Testing A Closed Field Coronal Heating Model Inspired by Wave Turbulence

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Abstract

To simulate the energy balance of coronal plasmas on macroscopic scales, we often require the specification of the coronal heating mechanism in some functional form. To go beyond empirical formulations and to build a more physically motivated heating function, we investigate the wave-turbulence driven (WTD) phenomenology for the heating of closed coronal loops. To do so, we employ an implementation of non-WKB equations designed to capture the large-scale propagation, reflection, and dissipation of wave turbulence along a loop. The parameter space of this model is explored by solving the coupled WTD and hydrodynamic equations in 1D for an idealized loop, and the relevance to a range of solar conditions is established by computing solutions for several hundred loops extracted from a realistic 3D coronal field. Due to the implicit dependence of the WTD heating model on loop geometry and plasma properties along the loop and at the footpoints, we find that this model can significantly reduce the number of free parameters when compared to traditional empirical heating models, and still robustly describe a broad range of quiet-sun and active region conditions. The importance of the self-reflection term in producing realistic heating scale heights and thermal non-equilibrium cycles is discussed, which has relevance to the heating and cooling signatures often observed in active region cores.

Motivation

- We'd like to go beyond the empirical analytic functions that we currently use to heat the global corona in our 3D thermodynamic MHD model.
- The basal heating rate, Q_0, and heating scale height, λ_Q, are two very important parameters for determining the densities and temperatures of Quiet-sun (QS) and Active Region (AR) structures, but ideally they would be determined by the physics of the system and not the user!
- Solving auxiliary equations inspired by Wave Turbulence Driven (WTD) phenomenology, is one way to approach this problem.

This Work

- Develop and test a simple WTD heating model applicable to the closed corona, where heating arises from the dissipation of parallel and anti-parallel propagating Alfvén wave turbulence.
- Study the heating properties and resulting plasma conditions for this model under a range of AR conditions using using our 1D loop hydro code.

Tried and True: Empirical Heating Functions in 3D

- Volumetric heating is empirically parametrized with analytic functions in 3D.
- The two key parameters are:
  - Heating scale height, λ.
  - Total heating rate Q (also written as H). Typically chosen with B proportionality.
- Interplay between the scale height (distribution) and basal heating rate (amount) lets you fine tune the model to match EUV observables.
- One function won't work for all regimes (e.g. QS vs. AR)
  - Long scale heights work well for the QS, shorter scale heights better for ARs.
  - The effect of the scale height is shown between Run A and B (similar total heating).
  - We use a combination of multiple functions + masks to treat each regime at once.

The "Mikić" version of empirical heating in 3D MAS

Total Coronal Heating

$$H = H_{QS+AR} + H_{NL} + H_{FW} + H_{SS}$$

Quiet Sun and Active Region Heating:

$$H_{QS+AR} = H_1 \exp\left(-\frac{(r-R_\odot)}{\lambda_1}\right) B_{photo}\, M(\mathbf{x})$$

$M(\mathbf{x})$ is a mask (1 in closed-field regions, 0 in open-field regions)

Neutral Line Heating:

$$H_{NL} = H_2 \exp\left(-\frac{(r-R_\odot)}{\lambda_2}\right) B_{photo} \sin^4\Theta$$

Θ is the inclination angle of $\mathbf{B}$ to the vertical in the photosphere

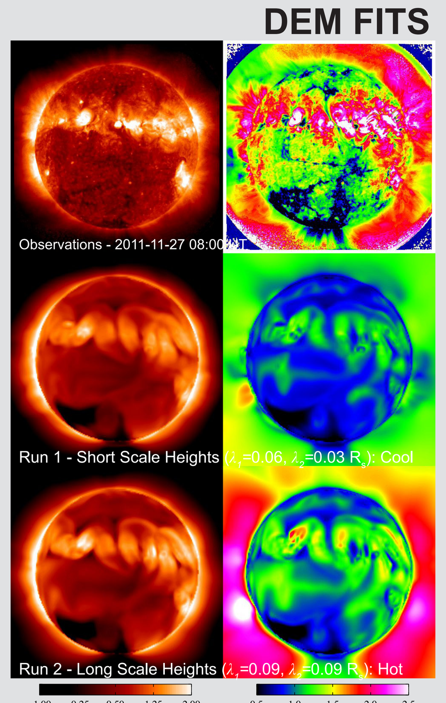
Fast Wind Heating:

$$H_{FW} = H_3 \exp\left(-\frac{(r-R_\odot)}{\lambda_3}\right)$$

Short-Scale Heating:

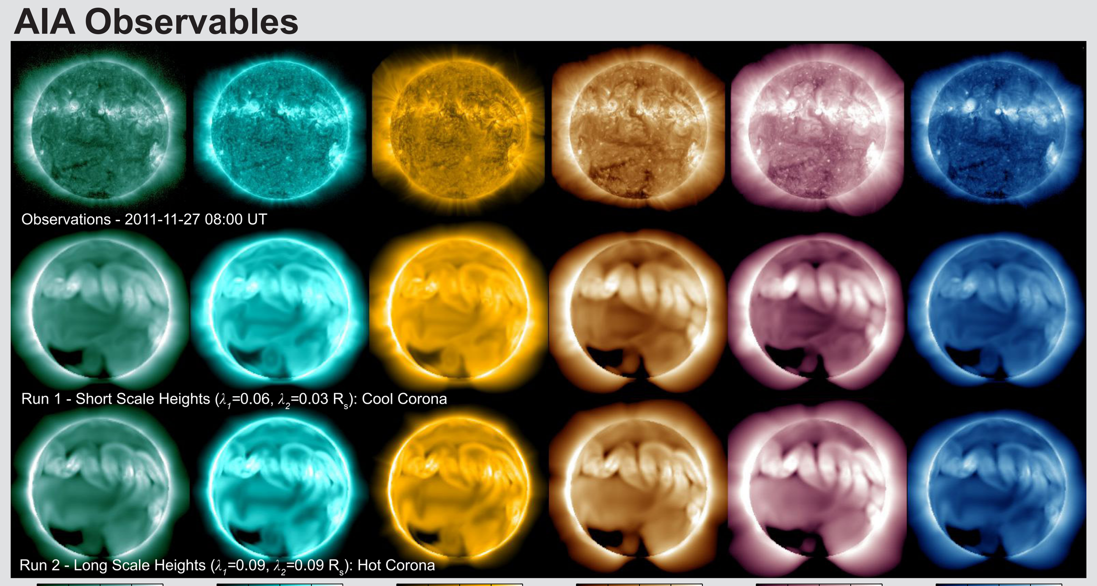
$$H_{SS} = H_4 \exp\left(-\frac{(r-R_\odot)}{\lambda_4}\right)$$

DEM FITS



These two runs of the empirical MAS model illustrate temperature and density implications between two choices of model parameterizations (short vs. long scale height).

AIA Observables



The Problem

Empirical coronal heating functions have many parameters, are chosen a priori.

The Solution?

A Simple Wave Turbulence Driven (WTD) Heating Model for Closed Fields:

- While there are many flavors of turbulence models, we explore a model based on Verdini et al., 2010.
- This model employs Alfvénic turbulence as source of heating and acceleration, and evolves the Elsässer variables (amplitudes) in time. Our prescription for the low frequency limit is as follows:

$$\frac{\partial z_\pm}{\partial t} + [\vec{v} \pm \vec{v_a}]\cdot\nabla z_\pm = R_1 z_\pm + R_2 z_\mp - \frac{|z_\mp| z_\pm}{2\lambda}$$

WKB term — Self-reflection term — Phenomenological dissipation by counter-propagating species

where

$$R_1 = \frac{1}{4}[\vec{v} \mp \vec{v_a}]\cdot\nabla(\log\rho) \qquad z_\pm = \delta u \mp \frac{\delta b}{\sqrt{4\pi\rho}}$$

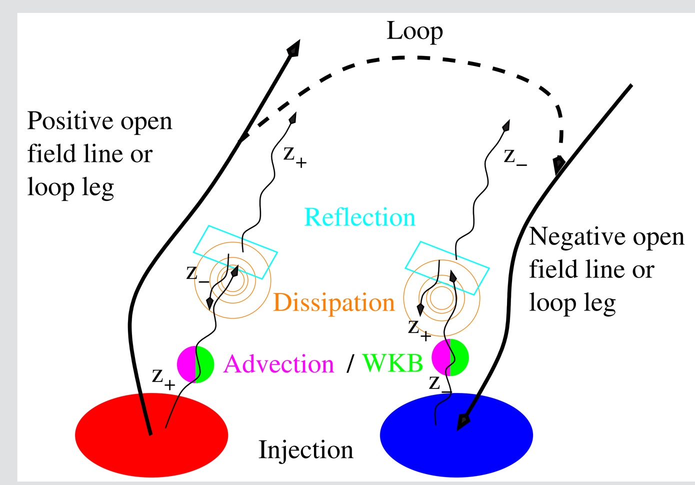
$$R_2 = \frac{1}{2}[\vec{v} \mp \vec{v_a}]\cdot\nabla(\log|\vec{v_a}|) \qquad p_w = \frac{\rho(z_- - z_+)^2}{8}$$

$$Q_{WTD} = \rho\frac{|z_-|z_+^2 + |z_+|z_-^2}{4\lambda} \qquad \lambda_\perp = \lambda_0\sqrt{\frac{B_0}{B}}$$

wave heating term

$$\mathbf{F}_R = -\frac{1}{2}\nabla\cdot\left[\rho z_+ z_- (\mathbf{I} - \hat{\mathbf{b}}\hat{\mathbf{b}})\right] \qquad e_\pm = \rho\frac{z_\pm^2}{4}$$

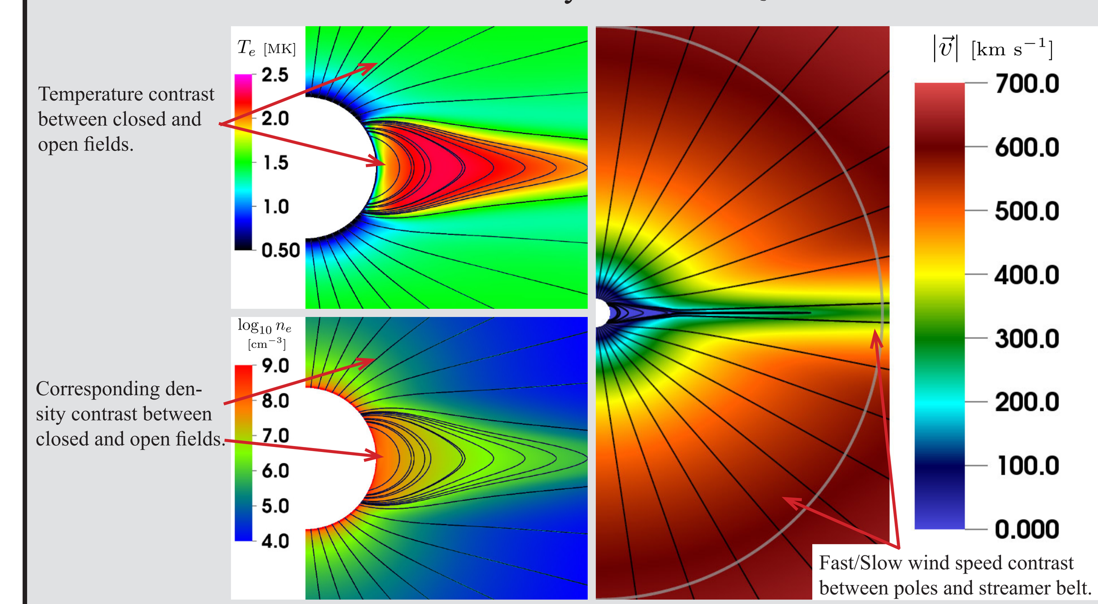
force due to Reynolds stress



- These two auxiliary equations can be solved along with the MHD equations (3D) or the 1D hydrodynamic equations.
- Adding reflective boundary conditions mimics resonance/non-linear growth.

2D Case: Simple Dipole

- We have added the full WTD equations to MAS, our thermodynamic MHD model. MAS can be run in two and three dimensions.
- This simple dipole case is used to contrast behavior of WTD model on open and closed field regions.
- We apply a uniform wave energy at boundary + reflective BC.
- The simulation is relaxed to steady state at $20R_s$.



***Strong closed/open contrasts despite uniformly specified plasma and wave boundary conditions!**

Key Aspects of the WTD Heating Model

1) Heating on loop is equal to the net Poynting flux → ~|B|/L scaling expected!

- Have direct relationship between Poynting flux at the boundary and heating over the loop.
- For simplicity assume $v_a >> U$ over the loop and the same boundary choice of ρ, get:

$$\text{pointing flux, } P = e\vec{v_a} = \frac{e\vec{B}}{\sqrt{4\pi\rho}}, \quad \text{and integrated heatflux, } H_F = \frac{1}{A_0 + A_L}\int_0^L A Q_{WTD}\, ds$$

$$\text{can show } H_F = \frac{1}{A_0 + A_L}\left(A_0 P_{r,b}(0) + A_L P_{r,b}(L)\right) = \frac{B_0 B_L}{B_0 + B_L}\frac{1}{\sqrt{4\pi\rho}}\left[2e_0 - e_r(L) - e_b(0)\right]$$

Total wave energy passing through footpoints — Flux IN — Flux OUT

2) Heating scale height is determined by the loop solution, *not the user*!

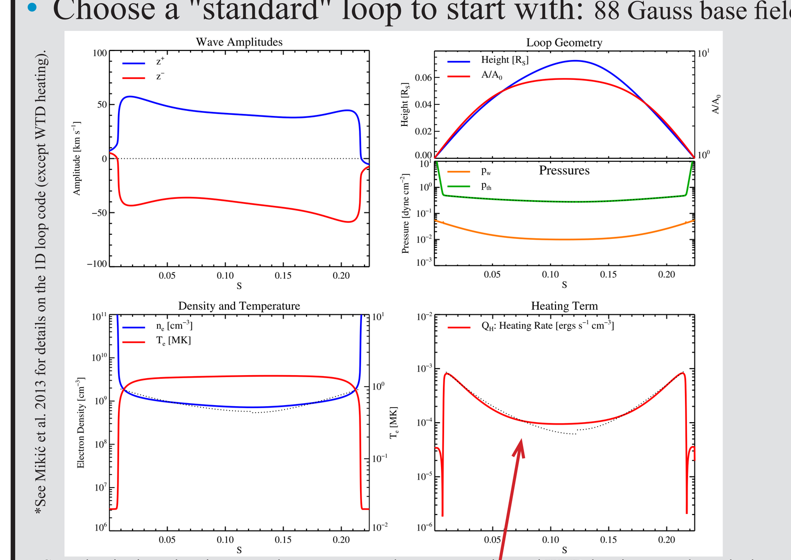
- Pure WKB propagation gives $e \propto \sqrt{\rho}$, implying Q_{WTD} dependence on ρ scale height.
- Areal expansion (i.e. B variation) now plays a role in Q_{WTD} variation both from the hydrodynamic solution, self-reflection, and the dependence of dissipation on $\lambda_\perp$.

3) Only two free heating parameters!

- Boundary Wave Energy: e_0
- Transverse Length Scale: λ_0
- This sounds too good... → need to test the relevance for realistic conditions.

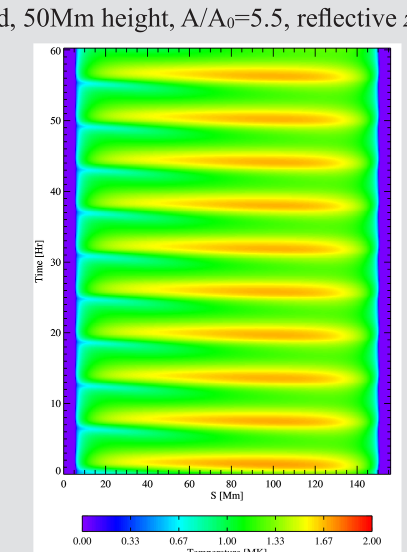
1D Experiments I: Parameter Space on an Idealized Loop

- Explore variation of WTD heating and apex T as a function of Area and basal field strength.
- Choose a "standard" loop to start with: 88 Gauss base field, 50Mm height, A/A_0=5.5, reflective z BC.



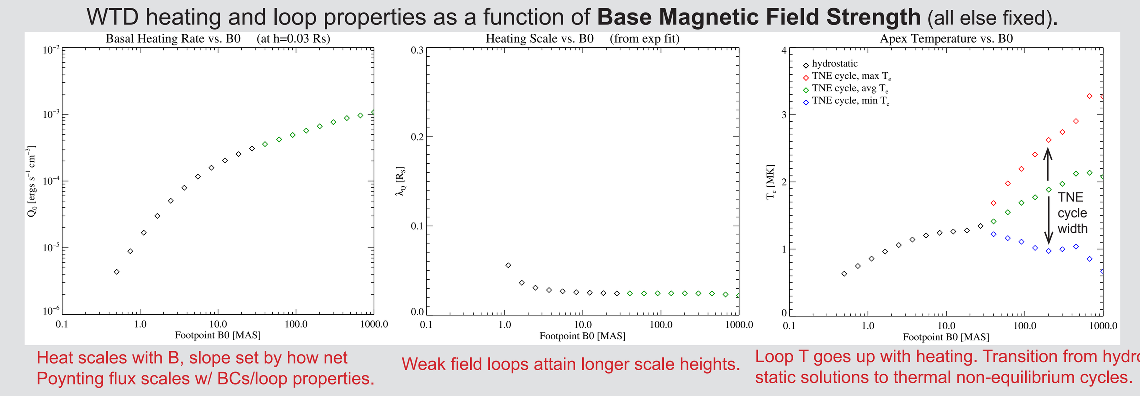
Snapshot in time showing z+ and z-, geometry, plasma properties and WTD heating rate along the loop.

***Short heating scale height results from WTD evolution adapting to loop properties.**



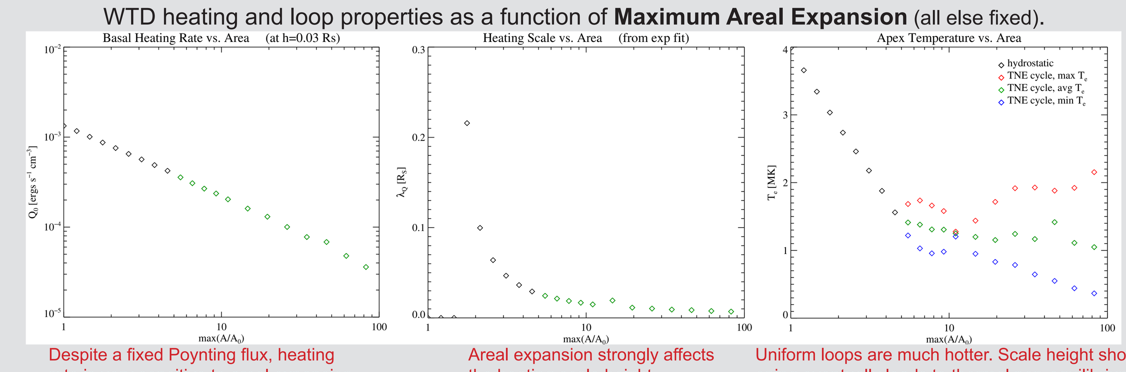
***WTD heating rate and scale height drive a mild thermal non-equilibrium (TNE) cycle on this loop.**

WTD heating and loop properties as a function of **Base Magnetic Field Strength** (all else fixed).



Heat scales with B, slope set by how net Poynting flux scales w/ BCs/loop properties. — Weak field loops attain longer scale heights. — Loop T goes up with heating. Transition from hydrostatic solutions to thermal non-equilibrium cycles.

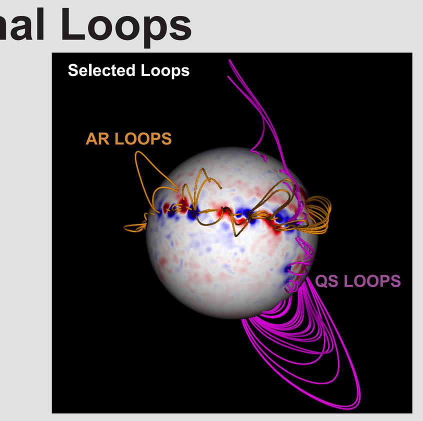
WTD heating and loop properties as a function of **Maximum Areal Expansion** (all else fixed).

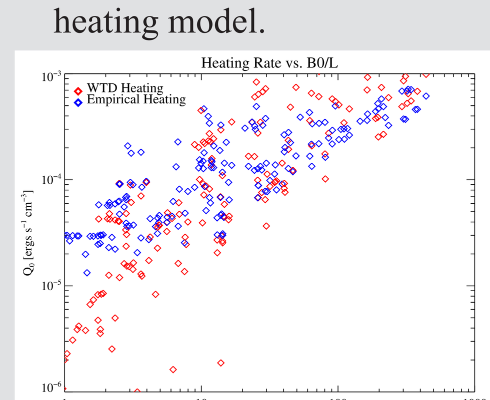


Despite a fixed Poynting flux, heating rate is very sensitive to areal expansion. — Areal expansion strongly affects the heating scale height. — Uniform loops are much hotter. Scale height shortening eventually leads to thermal non-equilibrium.

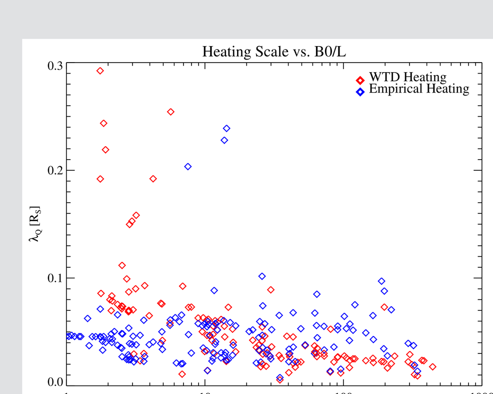
1D Experiments II: Application to Realistic Coronal Loops

- Trace over 10^3 loops from a 3D MHD simulation of the corona on December 15 2011.
- Select a sub-set of loops to test heating models in 1D.
- Select range of apex heights, 50 Quiet-Sun loops, 48 Active Region loops.
- Use these to compare the empirical heating model to the WTD heating model.

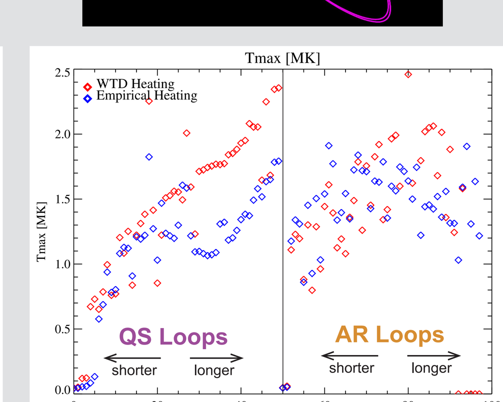




***Approximately B/L scaling from WTD model, even on wide range of loops.**



***Scale height decreases with B/L, → AR loops heated on shorter scales.**



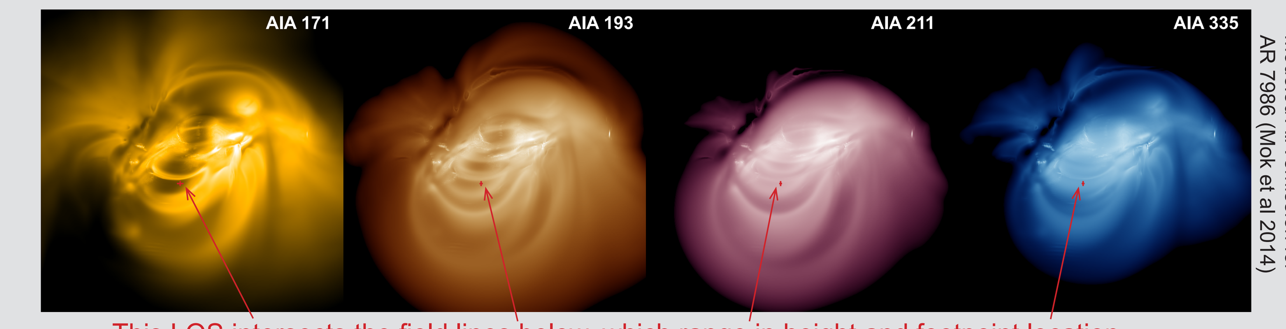
***Longer QS loops attain larger apex T**
*** AR loops similar to empirical model.**

Summary and Conclusions

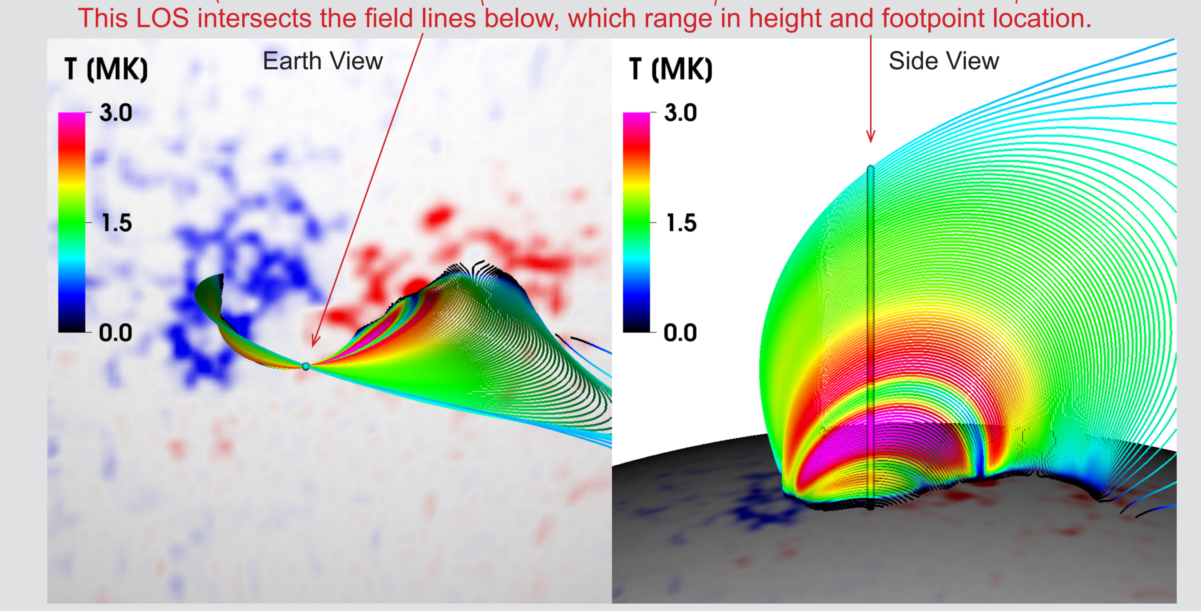
- Wave Turbulence Driven models offer an attractive framework for heating the corona and accelerating the solar wind.
- We study a minimally consistent evolutionary model for Alfvénic turbulence (which includes self-reflection) that is suitable for use in a 3D MHD model.
- We find that this WTD model can compete with our best analytic models used to heat the 3D corona, while significantly reducing the number of free parameters.
- Instead of choosing the heating scale height a priori, the WTD model adapts to the loop geometry and field strength.
  - This automatic scaling is a major benefit of the model.
- Encouragingly, the time-varying emission along an active region LOS heated with the WTD model seems to produce resonable observational signatures, despite the explicit lack of strongly time-dependent heating in the formulation.

1D Experiments III: Active Region Heating

- Want to see if the WTD heating model can produce the time-dependent emission profiles that is typical of Active Regions.
- Start from a 3D box simulation of an AR which used an empirically specified model for coronal heating applied on a 3D NLFF field (Mok et. al 2008 and Mok et al. 2014 in prep).
  - Pick a line-of-sight (LOS) through the AR core, trace 117 field lines that intersect it.

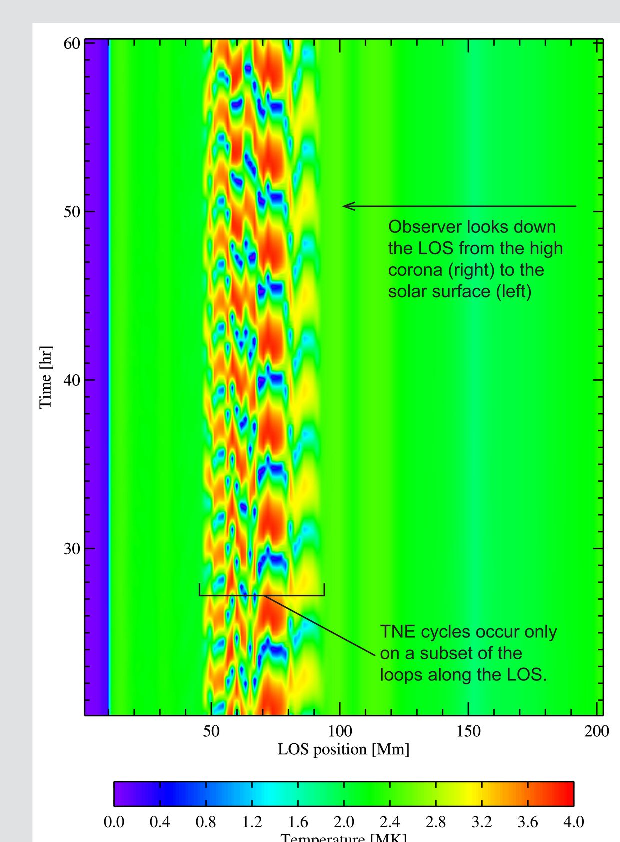


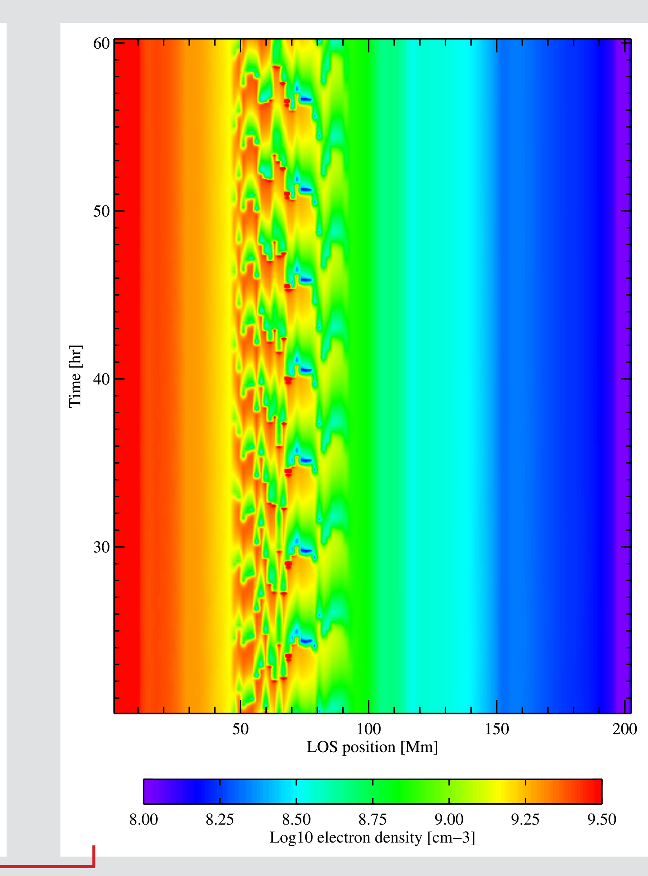
This LOS intersects the field lines below, which range in height and footpoint location.



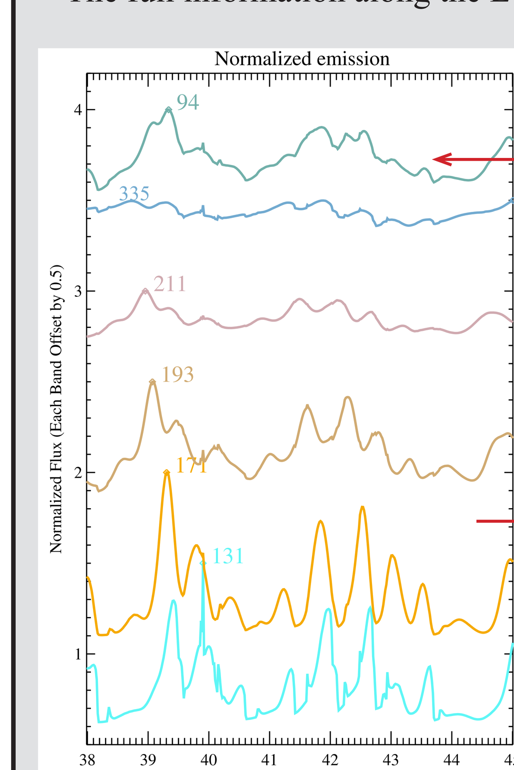
- Next we run the WTD heating model along each field line, and track the evolution of temperature and density at each point along the LOS (the true expansion factor and component of gravity is used at each point along the loop in this 1D simulation).
- As expected, we find that the WTD model heating varies slowly with time. However, the heating scale heights are such that some loops undergo thermal-non-equilibrium.
  - To illustrate this point, we run the simulations again, this time heating with the average WTD heating rate at each point **fixed** in time (shown below).

In other words, steady WTD heating can still lead to non-steady plasma conditions!

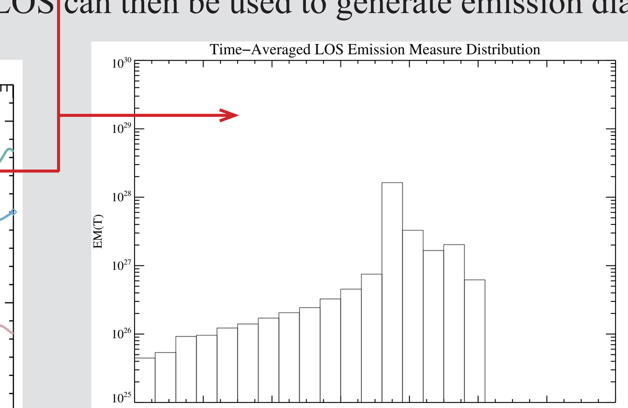




- The full information along the LOS can then be used to generate emission diagnostics:



Synthetic AIA lightcurves from the LOS



- The time-average of the LOS EM(T) distribution shows a range of high and low temperatures along the LOS. The high T peak and sharp falloff seem reasonable, but more investigation is required.

- See Warren et al. 2012 for observational examples.

-The computed AIA time lags show similar cooling characteristics and timescales to those reported by Vial & Klimchuk (2012).

-Here, the heating model is steady, but the cooling signature and emission fluctuations result from the assymetric TNE cycles that occur on some loops along the LOS.