2025 Community Space Weather Modeling And Data Assimilation Workshop

Next-Generation MHD Modeling of Solar Wind Using Neural Operators

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Thomas Berger

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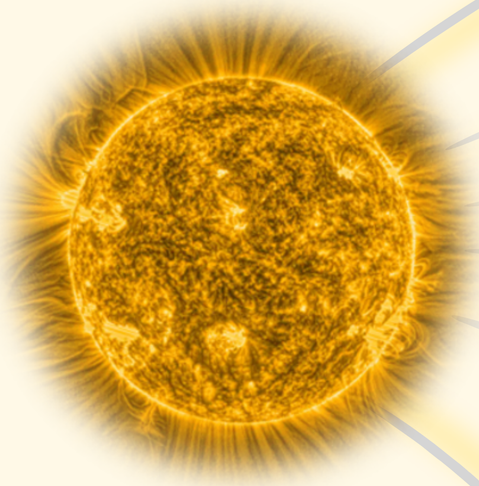
UNIVERSITY OF MICHIGAN Zhenguang Huang
Gabor Toth

Current Modeling Approaches



Solar Wind

0.1 AU

1.0 AU

WSA
(semi-empirical)

MHD
(physics-based)

MHD
(physics-based)

Provides: magnetic field (**B**), velocity (**V**), pressure (P) & density (ρ)

Runtime: >200 CPU hours

- ENLIL
  Odstrcil et al., 2003
- EUHFORIA
  Pomoell & Poedts 2018
- SWASTi
  Mayank et al., 2022

Empirical
(crude approximation)

Provides: only speed (|**V**|)

Runtime: few CPU minutes

- HUX
  Riley & Lionello 2011
- HUXt
  Owens et al., 2020

Machine Learning
(statistical pattern-based)

Provides: only speed (|**V**|)

Runtime: few CPU seconds

- *Yang et al., 2018*
- *Upendran et al, 2020*
- *Lin et al., 2024*
- *Cobos et al., 2025*

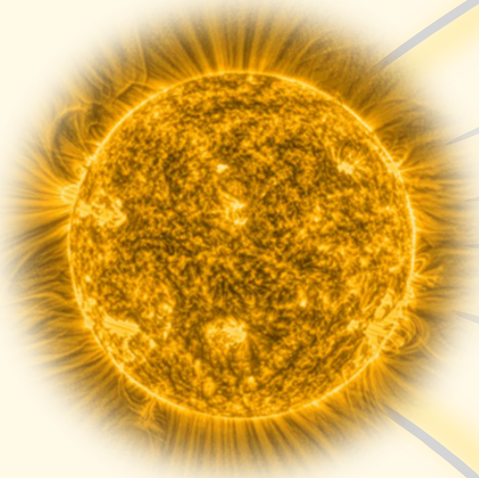
Remote Sensing and In-situ Spacecrafts
(SDO, SoHO, ACE)

Trade-off between physics and speed

Next Generation Approach

0.1 AU

1.0 AU



Solar Wind

WSA+

generalized optimization of WSA

MHD surrogate

Provides: magnetic field (**B**), velocity (**V**), pressure (P) & density (ρ)

Runtime: **few seconds**

Remote Sensing and In-situ Spacecrafts (SDO, SoHO, ACE)

Fast and Reliable

WSA — Solar Wind Relation

$$V = v_{\mathrm{min}} + \frac{v_{\mathrm{max}}}{(1+f_s)^{\mathrm{alpha}}} \times \left(\left(1.0 - a1 \exp\left(\frac{-D}{w} \right)^{\beta} \right)^{\mathrm{a2}} \right)$$

Magnetogram derived quantities:

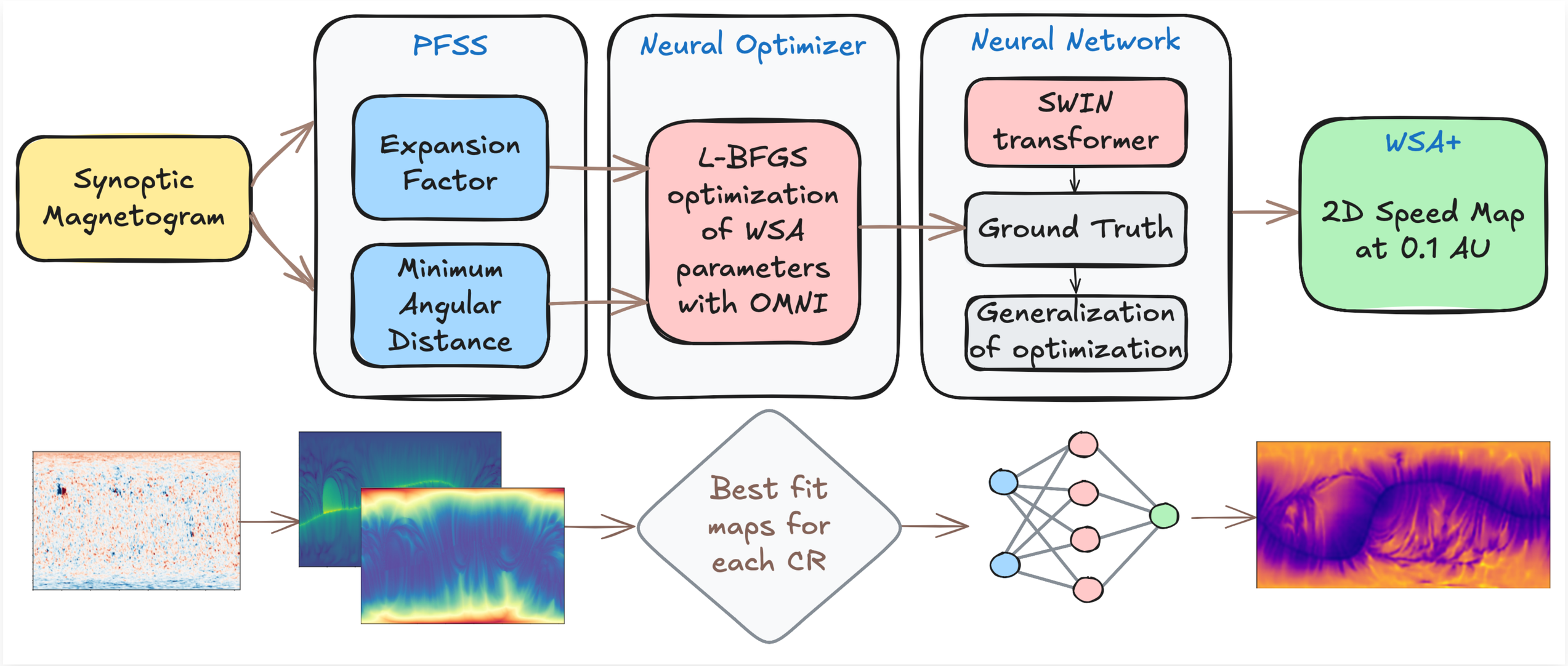
1. expansion factor
2. minimum angular distance from coronal hole boundary

v_max = 750, v_min = 250,

alpha = 0.222, w = 0.028, β = 1.25,

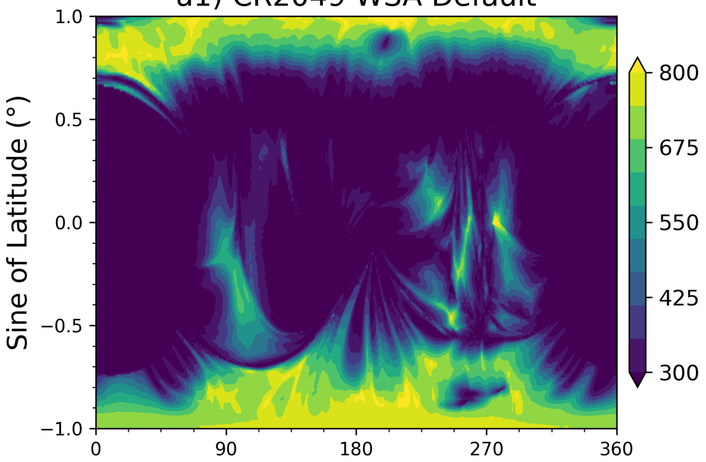
a1 = 0.8, a2 = 3.0

Development of WSA+

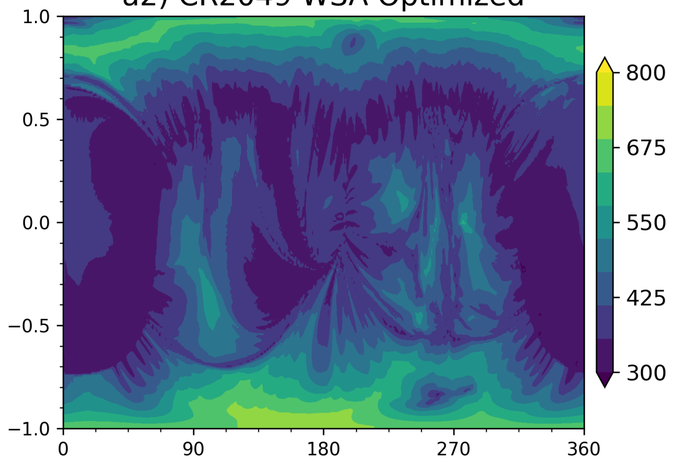


Comparison with WSA

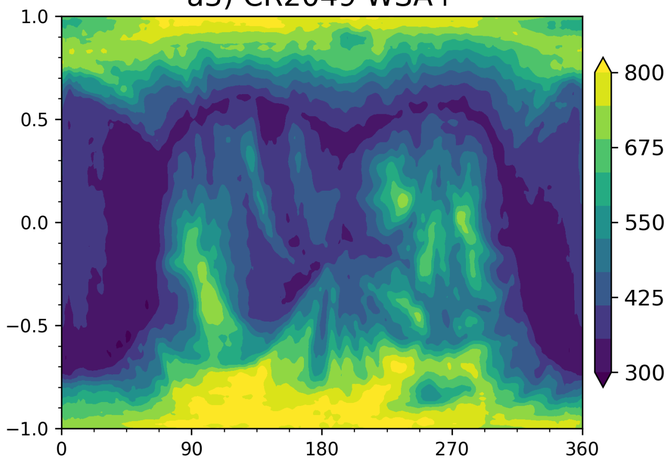
a1) CR2049 WSA Default



a2) CR2049 WSA Optimized



a3) CR2049 WSA+



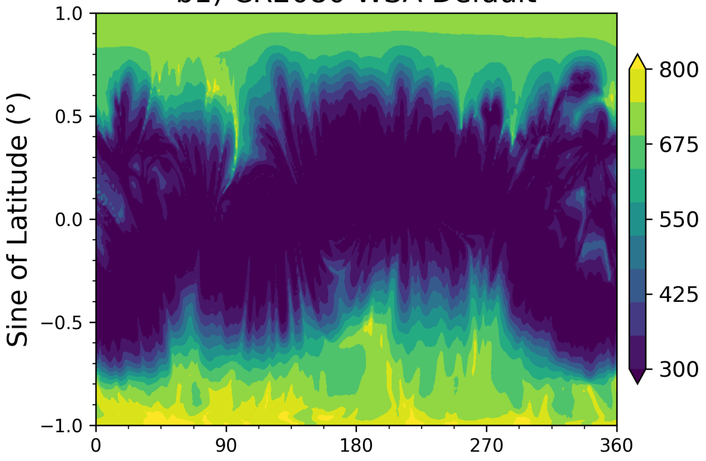
a4) Statistical Summary

```
CR2049 Analysis
========================

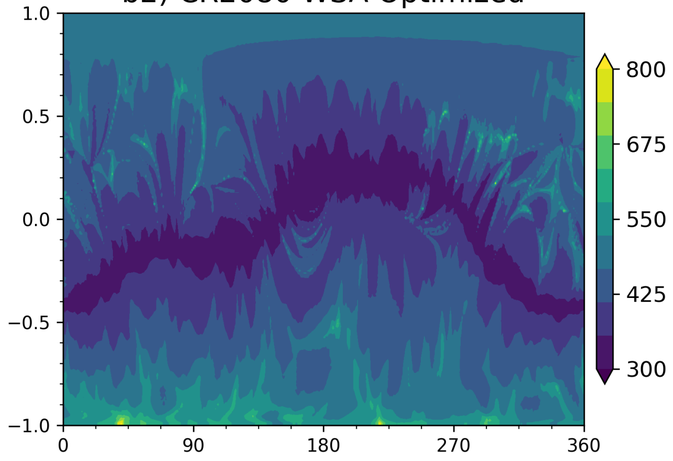
RMSE Comparison:
vs Default: 120.7 km/s
vs Optimized: 100.6 km/s

Correlation Comparision:
vs Default: 0.945
vs Optimized: 0.953
```

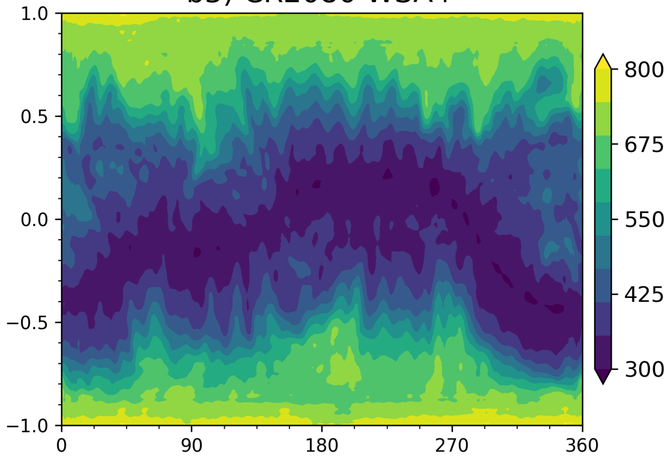
b1) CR2080 WSA Default



b2) CR2080 WSA Optimized



b3) CR2080 WSA+



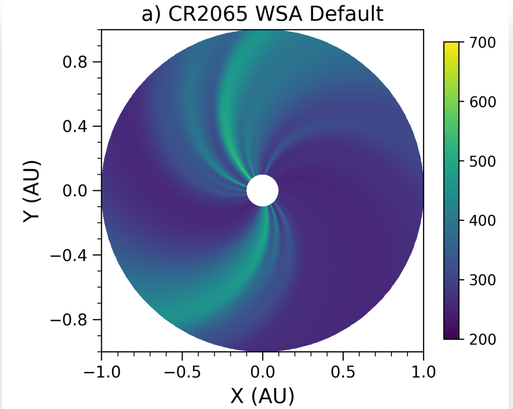
b4) Statistical Summary

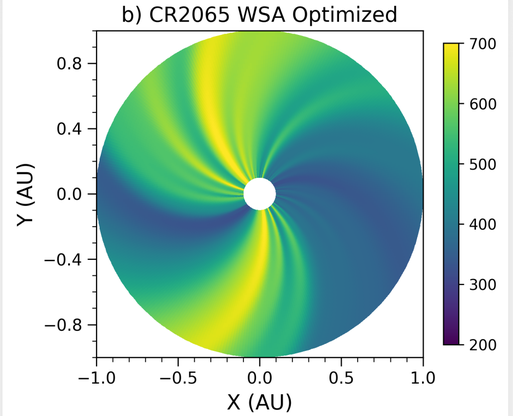
```
CR2080 Analysis
========================

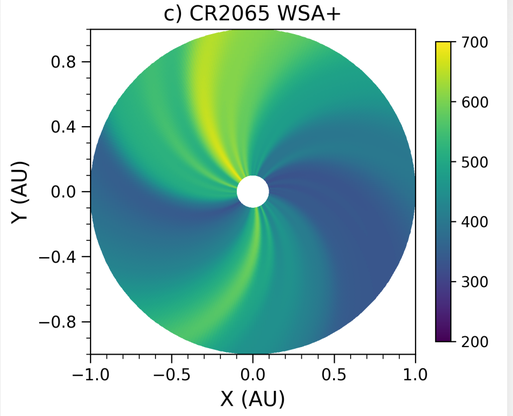
RMSE Comparison:
vs Default: 79.1 km/s
vs Optimized: 133.5 km/s

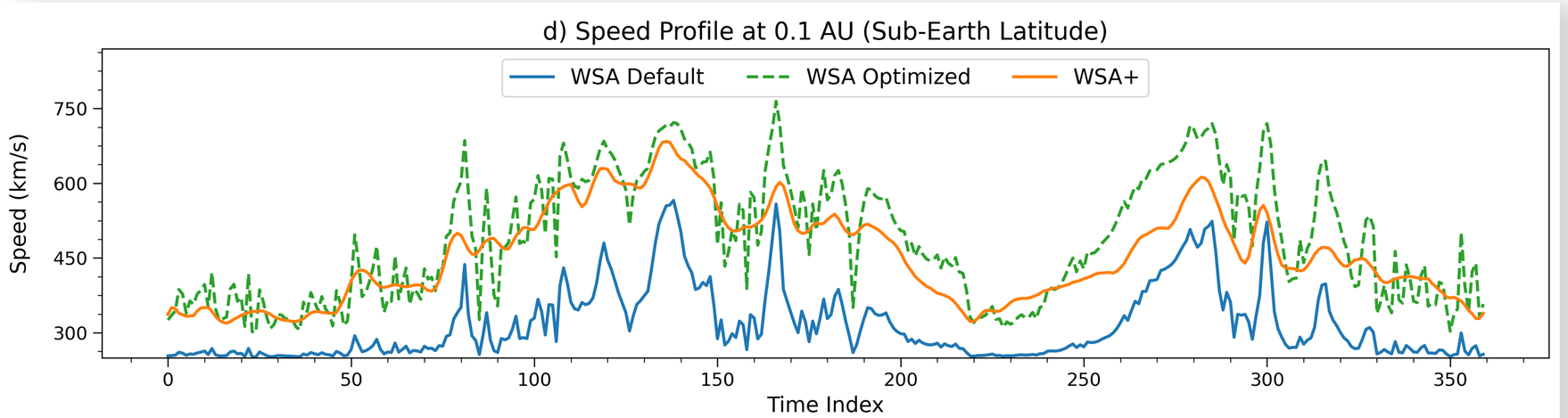
Correlation Comparision:
vs Default: 0.959
vs Optimized: 0.835
```

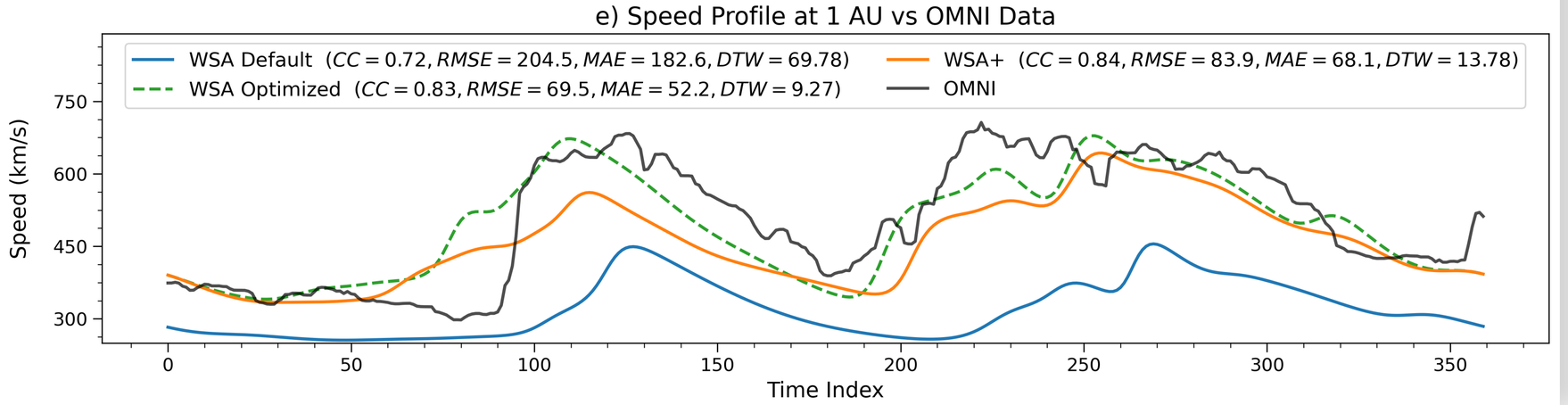
Comparison with OMNI



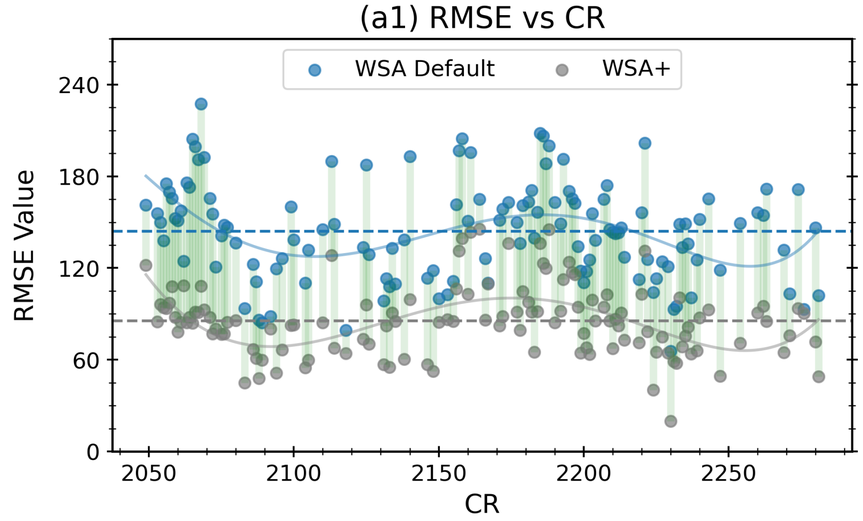


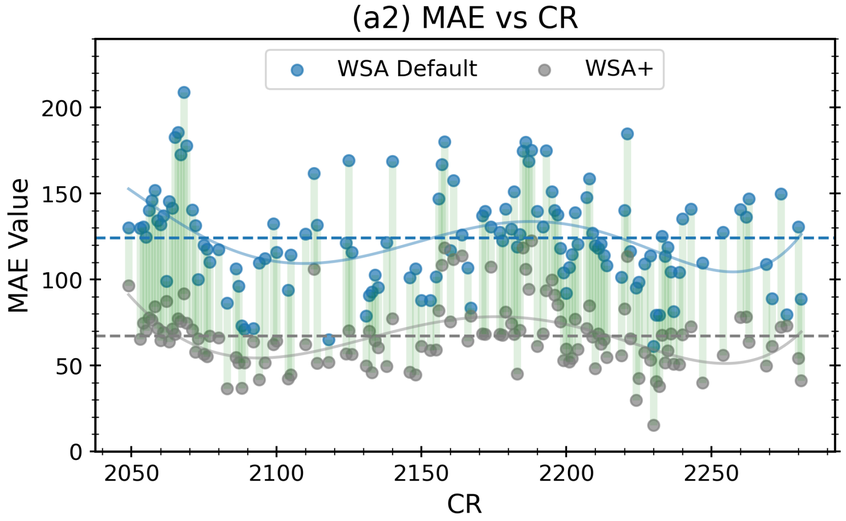


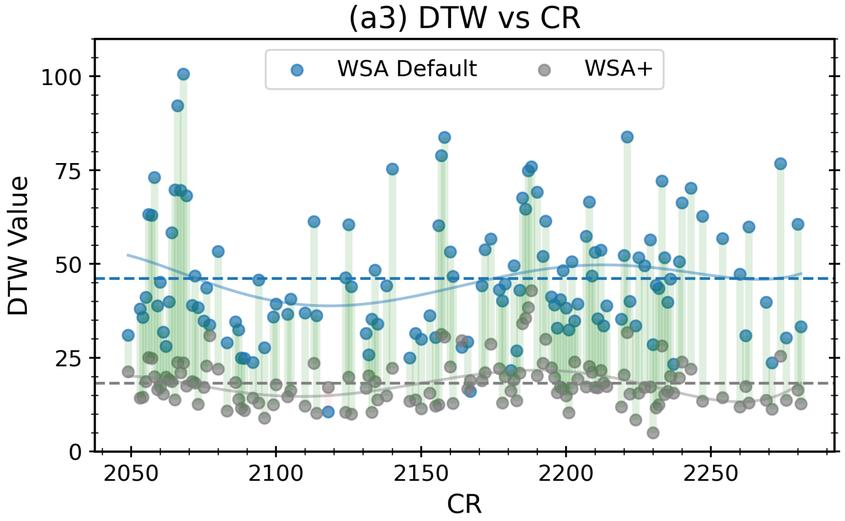


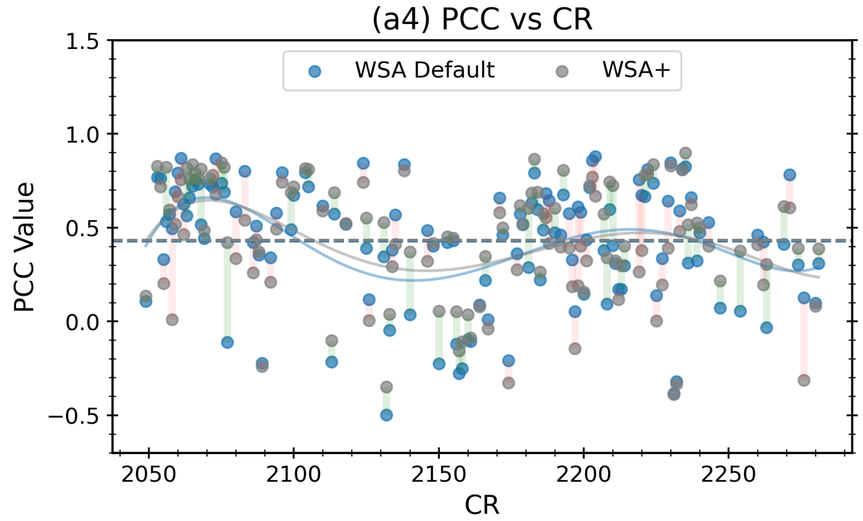


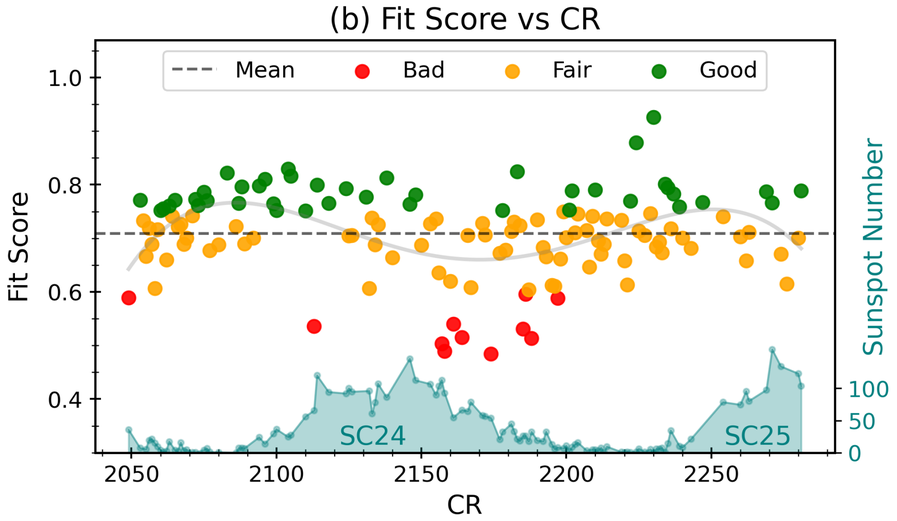
Long Term Analysis









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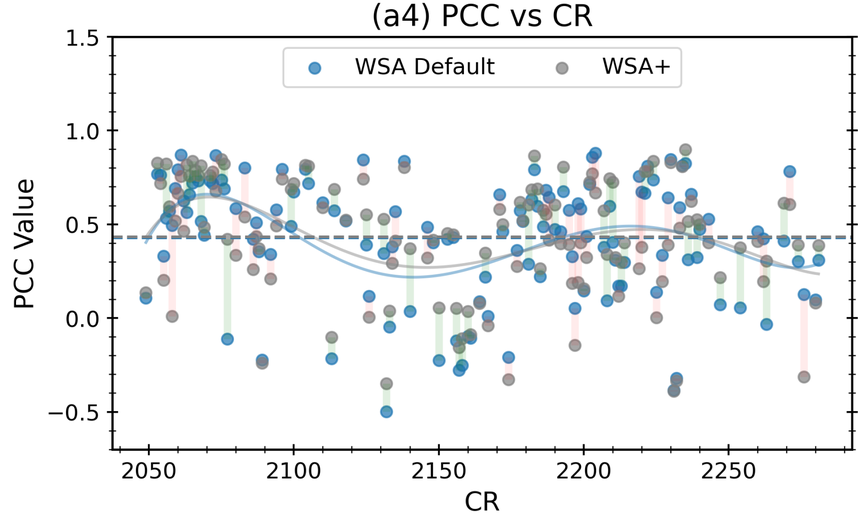
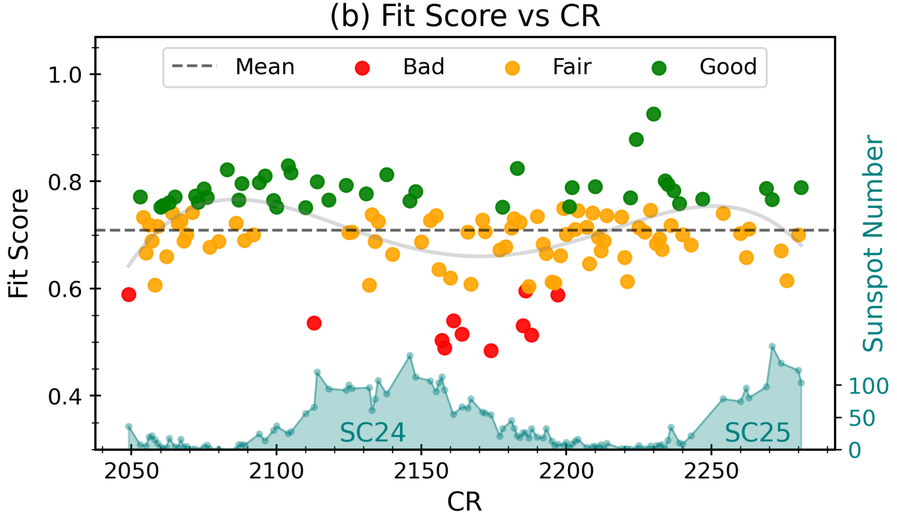
Performance Summary of 129 CRs
==========================================

Avg. Metric        WSA      WSA+     Improvement
------------------------------------------------

Fit Score         0.51      0.71      40.1%
DTW              46.07     18.21      60.5%
RMSE            144.00     85.53      40.6%
MAE             124.15     67.10      45.9%
PCC               0.43      0.43       1.3%
```

Long Term Analysis



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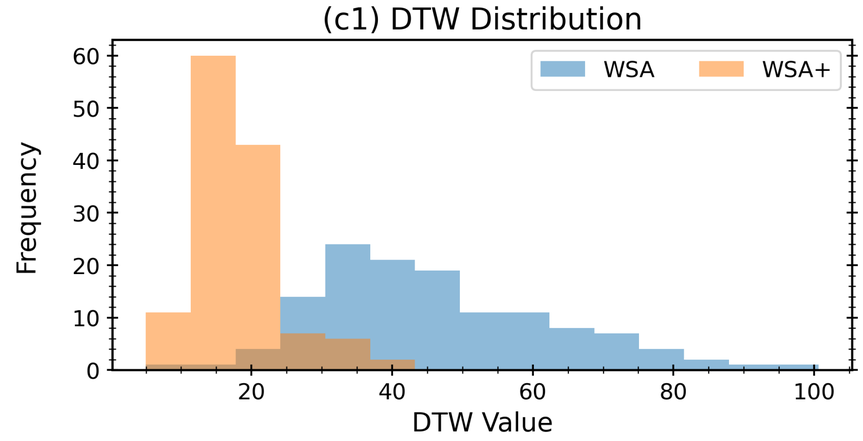

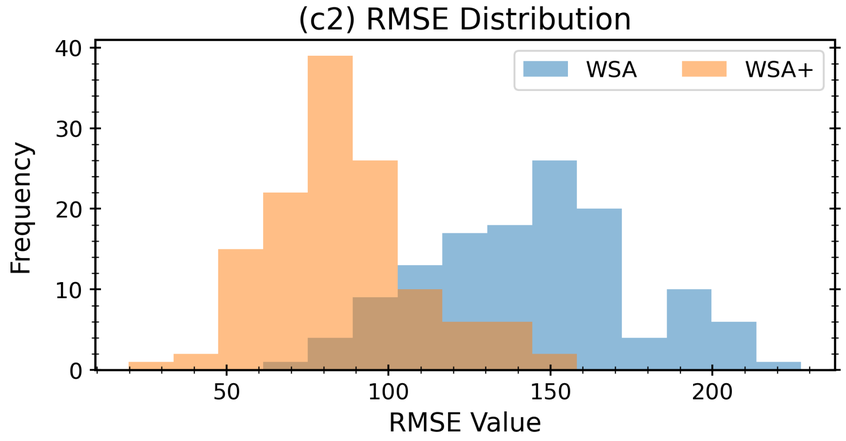

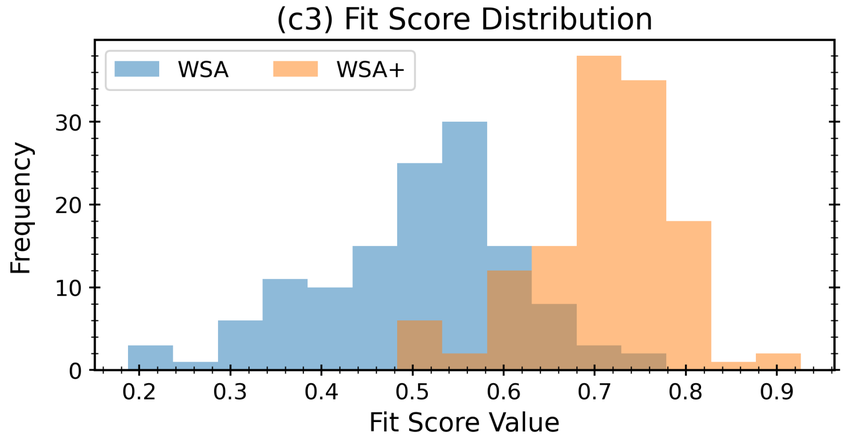

Python Package

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wsaplus 0.1.1

Latest version

```
pip install wsaplus
```

Released: Aug 18, 2025

WSA+: generate solar wind speed maps from synoptic magnetograms

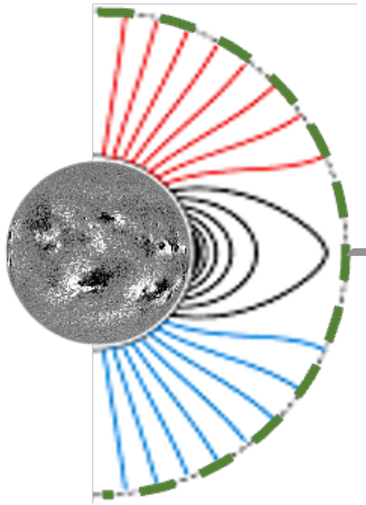
Astrophysics > Solar and Stellar Astrophysics

[Submitted on 7 Sep 2025]

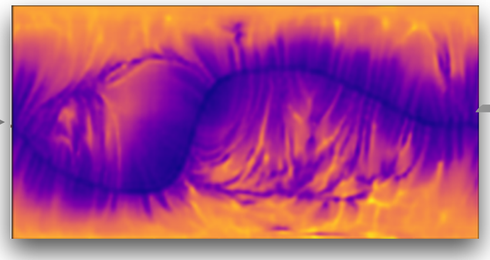
Neural Enhancement of the Traditional Wang-Sheeley-Arge Solar Wind Relation

Prateek Mayank, Enrico Camporeale, Arpit K. Shrivastav, Thomas E. Berger, Charles N. Arge

MHD Surrogate Pipeline



WSA+
solar wind
speed at 0.1 AU



MHD surrogate model

INPUT

2D plasma boundary condition at 0.1 AU

PINO

OUTPUT

3D plasma simulation from 0.1 to 2.0 AU

PDE Loss

Data Loss

INPUT

AWSoM simulation at 0.1 AU

B
V
P
ρ

2D Encoder

Neural Network

2D — 3D Lifting

Learning in Fourier space

Fourier Layers

FFT — iFFT

Neural Network

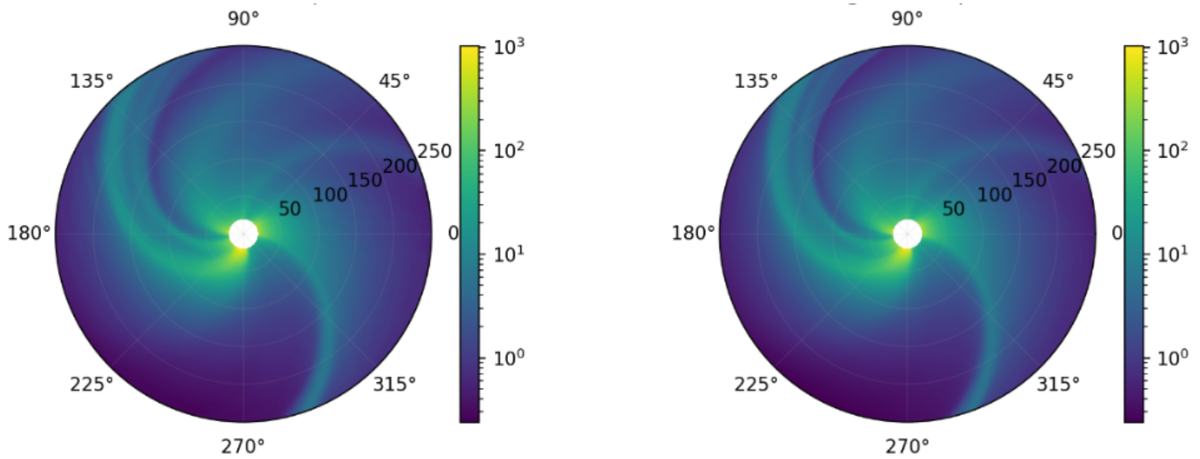
Project back to 8 channels

OUTPUT

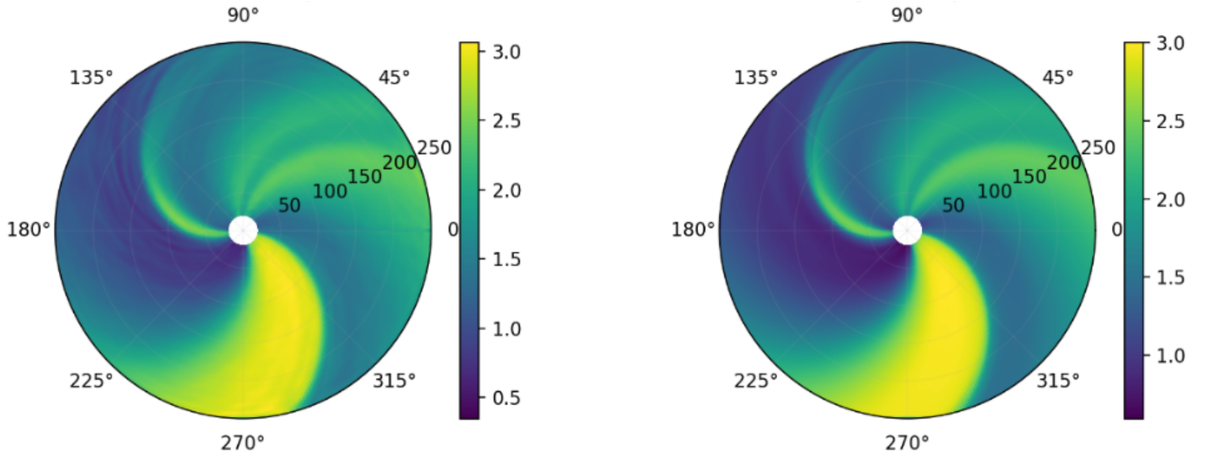
3D profiles of **B**, **V**, ***P***, ρ

Initial Results …

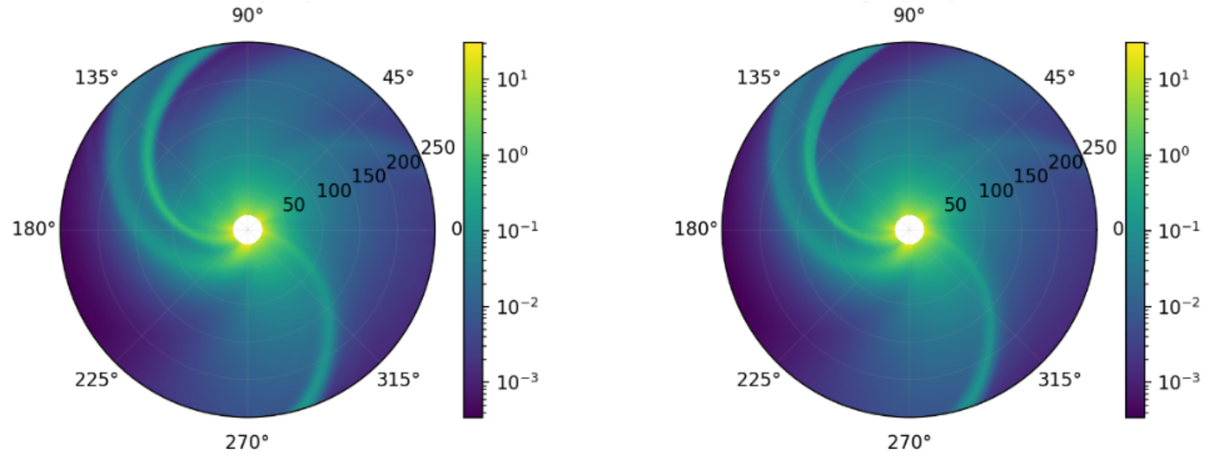
ML **Density** MHD



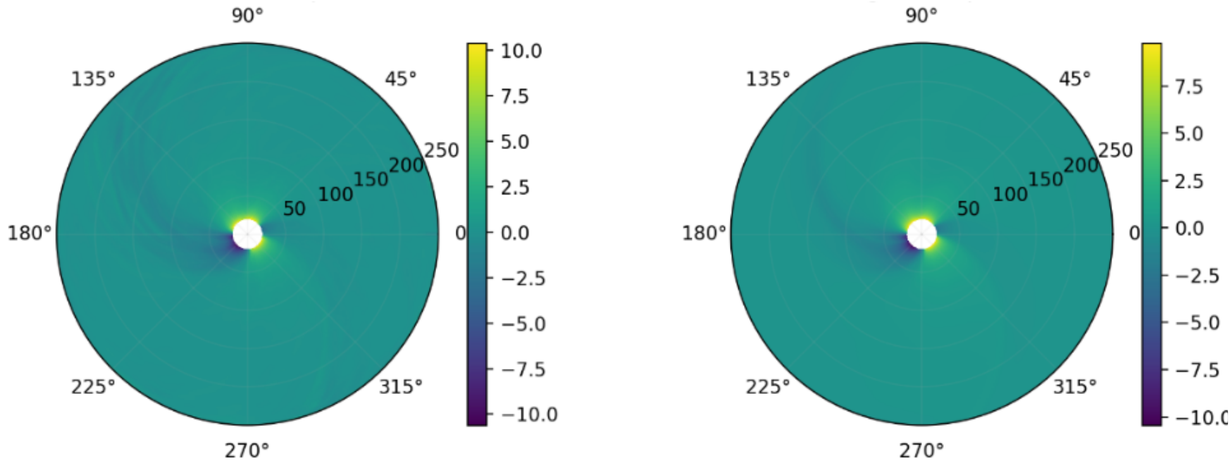
ML **Speed** MHD



ML **Pressure** MHD



ML **Magnetic Field** MHD

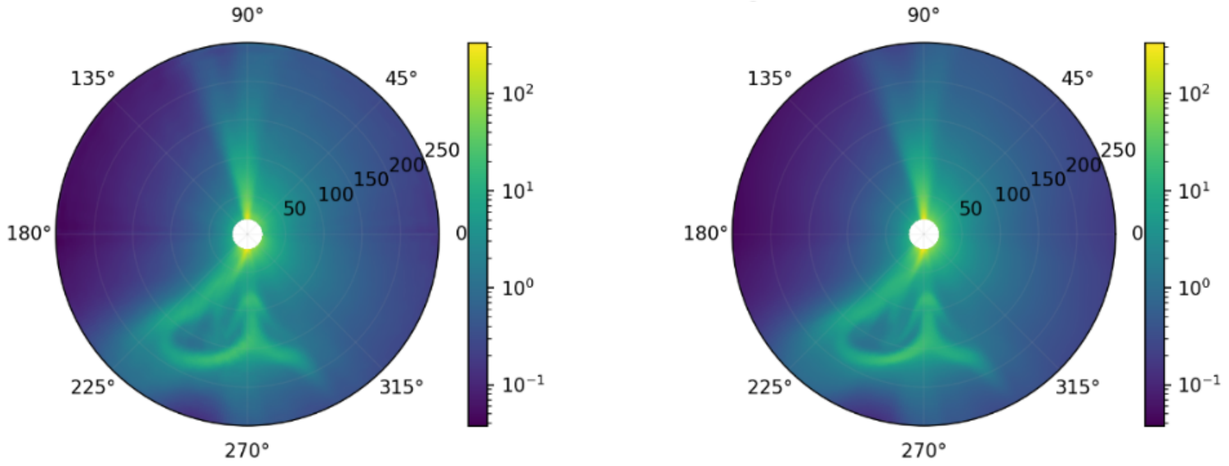


Initial Results …

ML

Density

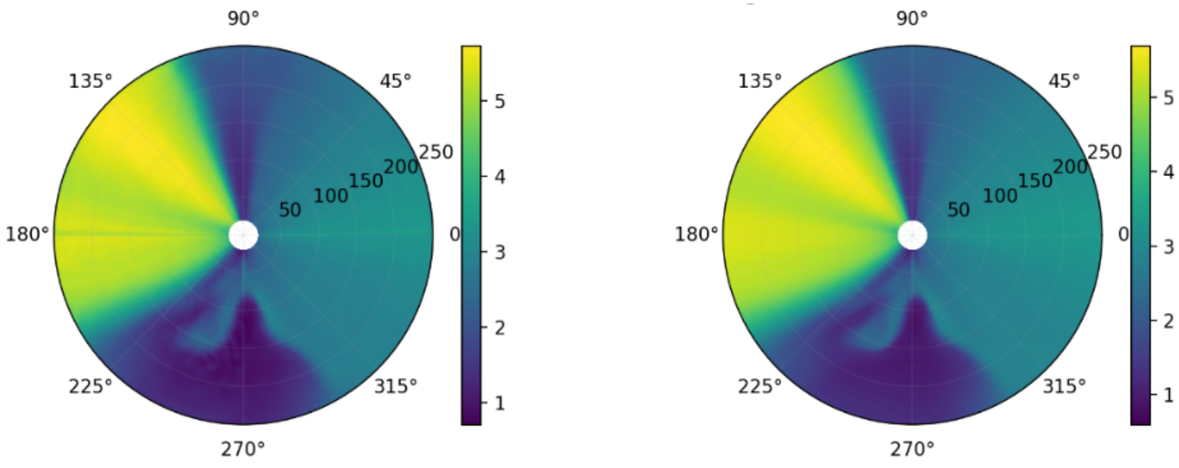
MHD



ML

Speed

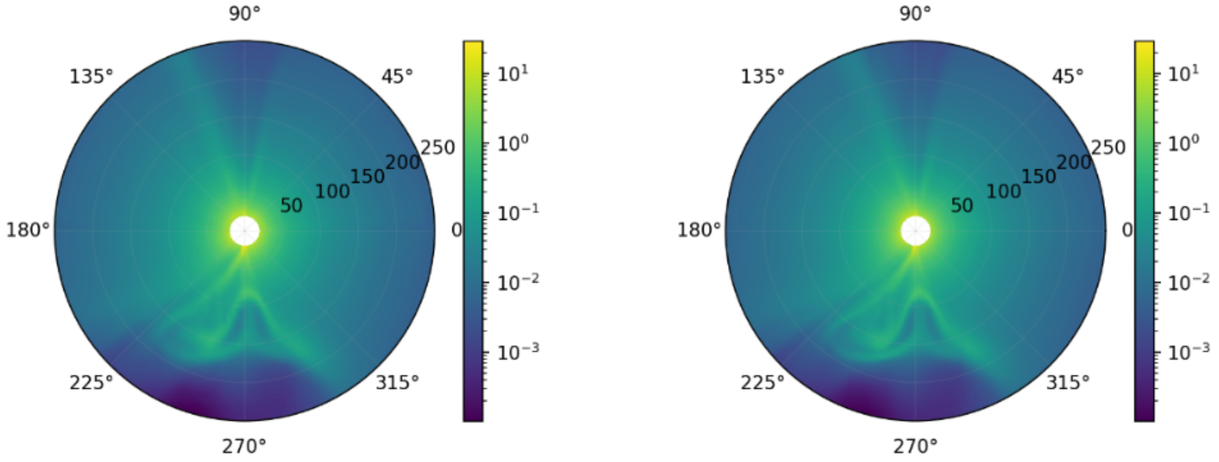
MHD



ML

Pressure

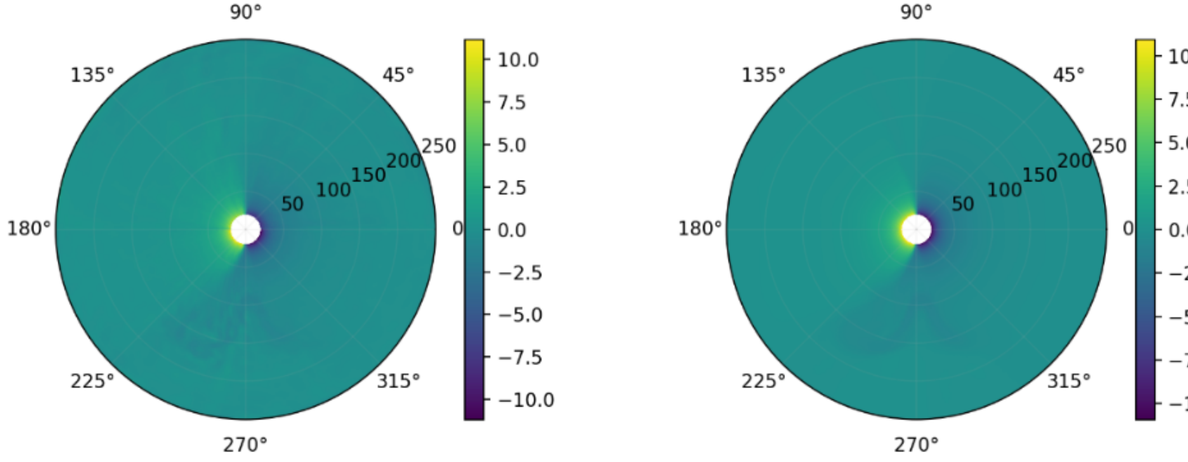
MHD



ML

Magnetic Field

MHD



Summary

1. WSA+

- 40% improvement over traditional WSA model
- Python package available: *pip install wsaplus*

2. MHD surrogate

- Full global MHD solution in seconds
- Can be extended to other PDE systems

3. Sun-Earth Connection

- Full differentiable pipeline from Sun to (near) Earth
- Tune with observations to overcome observational constraints