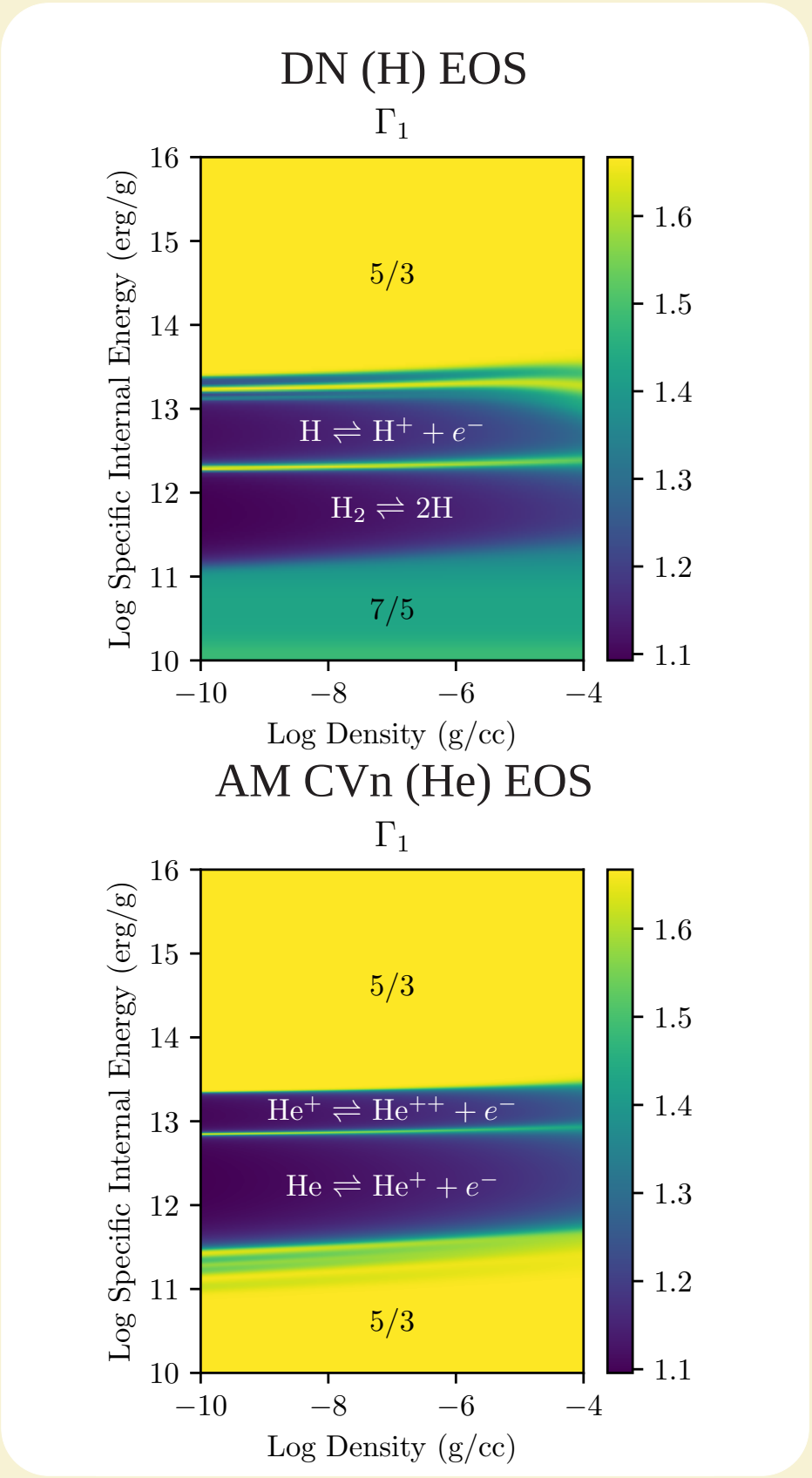
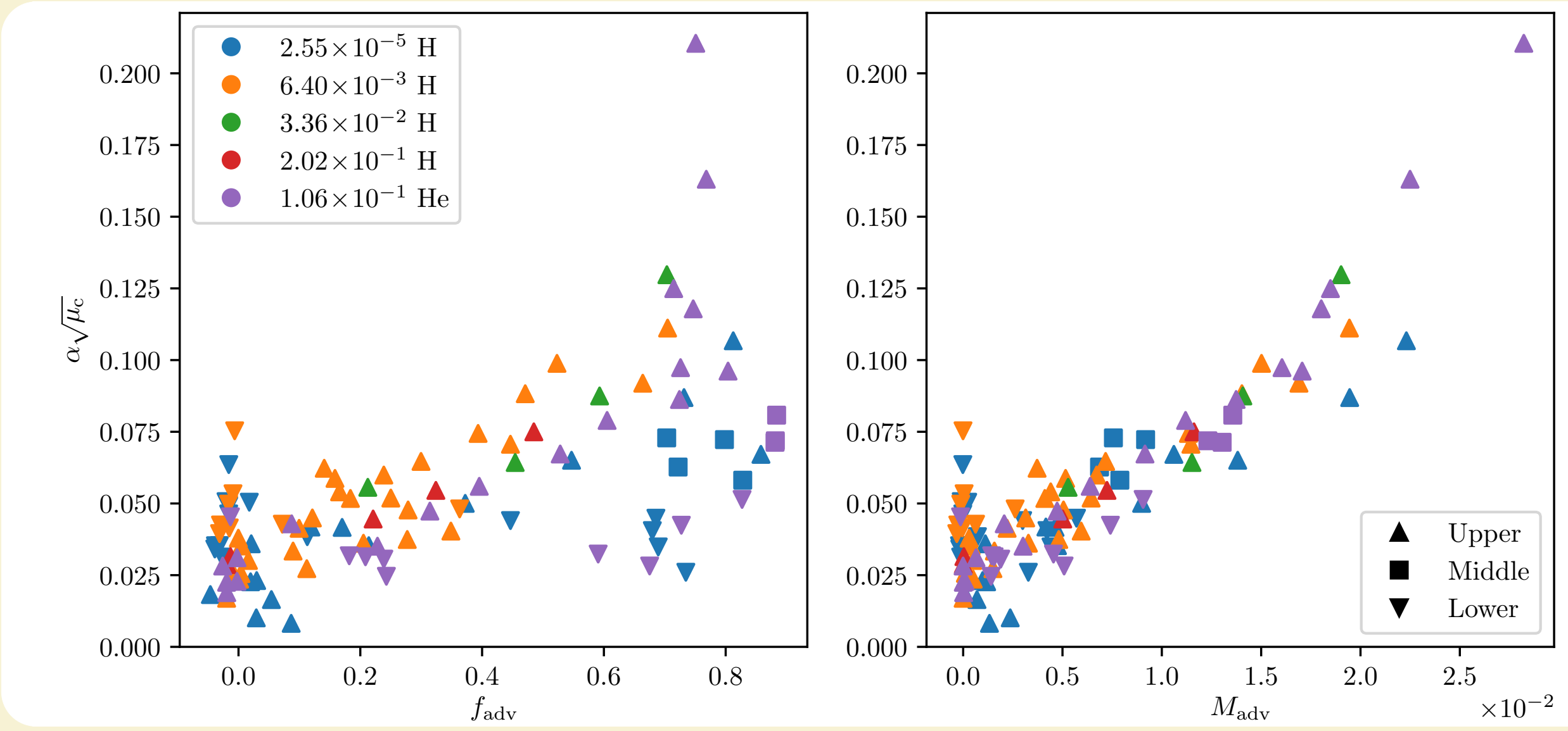


Fig 4: Adiabatic index Γ1 for our two equations of state.

Convection Modifies Magnetorotational Turbulence and Dynamos

Convection Enhances α

By including realistic opacities and equation of state appropriate for the hydrogen/helium ionization regimes, we found that convection occurs in the low temperature region of the outburst state (the upper branch of the s-curve). This convection enhances the magnetorotational turbulence and α, resulting in values of α which are consistent with those recovered from observations.



f_{adv}:
Fraction of energy transport done by convection

M_{adv}:
Mach number of convective eddies

Fig 5: Correlations of convective quantities with $\alpha\sqrt{\mu_c}$, where μ_c is the central/midplane mean molecular weight. The left panel shows the correlation with f_{adv} (fraction of energy transport done by advection), while the right panel shows the correlation with advective Mach number M_{adv} (speed of convective eddies). The color of each symbol denotes the orbital frequency Ω (in rad/s) and the most abundant element (H or He) in the assumed chemical composition as listed in the upper left legend. The shape of the symbol corresponds to the branch to which the simulation settled, as listed in the lower right legend.

Convection Quenches Magnetic Field Reversals

We noticed that the dynamo behavior of our simulations is very different when convection is present (see Fig. 6). Typically, MHD shearing box simulations with low magnetization exhibit a so-called butterfly diagram of quasi-periodic azimuthal magnetic field (B_y) reversals. For our simulations which exhibit convection, the convection is intermittent and so are the disturbances of the dynamo. During convective epochs the azimuthal field no longer reverses.

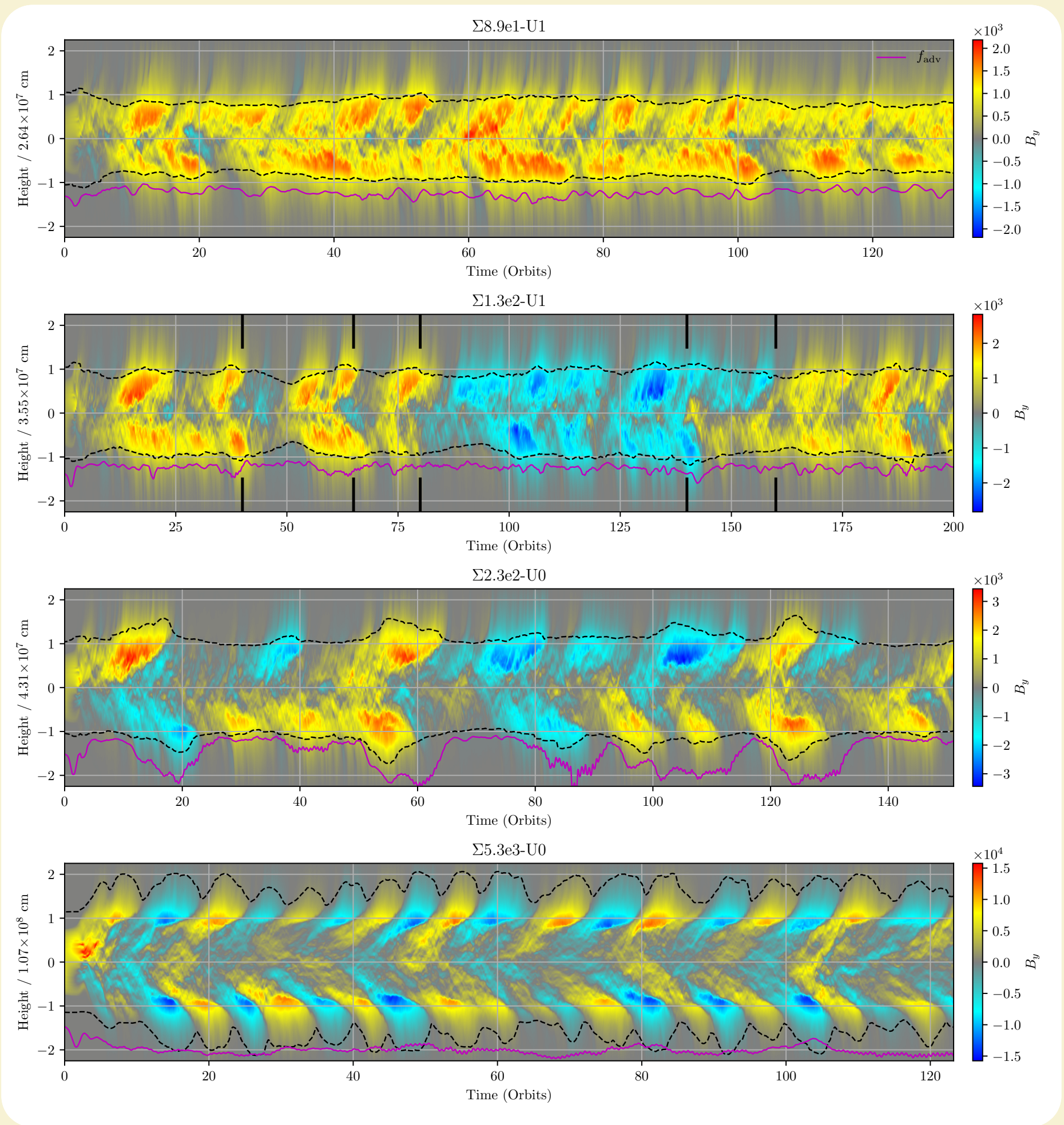


Fig 6: Horizontally-averaged (averaged in x and y) azimuthal magnetic field (B_y) as a function of time and height for four AM CVn simulations which exhibit varying levels of convection (with strongest on top). The dashed black lines show the time-dependent heights of the photospheres in the horizontally averaged structures. The convective fraction f_{adv}-2 is plotted in magenta, and uses the same vertical scale as B_y, i.e. when the magenta line is near -1 then $f_{adv} \approx 1$. In the simulation which exhibits intermittent convection (Σ2.3e2-U0) where f_{adv} is high, the field tends to maintain its sign and changes in sign/parity are often associated with a dip in f_{adv}. Of the two persistently convective simulations displayed here, Σ8.9e1-U1 shows no global field reversals, and Σ1.3e2-U1 has a few reversal events which seem uncorrelated with f_{adv}, however the marked times for this simulation which correspond to field reversals also correspond to dips in M_{adv}. The simulations from the top three panels are also shown in Fig. 6.

He Opacity Stabilizes Convection

All Convection in DN (H dominated) simulations exhibit intermitent convection (similar to Σ2.3e2-U0 in Fig. 6). However, several of our AM CVn simulations exhibit persistent convection (see Σ8.9e1-U1 and Σ1.3e2-U1 above). In Fig. 7 we show the evolution of the midplane Rosseland mean opacity κ_R. Simulations which exhibit percistent convection stay between the two maxima in opacity resulting from the two ionizations of helium, implying that this stabilizes the convective transport within the disk.

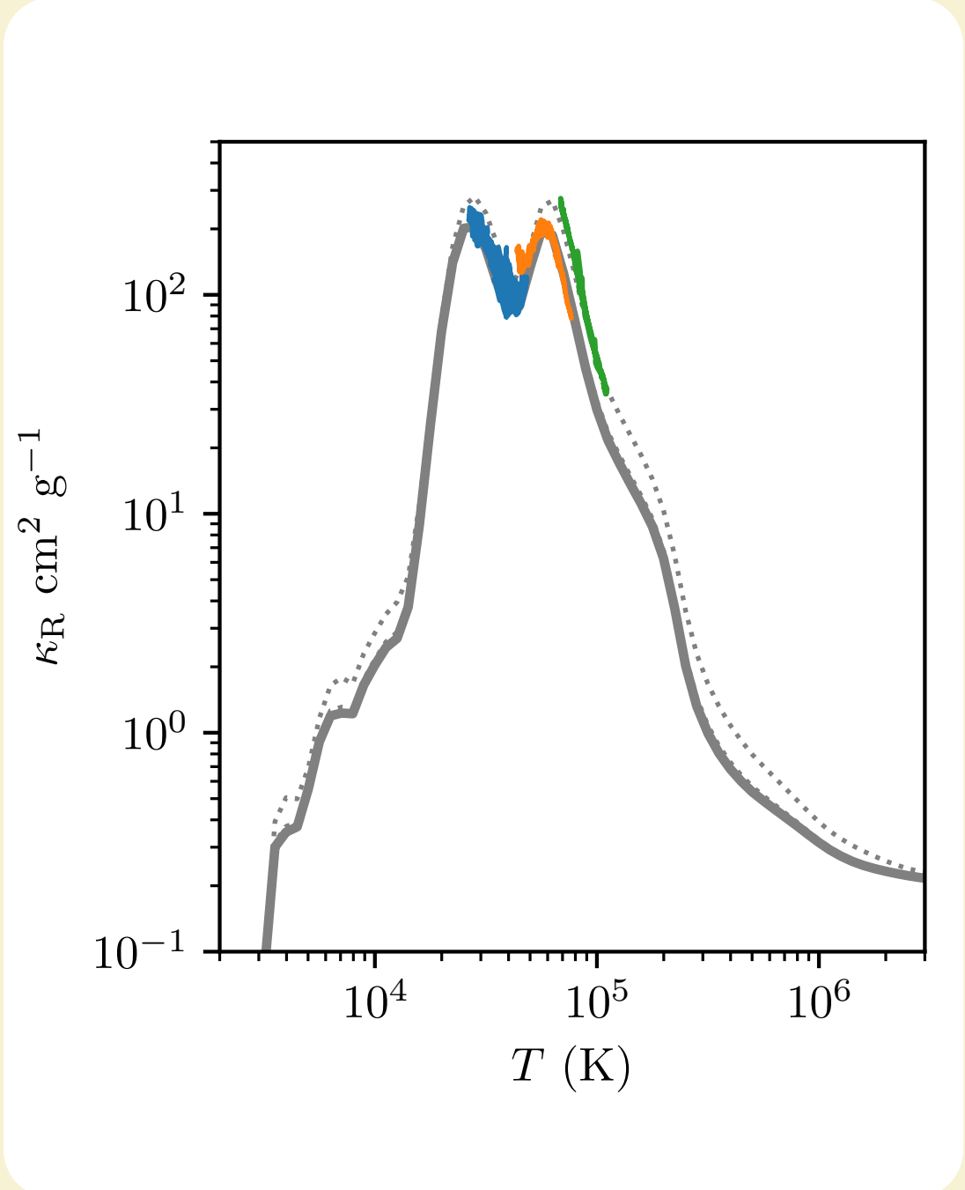


Fig 7: Rosseland mean opacity as a function of temperature for three simulations: Σ8.9e1-U1 (blue), Σ1.3e2-U1 (orange) and Σ2.3e2-U0 (green). These simulations exhibit persistent convection, mostly persistent convection, and intermittent convection respectively (also shown in Fig. 6). Each gray curve corresponds to the opacity functions for a fixed density. The solid gray line corresponds to the time average central density of simulation Σ8.9e1-U1 while the dotted lines correspond to those of the other two simulations. The colored lines correspond to the time evolution of the mean midplane values for each of the simulations.

Generating Lightcurves (for DNe)

The Disk Instability Model (DIM) has been successful in reproducing the observed light curves of dwarf nova outbursts by invoking an ad hoc enhanced α parameter ~0.1-0.2 in outburst compared to a low value ~0.01 in quiescence. The convective enhancement of α in outburst we found only acts near the hydrogen ionization transition. To check if this enhancement is sufficient to reproduce observed light curves, we incorporate this MRI-based variation in α into the DIM, as well as modifications to the vertical structure, using simulation-based models of turbulent dissipation and convective transport.

The Equilibrium S-curve

The DIM uses a library of equilibrium vertical structures to determine how adjacent annuli in the accretion disk communicate. The equilibrium structures for a single annulus are typically plotted in the surface mass density, effective temperature plane, resulting in the standard S-curve. The mass transfer rate from the secondary tries to drive the accretion disk to the middle unstable branch, however due to its unstable nature, the disk instead switches between quiescence (lower branch) and outburst (upper branch). The edges of the branches of the s-curve and the value of α, shape the outburst lightcurve.

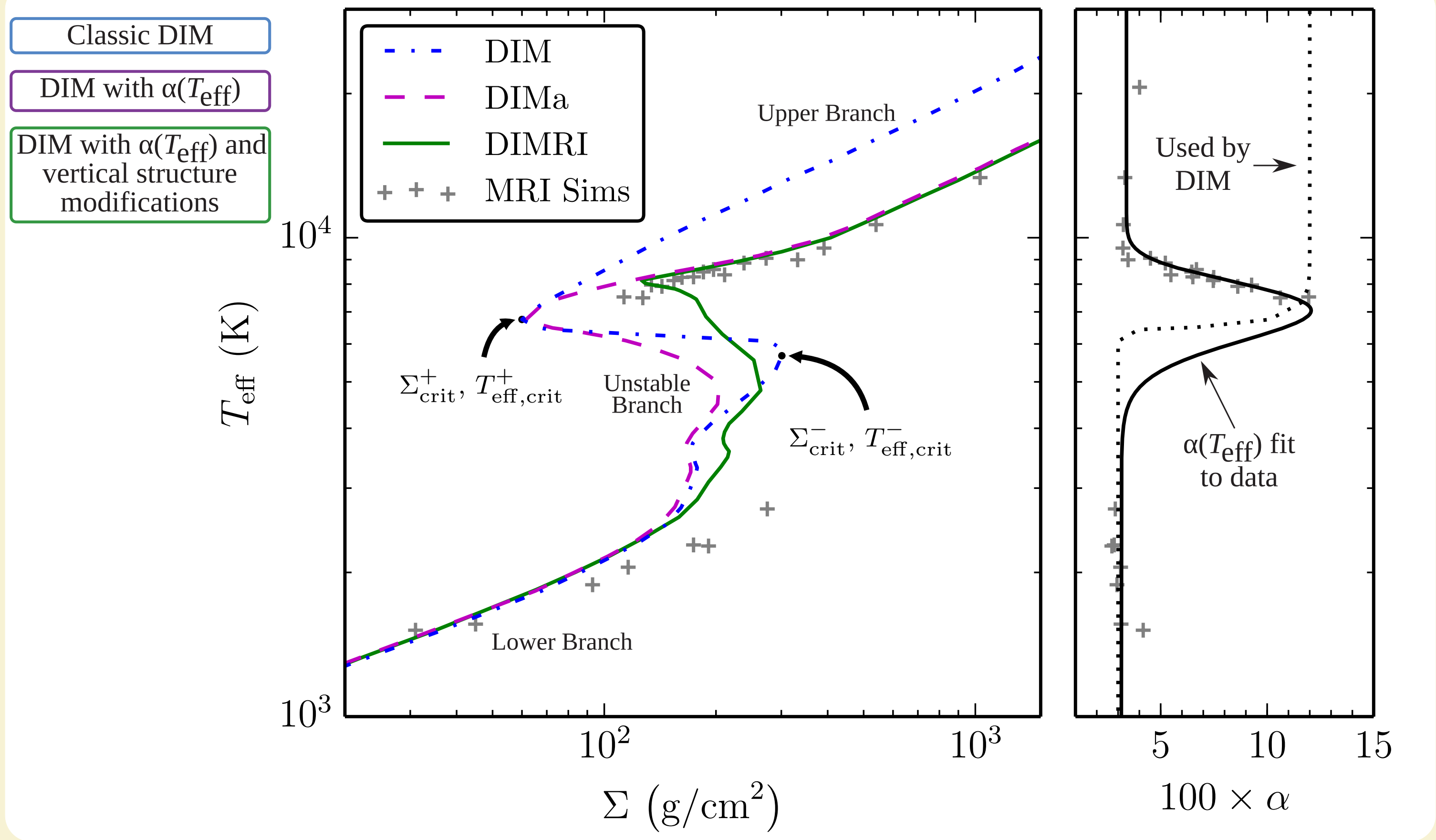


Fig 8: Left: Loci of thermal equilibria in the effective temperature T_{eff} vs. surface mass density Σ plane (the "S-curve") at radius R=1.25×10^{10} cm for the standard DIM, DIMa and DIMRI. The MRI simulation results are gray crosses (one point for each stable simulation). Additionally, the ends of the upper (Σ^{+}_{crit}, $T^{+}_{eff,crit}$) and lower (Σ^{-}_{crit}, $T^{-}_{eff,crit}$) branches are marked for DIM. Right: The MRI-based α(T_{eff}) fit to simulation plotted sideways in solid black (DIMa and DIMRI both use this fit) with the results from the same MRI simulations from the left plotted as gray crosses. The variation of α used by DIM is plotted as the dotted black line.

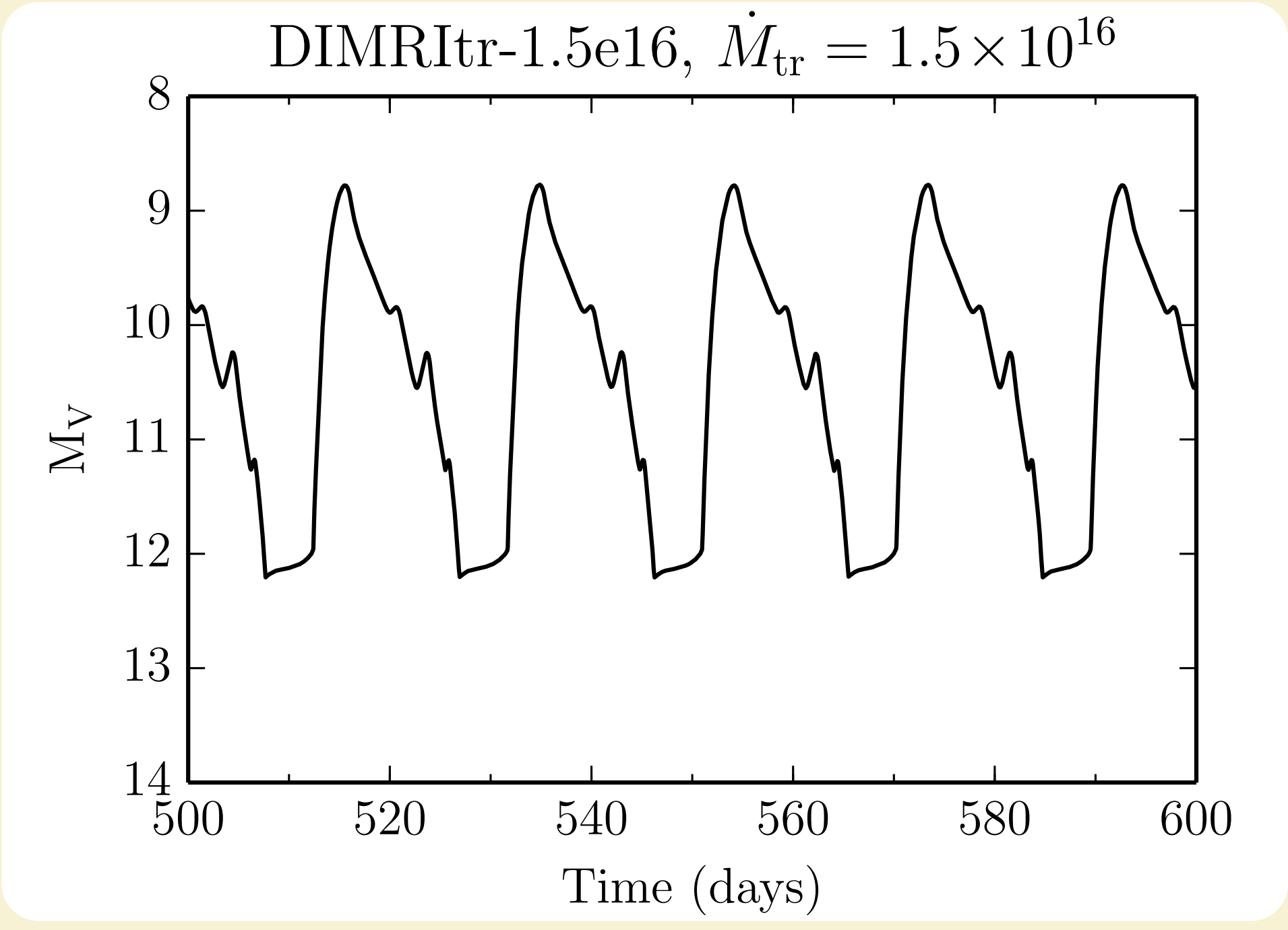


Fig 9: Light curves calculated from DIMRI with inner disc radius truncated by a magnetic field with magnetic moment μ=8×10^{30} G cm^3.

Resulting lightcurve

With the exception of the decay from outburst, the synthesized lightcurve does a reasonable job at reproducing the features of dwarf nova lightcurves, with outburst durations, magnitudes and recurrence times in the range seen in observations. The decay from outburst is prolonged due to the occurrence of reflares (sawtooth like features in Fig. 9) which are likely a result of physical uncertainty on the lower branch. This uncertainty primarily stems from the exclusion of important non-ideal MHD effects associated with the lower branch. This gives us a clear direction for future work.

My Related Publications:
Convection Enhances Magnetic Turbulence in AM CVn Accretion Disks
Coleman M. S. B., Blaes O., Hirose S., Hauschildt, P. H., 2018, 857, 52
Convective Quenching of Field Reversals in Accretion Disc Dynamos
Coleman, M. S. B., Yerger, E., Blaes, O., Salvesen, G., & Hirose, S., 2017, MNRAS, 467, 2625
Dwarf nova outbursts with magnetorotational turbulence
Coleman, M. S. B., Kotko, I., Blaes, O., Lasota, J.-P., & Hirose, S., 2016, MNRAS, 462, 3710
Convection Causes Enhanced Magnetic Turbulence in Accretion Disks in Outburst
Hirose, S., Blaes, O., Krolik, J. H., **Coleman, M. S. B.**, & Sano, T., 2014, ApJ, 787, 1

My publications and posters

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