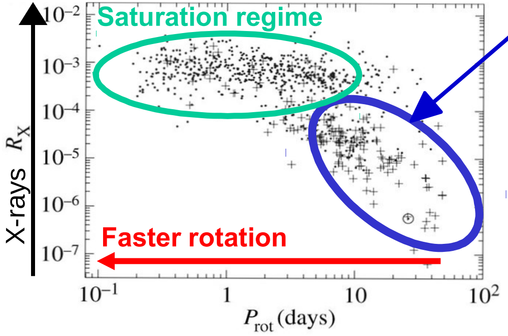
Modeling the corona of stars more active than the Sun using 3D MHD simulations

P-04

Juxhin Zhuleku, Hardi Peter, Jörn Warnecke

Max Planck Institute for Solar System Research, Göttingen, Germany

Motivation and Setup



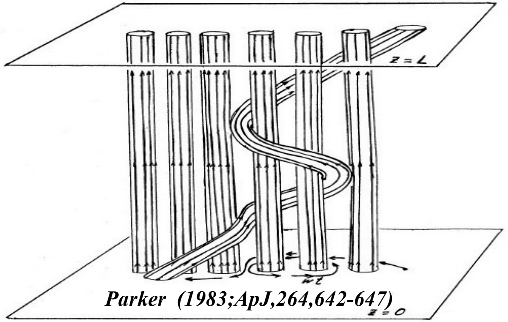
Testa et al. (2015; The Royal Society,373)

X-ray luminosity depends on rotation

Faster rotation:

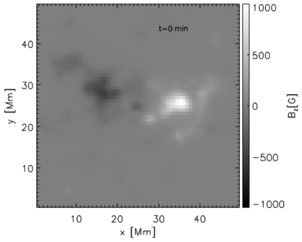
- **stronger magnetic field (Dynamo)**
- **higher coronal energy input**
- **higher coronal temperature**
- **higher X-ray luminosity**

Model 3D Corona



Parker (1983;ApJ,264,642-647)

Initial Condition



- **Photospheric driver motion.**
- **Based on model by S. Bingert, H. Peter (2011,A&A,530,A112)**
- **Resolution of 64x64x64 grid points.**
- **Change the total unsigned magnetic flux** $\Phi = \iint |B_z| dxdy$ **at the bottom boundary by a factor of 20 (by simply multiplying B at bottom boundary).**
- **All other parameters remain the same.**
- **Pencil Code (https://github.com/pencil-code/).**

Cases	Φ[Mx]
Reference	8.4×10^{20}
2B	1.7×10^{21}
5B	4.2×10^{21}
10B	8.4×10^{21}
20B	1.7×10^{22}

IRIS-9, Göttingen, 25-29 June 2018

Poster

1. Fundamental physical processes and modeling

Modelling the corona of stars more active than the Sun using 3D MHD simulations

J. Zhuleku[1], H. Peter[1], J. Warnecke[1]

[1] *Max Planck Institute for Solar System Research, Göttingen, Germany*

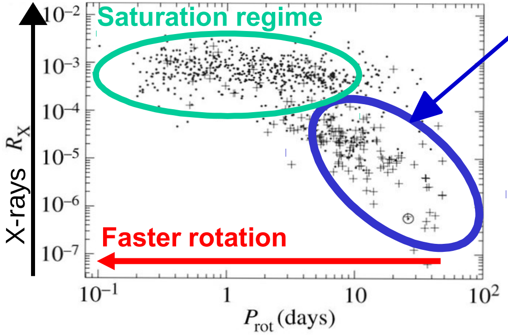
Solar-like stars are surrounded by a million K hot corona. Observations show that faster rotating stars tend to have stronger magnetic field at the surface. This should lead to an increased energy input to the corona and thus to a brighter and hotter corona, just as seen in X-ray observations.
3D numerical magnetohydrodynamic (MHD) models of an active region in the Sun were successful in reproducing aspects of the coronal structure and dynamics. Our goal is to apply this model to stars more active than the Sun and understand the relation between the surface magnetic field and the heat input into the corona. For this purpose we use the Pencil Code to solve the MHD equations with the heating being through the Ohmic dissipation of currents. These are induced by the surface magnetic field being driven around by convective motions.
In our project we change the strength of the magnetic field at the bottom boundary (i.e the unsigned flux) as a first step to understand how the heat input into the corona will change quantitatively. Preliminary results show that the average temperature in the model corona relates to the coronal energy input as expected from the Rosner, Tucker, Vaiana(RTV) scaling laws. More importantly, we can also quantify how the coronal energy input relates to the magnetic flux at the surface indicating that the corona with temperatures from 1 MK to 10 MK can be heated by flux-braiding/nanoflare heating.

P-04

Modeling the corona of stars more active than the Sun using 3D MHD simulations

Juxhin Zhuleku, Hardi Peter, Jörn Warnecke
Max Planck Institute for Solar System Research, Göttingen, Germany

Motivation and Setup



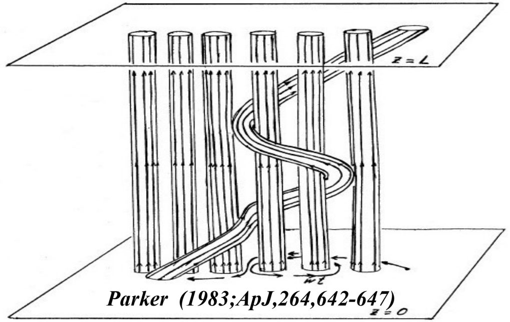
Testa et al. (2015; The Royal Society,373)

X-ray luminosity depends on rotation

Faster rotation:

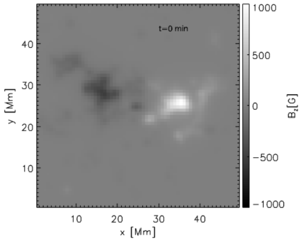
- stronger magnetic field (Dynamo)
- higher coronal energy input
- higher coronal temperature
- higher X-ray luminosity

Model 3D Corona



Parker (1983;ApJ,264,642-647)

Initial Condition



- Photospheric driver motion.
- Based on model by S. Bingert, H. Peter (2011,A&A,530,A112)
- Resolution of 64x64x64 grid points.
- Change the total unsigned magnetic flux $\Phi = \iint |B_z| dxdy$ at the bottom boundary by a factor of 20 (by simply multiplying B at bottom boundary).
- All other parameters remain the same.
- Pencil Code (https://github.com/pencil-code/).

Cases	Φ[Mx]
Reference	$8.4\text{x}10^{20}$
2B	$1.7\text{x}10^{21}$
5B	$4.2\text{x}10^{21}$
10B	$8.4\text{x}10^{21}$
20B	$1.7\text{x}10^{22}$

SOLAR SYSTEM SCHOOL

MAX-PLANCK-GESELLSCHAFT

Modeling the corona of stars more active than the Sun using 3D MHD simulations

P-04

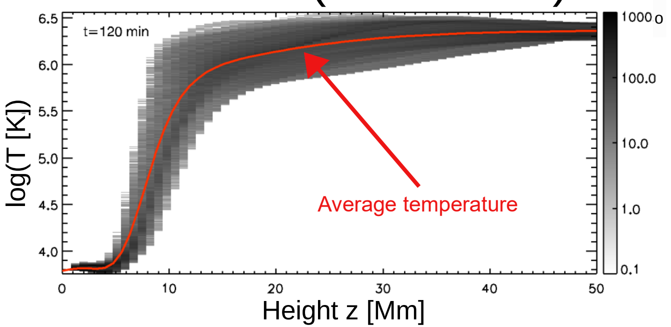
Juxhin Zhuleku, Hardi Peter, Jörn Warnecke

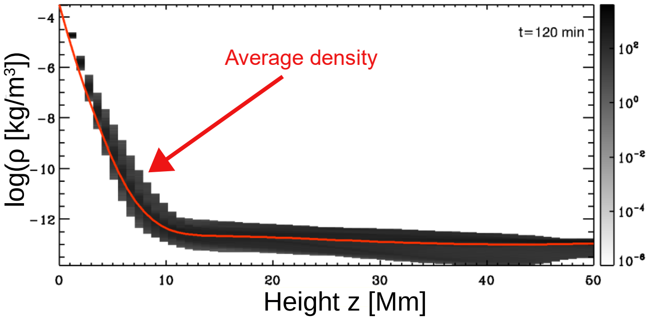
Max Planck Institute for Solar System Research, Göttingen, Germany

MPS

Average properties of a typical solar active region

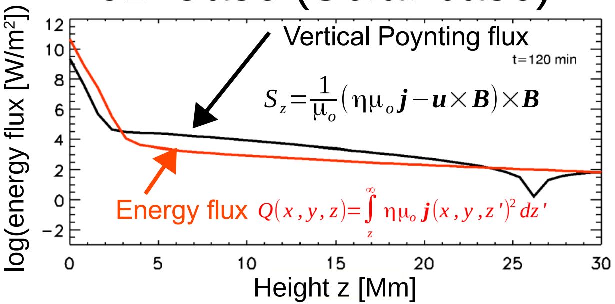
5B Case (Solar case)





- **Probability density function of logT, logρ**
- **Snapshot at t=120 min (saturated phase).**
- **Spatial variability at any height.**
- **Temperature rises to 1 MK, consistent with previous models.**
- **Density drops to 10^{-13} kg/m^3, consistent with previous models.**

5B Case (Solar case)



- **Energy flux drops with height.**
- **Poynting flux roughly follows the heat flux.**
- **The 5B case successfully reproduces the basic aspects of coronal dynamics.**
- **Consistent with previous results.**

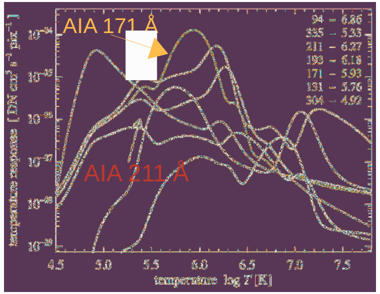
P-04

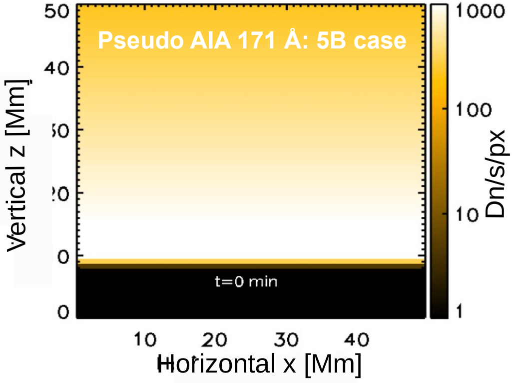
Modeling the corona of stars more active than the Sun using 3D MHD simulations

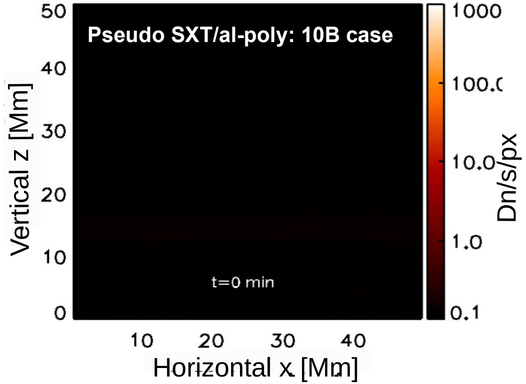
Juxhin Zhuleku, Hardi Peter, Jörn Warnecke
Max Planck Institute for Solar System Research, Göttingen, Germany

Synthetic emission

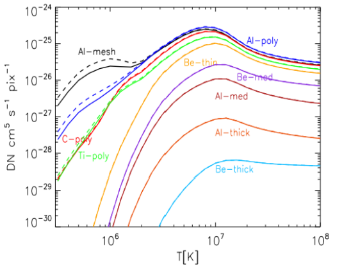
AIA response function







XRT response function



Temperature response function provides emissivity at each gridpoint:

- Emissivity calculated through CHIANTI atomic data base or simpler approximations

- To synthesize observations: integrate along line-of-sight through box

- The loop structure in both cases is similar but in different temperature.

- With our model we can synthesize EUV and X-ray emission despite low resolution.

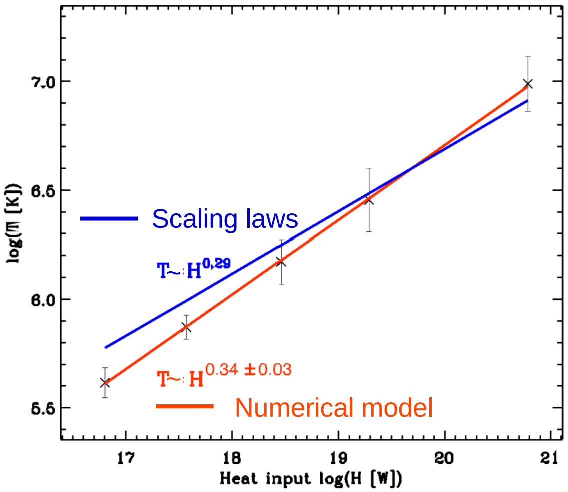
P-04

Modeling the corona of stars more active than the Sun using 3D MHD simulations

Juxhin Zhuleku, Hardi Peter, Jörn Warnecke
Max Planck Institute for Solar System Research, Göttingen, Germany

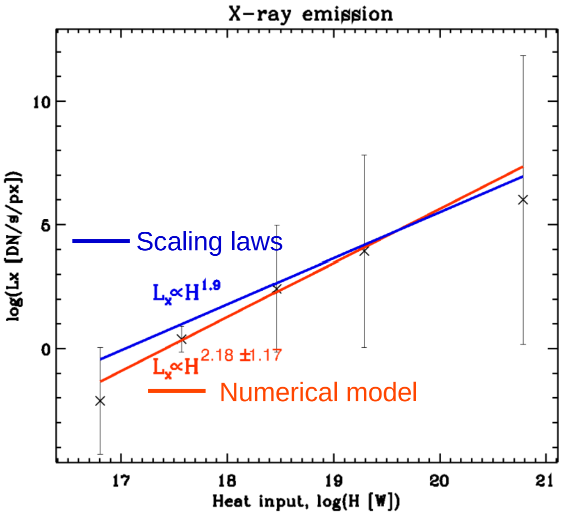
Scaling laws

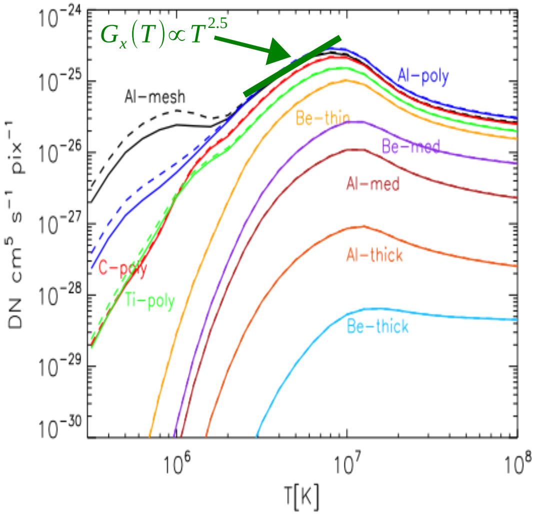
Temperature versus heat input



- Compare model to scaling laws for a heat conduction corona

- Simulations seem to roughly follow the RTV scaling laws.





- Extending scaling laws

RTV: $T \propto H^{2/7}$, $n \propto H^{4/7}$

X-ray response: $G_x(T) \propto T^{2.5}$

$$L_x = n^2 G_x(T)$$

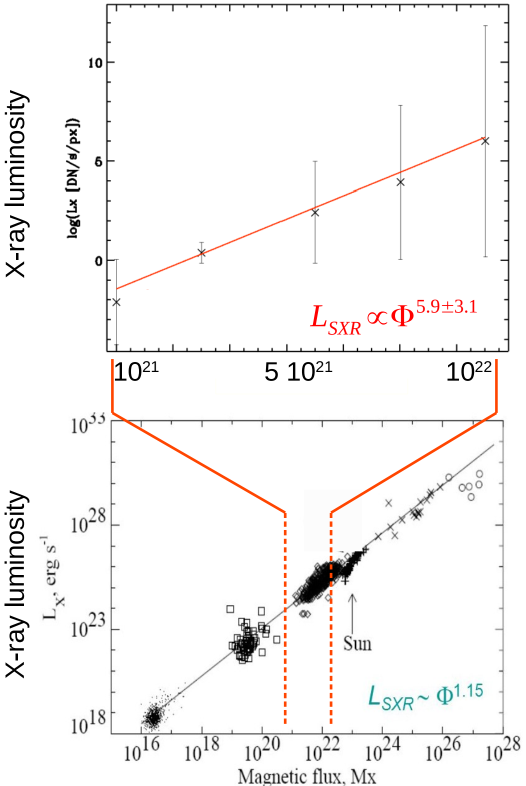
$$\rightarrow L_x \propto H^{1.9}$$

P-04

Modeling the corona of stars more active than the Sun using 3D MHD simulations

Juxhin Zhuleku, Hardi Peter, Jörn Warnecke
Max Planck Institute for Solar System Research, Göttingen, Germany

Conclusions & future work



Pevtsov et al. (2003,ApJ,598,1387-1391)

Main conclusions

- Increase of X-ray with total surface magnetic flux.
- Slope of power law relating X-ray luminosity to magnetic flux is much steeper in Models than in observations.
- Preliminary results from high resolution simulations confirm previous result.
- Problem: We only increase |B| and keep structure of B at bottom boundary constant Then Poynting flux S~$|B|^2$ is consistent with our results.
- Solution: More realistic models with different filling factors of B at the bottom Boundary or larger spatial extent of active region.

Future work

- Change the spatial distribution of initial magnetogram (e.g. filling factor).
- Change the velocity distribution profile for other stars.

Modeling the corona of stars more active than the Sun using 3D MHD simulations

Juxhin Zhuleku, Hardi Peter, Jörn Warnecke
Max Planck Institute for Solar System Research, Göttingen, Germany

Back up slides

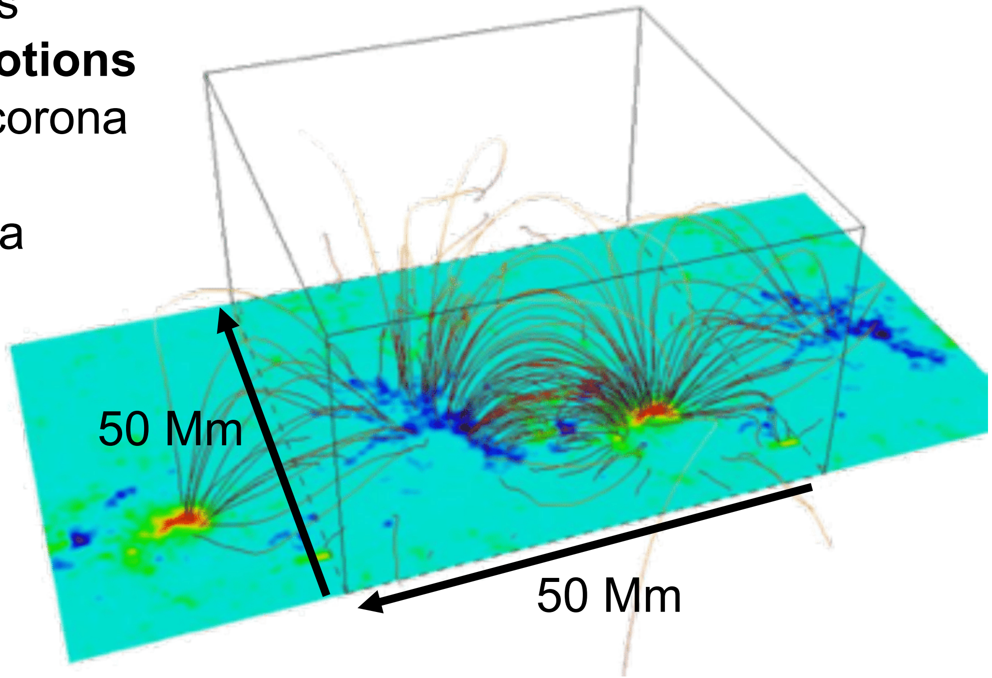
P-04

Modeling the corona of stars more active than the Sun using 3D MHD simulations

Juxhin Zhuleku, Hardi Peter, Jörn Warnecke
Max Planck Institute for Solar System Research, Göttingen, Germany

Computational box

Braiding of fieldlines through **surface motions** induce currents in corona that are dissipated and heat the plasma



Modeling the corona of stars more active than the Sun using 3D MHD simulations

P-04

Juxhin Zhuleku, Hardi Peter, Jörn Warnecke
Max Planck Institute for Solar System Research, Göttingen, Germany

MHD equations

- Mass Conservation $$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0$$
- Momentum Equation $$\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla)\vec{u} = \frac{1}{\rho}(-\nabla P + \rho \vec{g} + \vec{j} \times \vec{B} + 2\nu \nabla \times (\rho \bar{S}))$$
- Energy Equation $$\frac{\partial e_{th}}{\partial t} + (\vec{u} \cdot \nabla) e_{th} = -\frac{\gamma}{\gamma - 1} P(\nabla \cdot \vec{u}) + \eta \mu_0 j^2 - L_{rad} - \nabla \cdot \vec{q}$$
- Induction equation $$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{u} \times \vec{B}) - \eta \nabla^2 \vec{B}$$
- Equation of State $$P = \frac{k_B}{\mu m_p} \rho T$$
- Spitzer Heat Conduction $$\vec{q} = K T^{5/2} \hat{b} (\hat{b} \cdot \nabla T)$$

Ohmic Heating

Modeling the corona of stars more active than the Sun using 3D MHD simulations

Juxhin Zhuleku, Hardi Peter, Jörn Warnecke
Max Planck Institute for Solar System Research, Göttingen, Germany

EUV emission

- Line emission of electrons collisional excitation
- Emissivity is defined as $E_i = n^2 G_i(T)$
- For each line:
  - ➢ G(T): Contribution function(atomic properties)
  - ➢ n: number density
  - ➢ Squared: we have exciting ions and electrons
- G(T) is dominated by ionization equilibrium

$$G_i(T) \propto \exp(-\frac{(\log T - \log T_o)^2}{(\Delta \log T)^2})$$

- The response function is $E_{total} = \sum E_i = \sum G_i(T) n^2 = R_{AIA} n^2$

P-04

Modeling the corona of stars more active than the Sun using 3D MHD simulations

Juxhin Zhuleku, Hardi Peter, Jörn Warnecke
Max Planck Institute for Solar System Research, Göttingen, Germany