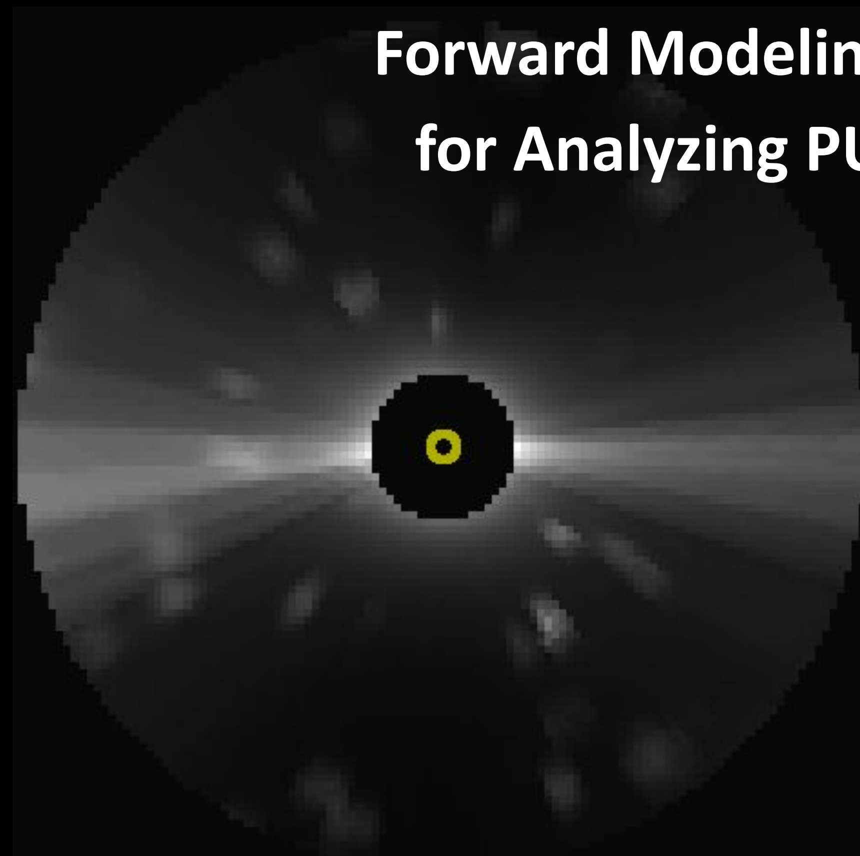
Polarimeter to Unify the Corona and Heliosphere

Forward Modeling as a Tool for Analyzing PUNCH Data



Gilly
PUNCH AI

PUNCH Meeting 2
Aug 11th, 2021
Virtual Meeting

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Who am I? Science

Gilly!

I like to be called **Gilly (he/him),** though I publish under Chris R. Gilly.

1 Paper Published, ~4 in prep, and several collaborations in the works!

The Astrophysical Journal, In Press, August 20, 2020

Typeset using LaTeX **twocolumn** style in AASTeX63

The Effect of Solar Wind Expansion and Non-Equilibrium Ionization on the Broadening of Coronal Emission Lines

Chris R. Gilly[1] and Steven R. Cranmer[1]

[1] *LASP; Department of Astrophysical and Planetary Sciences, University of Colorado, Boulder, Colorado, 80309, USA*

(Received 06/17/2020; Revised 07/28/2020; Accepted 08/20/2020)

Graduate Research Assistant @ CU Boulder
PhD Candidate in Astrophysical and Planetary Science
LASP Researcher (SPSC), Advisor: **Steve Cranmer**
PUNCH Associate Investigator, Advisor: **Sarah Gibson**

Presentation Title: FORWARD Modelling for PUNCH

Who am I? Service

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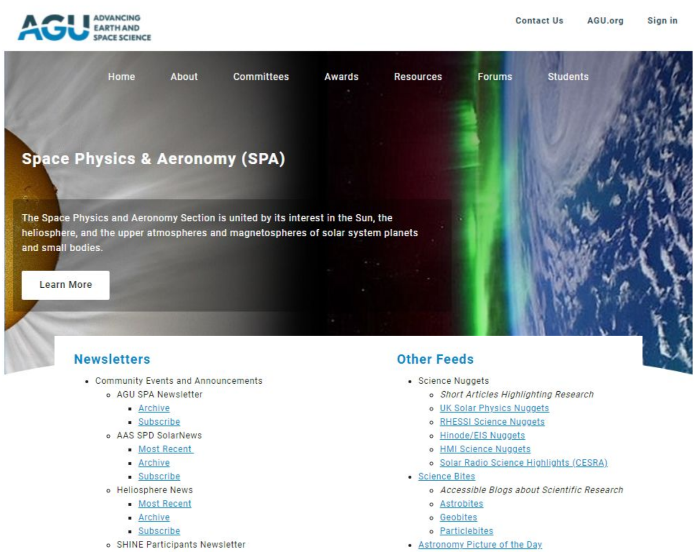
Gilly!

AGU/SPA Student Representative
(Chair of Student Committee)

AGU/SPA Webmaster
https://connect.agu.org/spa/resources



https://helionauts.org/, ask Barbara Thompson for an Invite

SHINE Student Representative
(Chair of Student Committee)

Presentation Title: FORWARD Modelling for PUNCH

Who am I? Outreach

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Gilly!

Science Under the Dome

Public Talk Facilitator
Fiske Planetarium
(website, YouTube)

Author of Program
Whittier Elementary

Author/Founder of
Spark, Spin, and Freeze
GT Physics Outreach Arm

My Work

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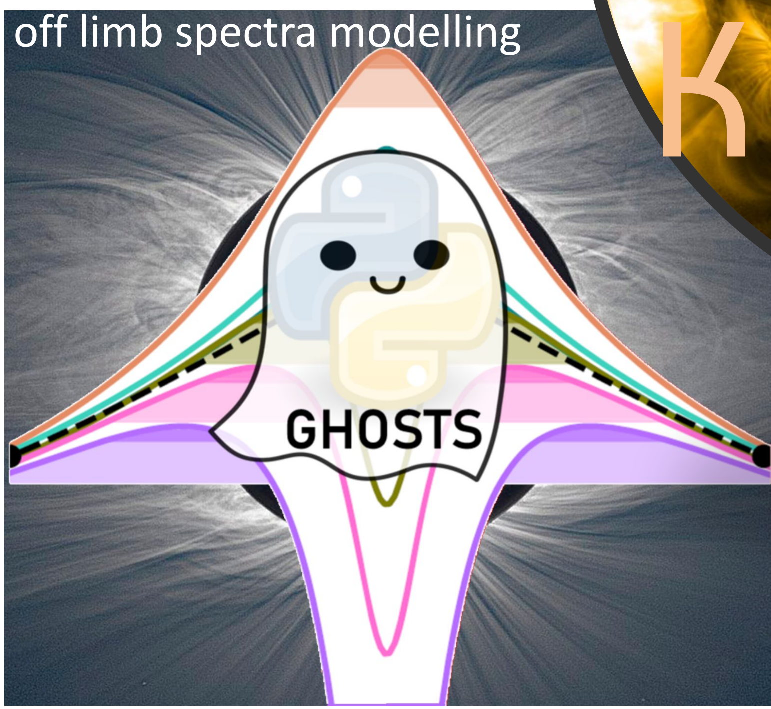

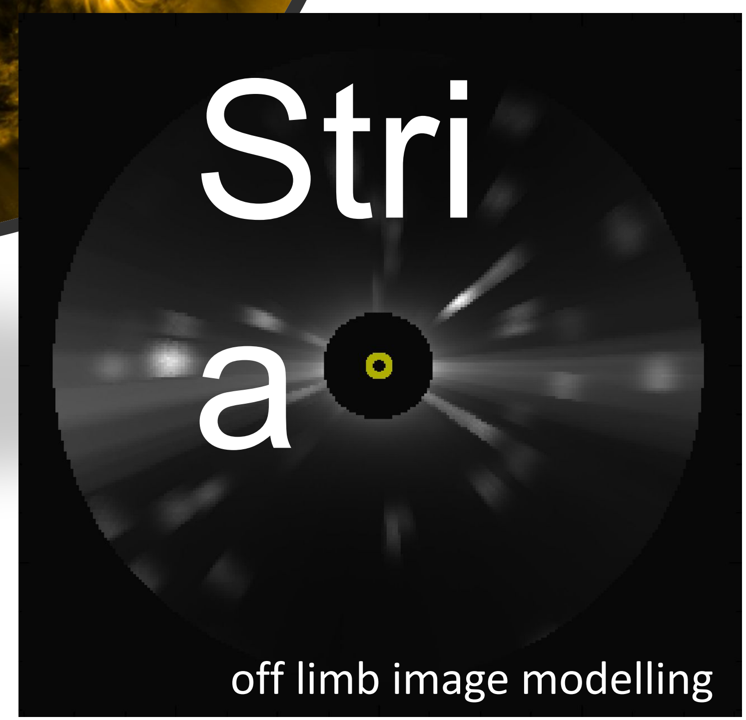

The GHOSTS Model

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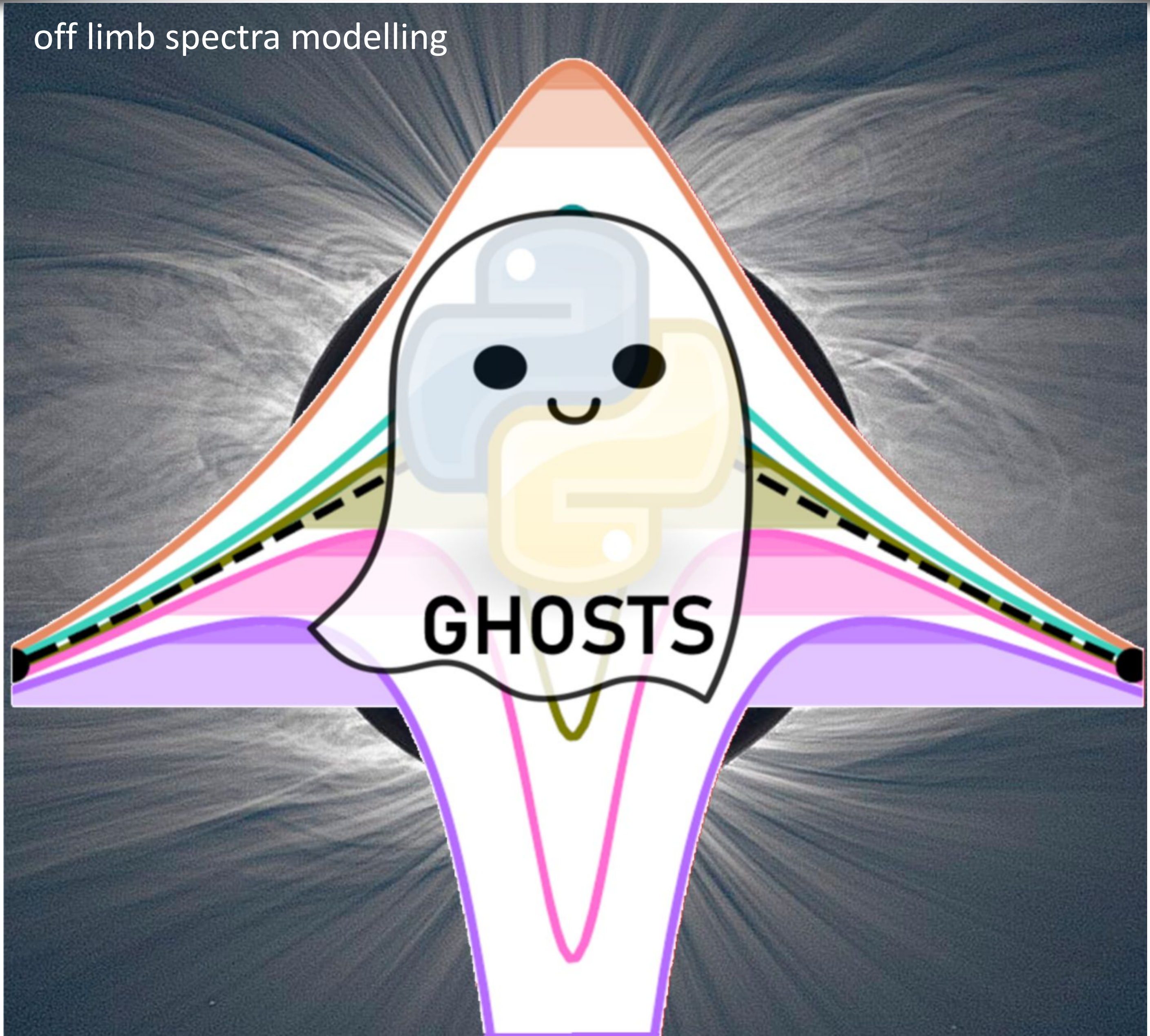

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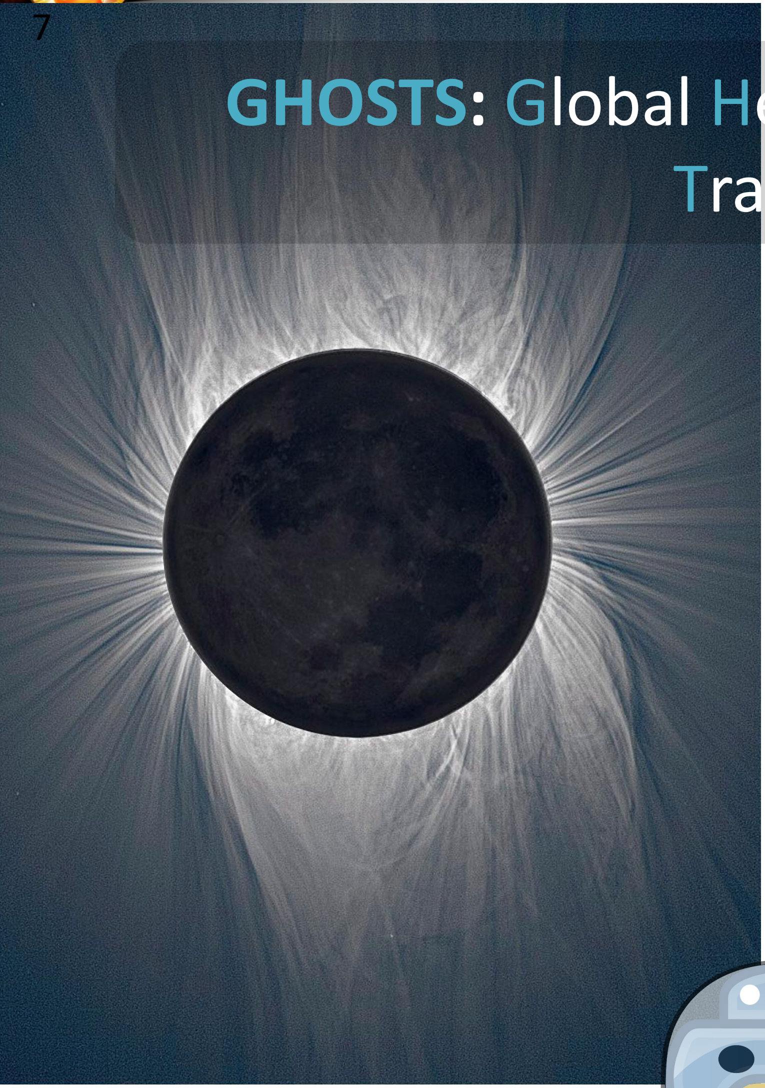
GHOSTS: Global Heliospheric Optically-thin Spectral Transport Simulation



- GHOSTS simulates LOS integration of off-limb coronal emission lines*, in the optically-thin approximation.
- This is a forward model
  - Start with physics -> get observations
- It is semi-empirical: it uses the output from several other models and a few observations to build the solar environment (See Gilly & Cranmer 2020 for details)
  - The code is written in python, and will help us unveil the ghosts in the data.

**for example, the lines seen by Hinode/EIS and SOHO/UVCS*

What kind of observation?

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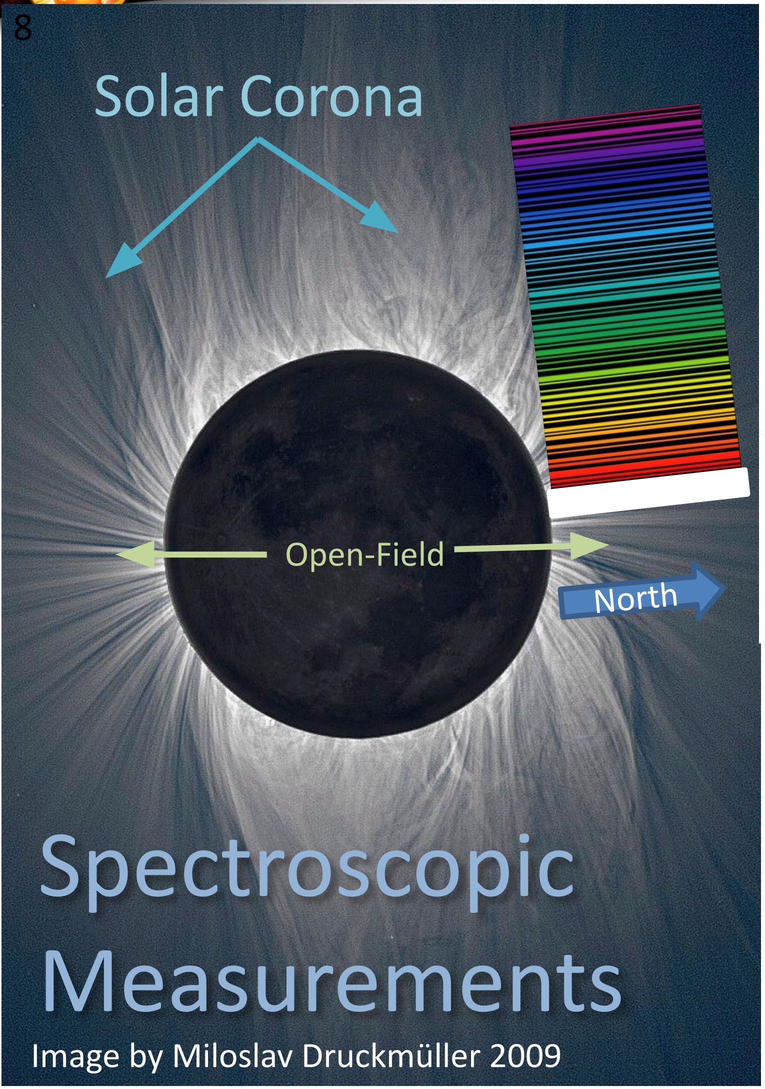

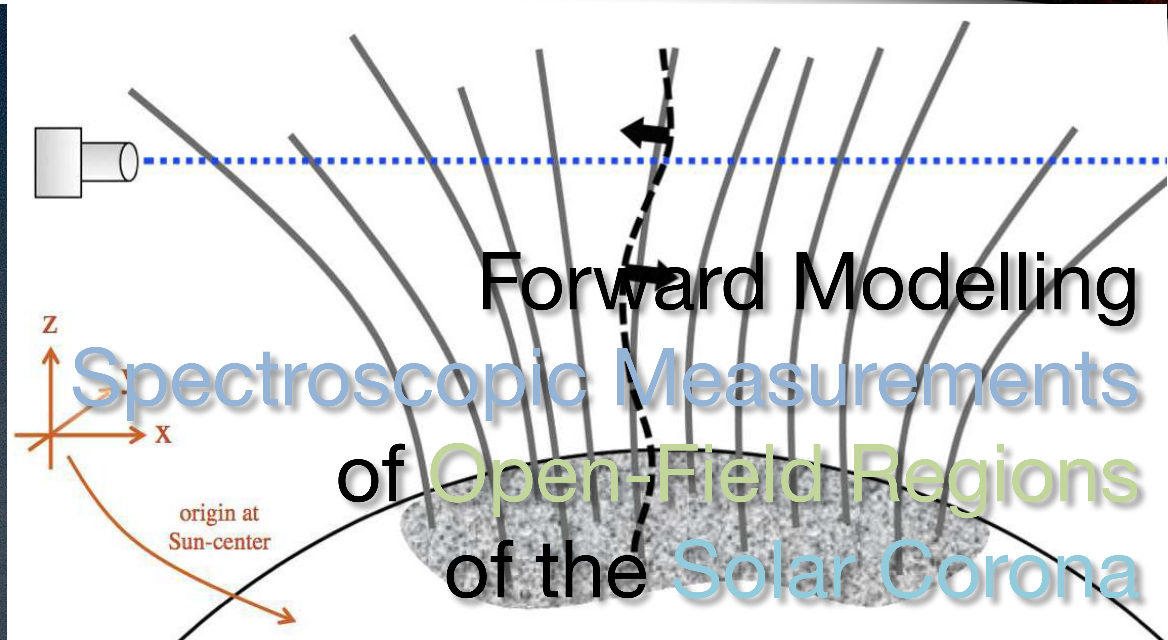

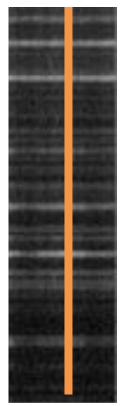

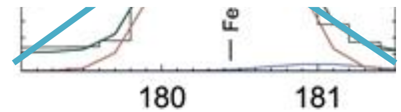

Line of Sight velocity
causes a Doppler shift
in the rest wavelength

Velocity Distribution ->
Wavelength Distribution

Some Physics that Contribute to Line Width:

- Natural Thermal Width
- Solar Wind Outflow Doppler Broadening
- *Alfvén Wave Doppler Broadening (in prep!)*

Elemental Abundance and Ion Fractions

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We use CHIANTI for quantum mechanical parameters

- Provides coronal elemental abundances A_b
- Provides temp-dependent ionization fractions $f(T)$

A caveat: the *ionization fraction stops being dependent on temperature* when the *collision rate gets too low.*

When $\tau_{collision} > \tau_{expansion}$ the particles are unable to reach a collisional equilibrium before they are swept out by the solar wind, and the ionization state becomes frozen-in

$$\frac{1}{fr^2}\frac{\partial}{\partial r}(fr^2 n_i u_i) =$$
$$n_{i-1}C_{i-1} + n_{i+1}R_{i+1} - n_i(C_i + R_i)$$

Equilibrium and NEI Charge States of Oxygen

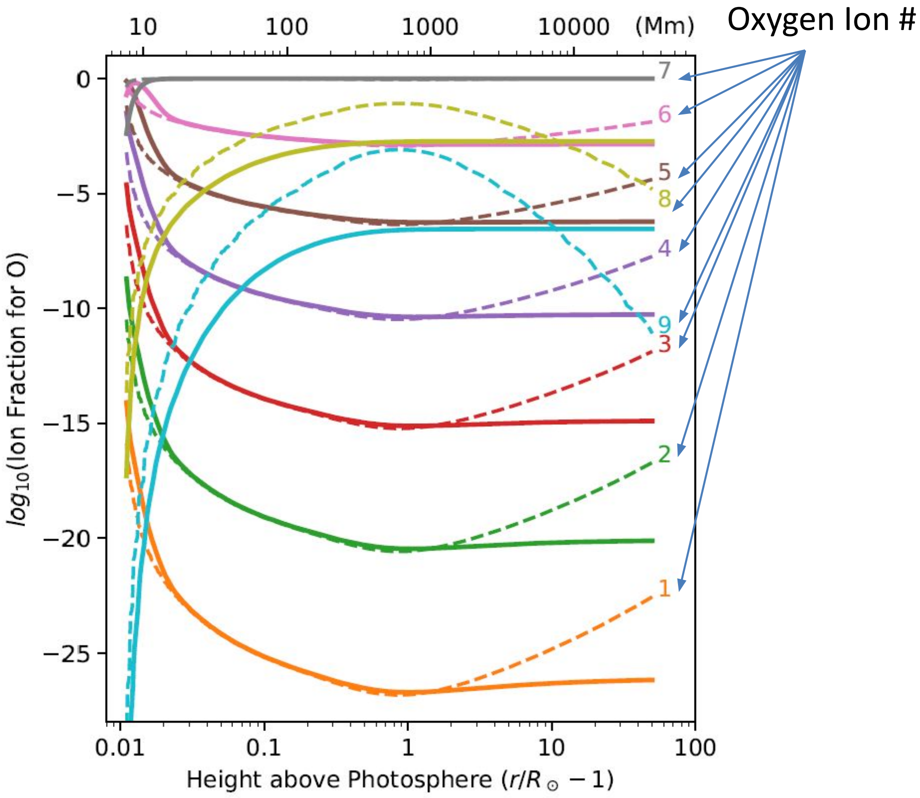

Figure 2. The ionization fractions n_i/n_Z of each of the ions of oxygen. Dashed lines show the equilibrium calculation and solid lines show numerical solutions to Equation (6).

Freezing Heights

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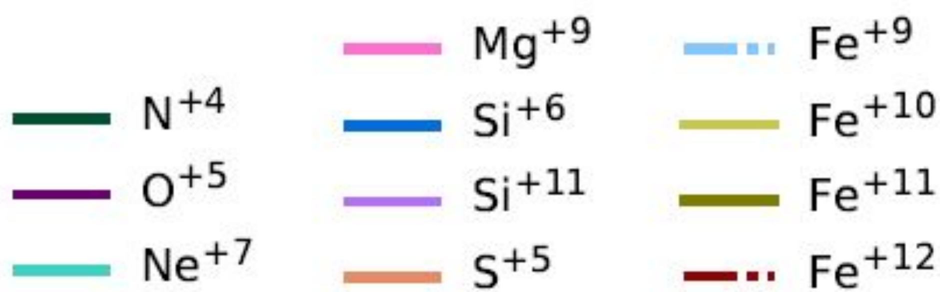
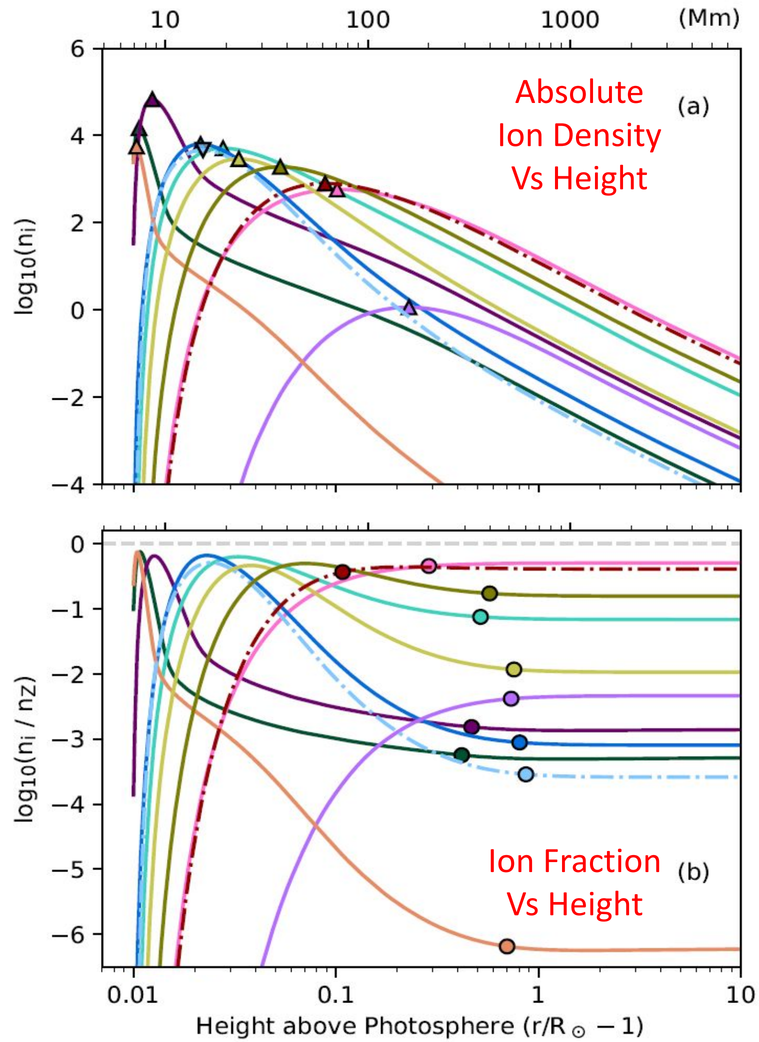
Table 1. Simulated Coronal Emission Lines

Ion	λ_0 (Å)	T_{eq} $\log_{10}$(K)	$q(T_{eq})$ $\log_{10}$(cm^3 s^{-1})	E_1	z_p ($R_\odot$)	z_{fr} ($R_\odot$)	z_p (Mm) ▲	z_{fr} (Mm) ●
N V	1238.82	5.17	−7.97	1/2	0.011	0.417	7.4	290.6
O VI	1031.91	5.36	−8.10	1/2	0.012	0.467	8.6	325.4
O VI	1037.61	5.36	−8.40	0	0.012	0.467	8.6	325.4
Ne VIII	770.43	5.69	−8.35	1/2	0.028	0.517	19.3	360.1
Mg X	624.97	5.95	−8.87	0	0.101	0.287	70.5	200.1
Si VII	275.36	5.62	−9.25	7/20	0.021	0.807	14.9	561.6
Si XII	499.41	6.18	−8.78	1/2	0.229	0.732	159.7	509.9
S VI	933.38	5.12	−7.87	1/2	0.010	0.699	7.2	486.9
Fe X	184.54	5.68	−9.36	0	0.022	0.866	15.3	603.2
Fe XI	188.22	5.76	−8.99	7/20	0.033	0.756	23.1	526.6
Fe XII	195.12	5.84	−8.70	7/25	0.053	0.574	37.0	399.4
Fe XIII	202.04	5.91	−8.55	1	0.088	0.108	61.5	75.02

We chose 12 lines to model for this work





Flow Free Run (Thermal Case)

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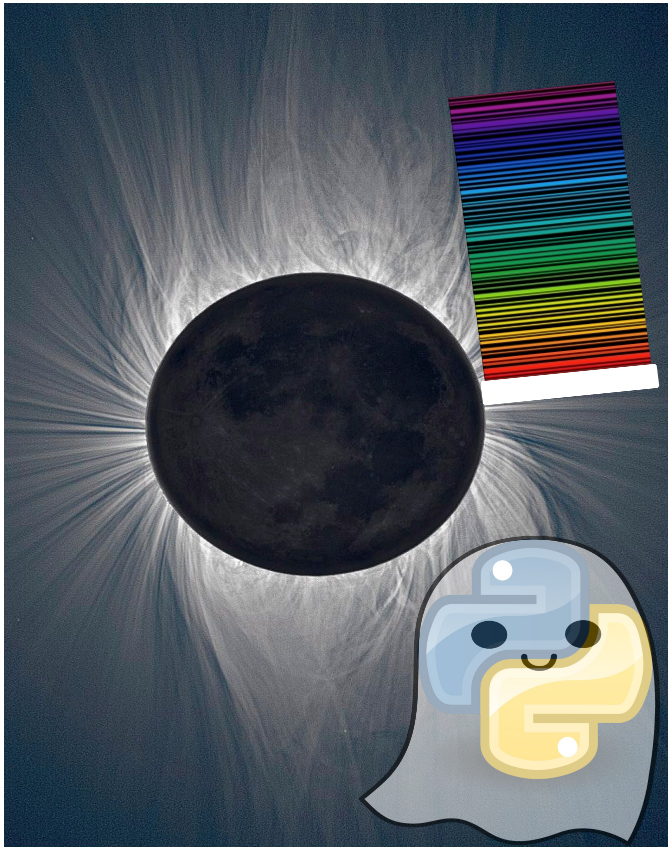
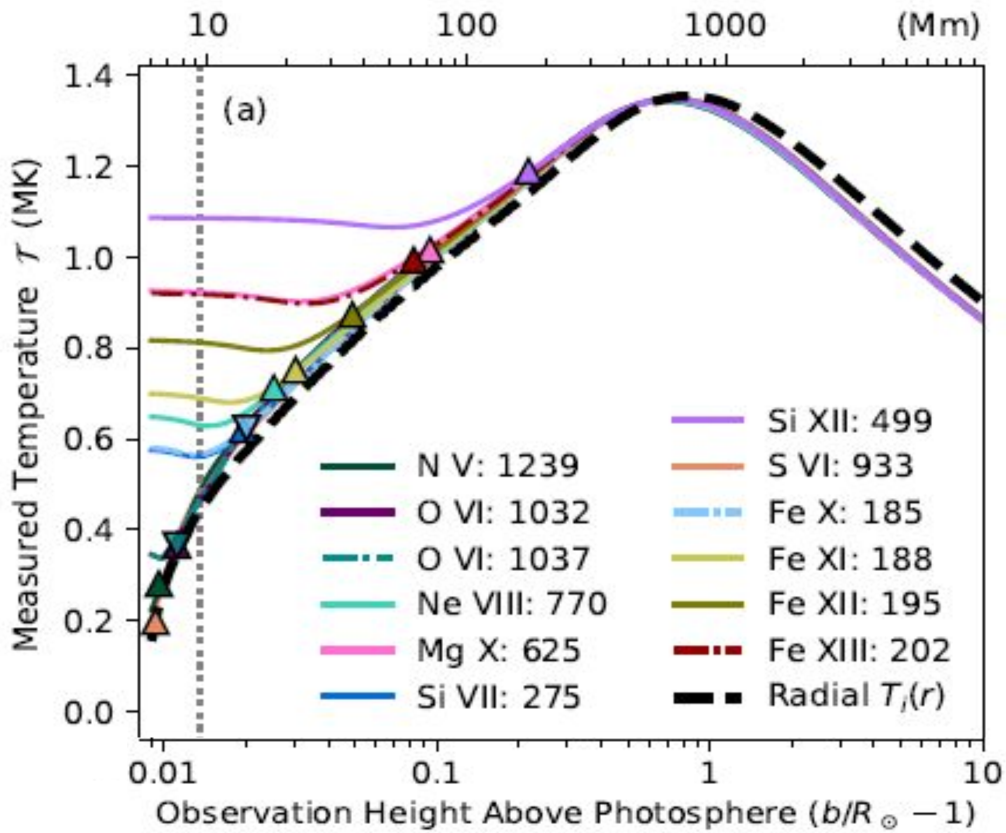


Figure 5. (a) Line-fit temperature measurements $\mathcal{T}$ in flow-free ($B = 0$) case. Triangles denote height of maximum ion number density T_{eq}. Dotted vertical line marks the observation height b of the LOS in Figure 6. Dash-dot and dash-double-dot curves show $\langle T_R \rangle$ and $\langle T_C \rangle$, respectively. (b) Observations normalized to radial variation of $\mathbf{T}_i(\mathbf{r})$. (c) Observations compared to the model $\langle T \rangle$.

- Ran Model from 0.01 to 10 R_s off the North limb
- 12 ion lines were Gaussian fit at each height
- The measured width is converted easily to a temperature because there are no flows

$$\mathcal{V}^2 = V_{th}^2 + \xi^2 = \frac{2k_bT}{m_i} + \xi^2,$$



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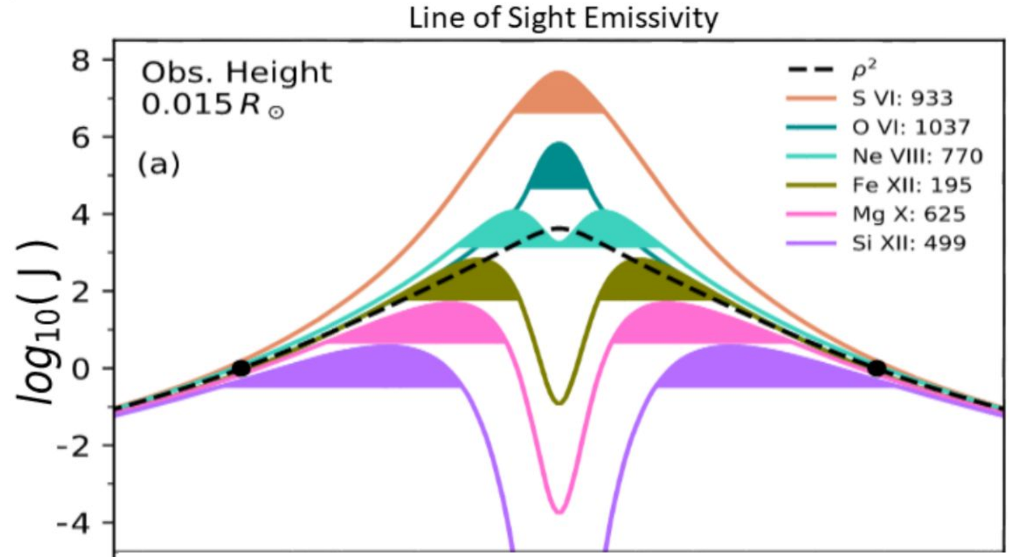
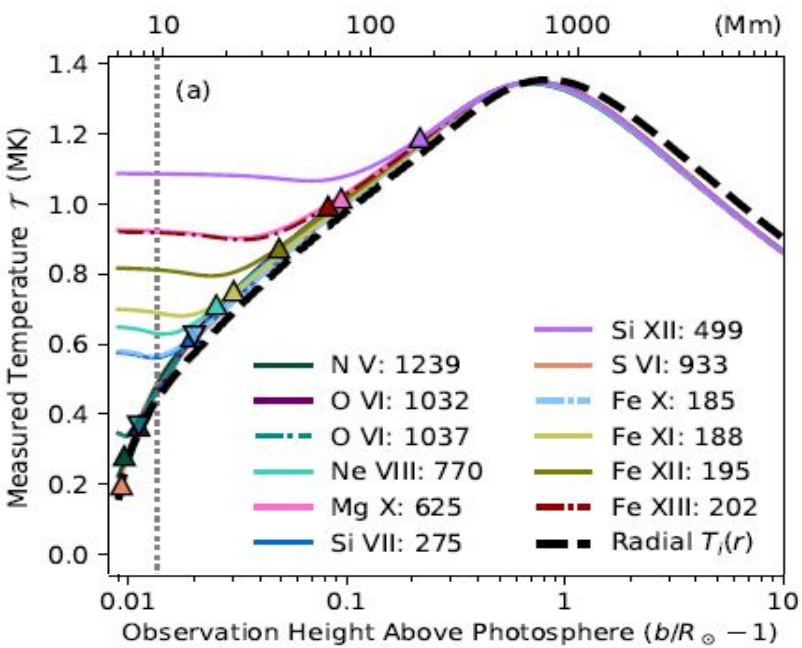
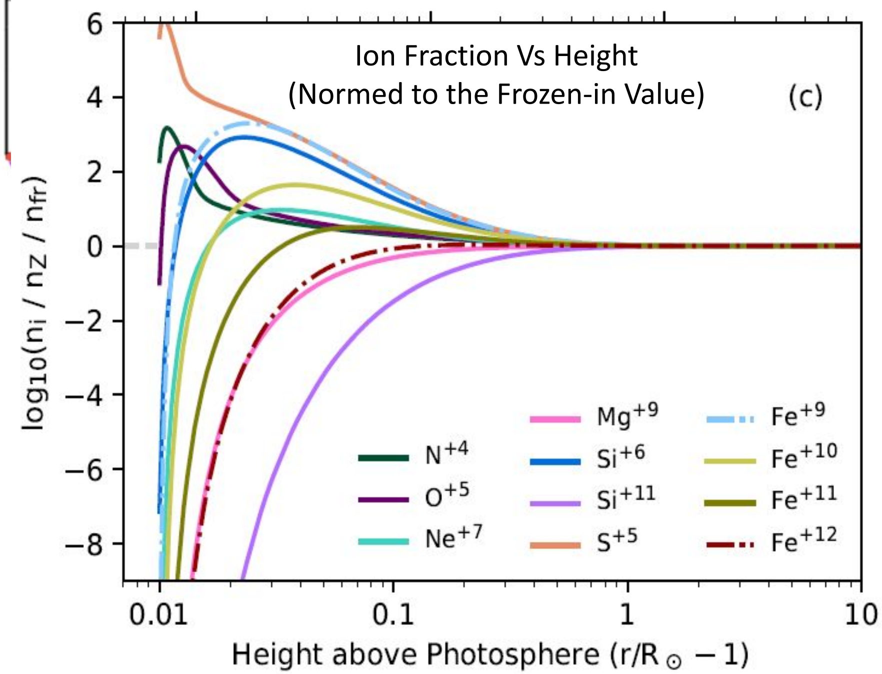
Result: Plateau Heights

What: Your measurements are flat in the low corona

Why: **When measuring below the height of peak density** (the plateau height) **the measurement is contaminated** by the bright foreground and background.







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SUNBACK

off limb image filtering

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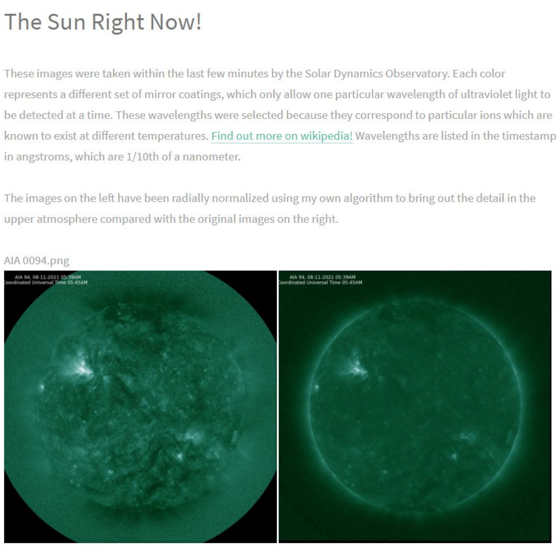
SUNBACK

- Evolution of the Project
  - Fun side project to set desktop background to solar imagery
    - Implemented a Radial Filter
    - Ran on laptop, Output Hosted Synoptically on Website
  - Exposed API for the core algorithm
    - Compute Migrated to Amazon Web Service AWS
    - Desktop client just gets from the web

```
pip install sunback
import sunback as sb
sb.run()
```

  - Image Processing Pipeline
    - Modular Get, Process, Put Architecture



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Outline of the Paper (in prep)

Statistical Radial Normalization of Solar Images

Chris R. Gilly[1,2] and Steven R. Cranmer[1,2]

[1] *Laboratory for Atmospheric and Space Physics*
[2] *Astrophysical and Planetary Sciences Department, University of Colorado Boulder*

- Review of radial filtering methods
  - MGN, aia_rfilt, Rolling Hough, + noise gating
- Presentation of Statistical Radial Normalization
- Compare and Contrast algorithms, and try many in series in different permutations

Statistical Radial Norm

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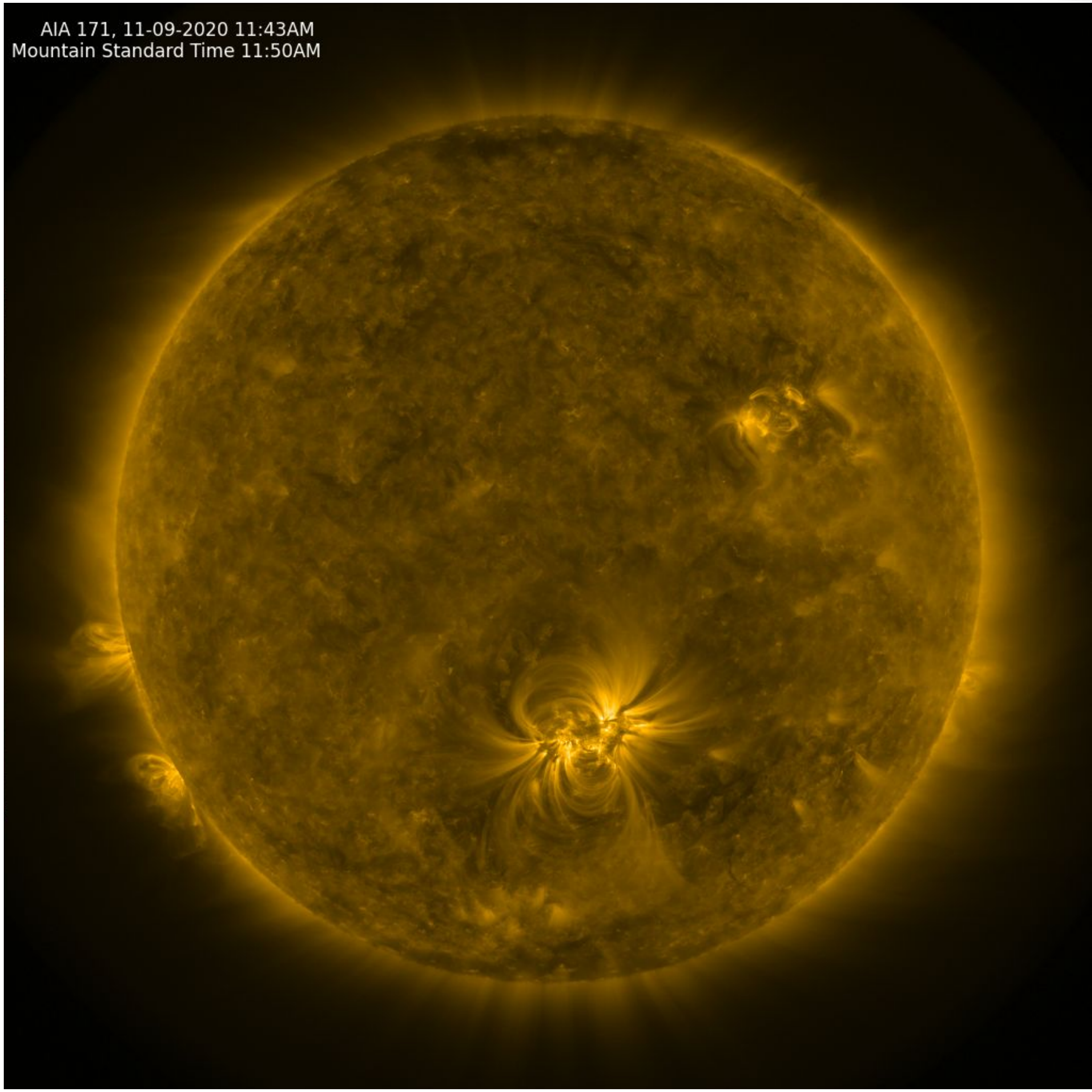
So how does it work?



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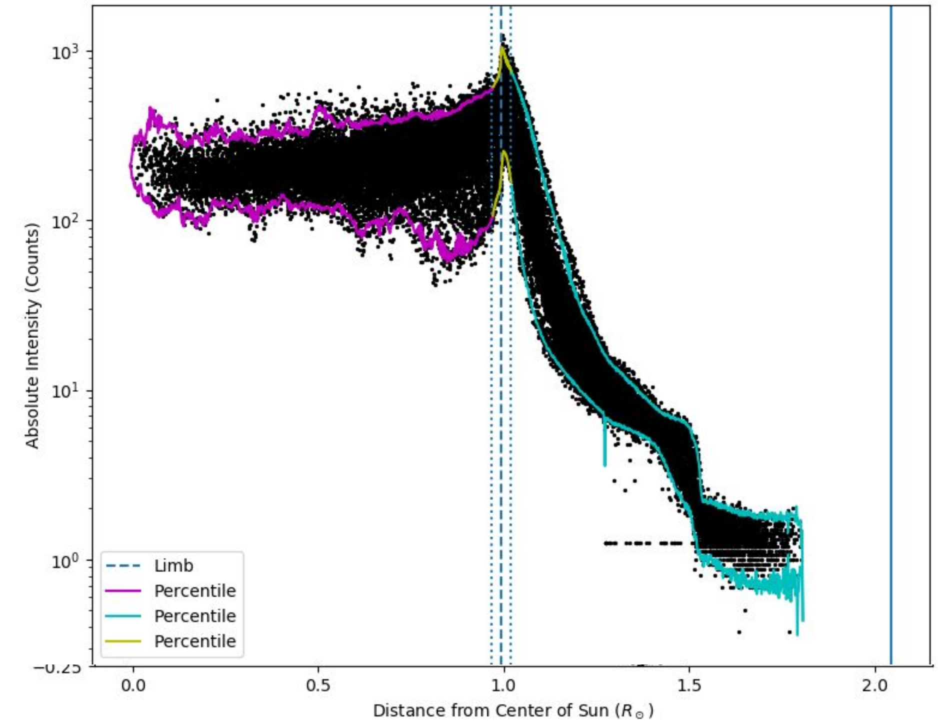
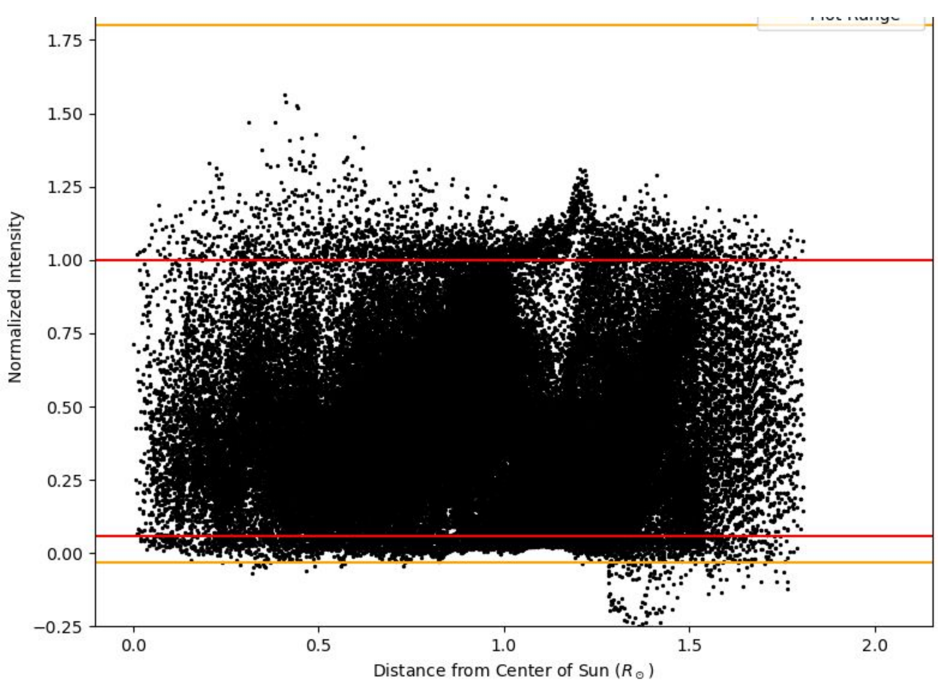
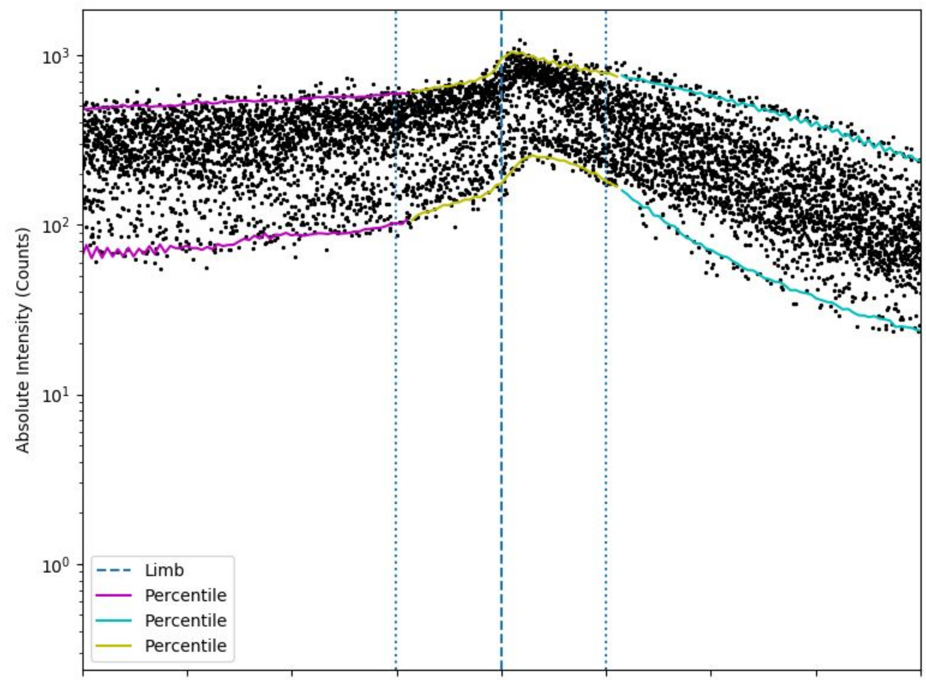


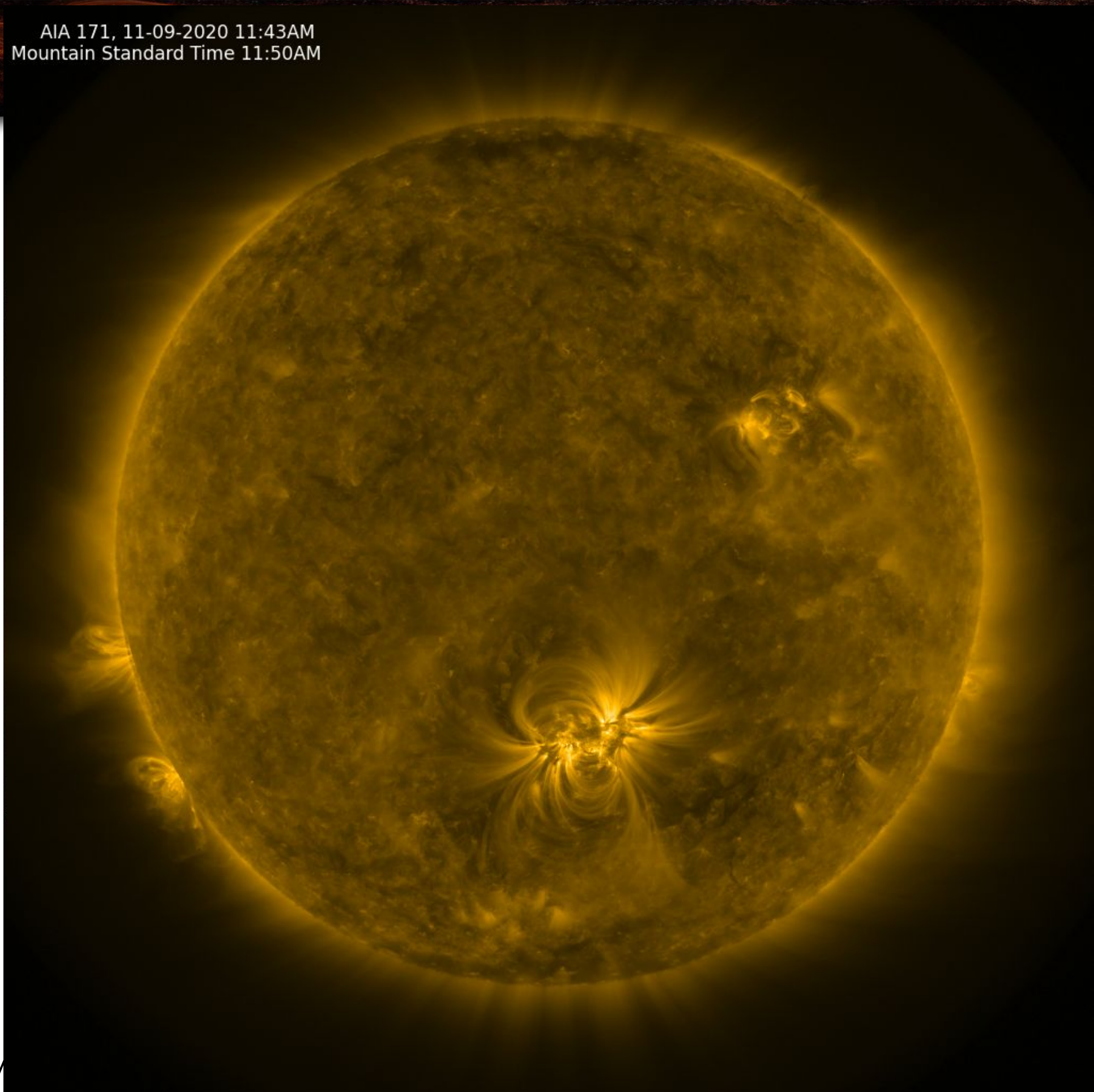
SUNBACK Algorithm

- Sort the pixels by radius
- Find Percentile Curves
- Normalize between 0-1
- Take care at the limb

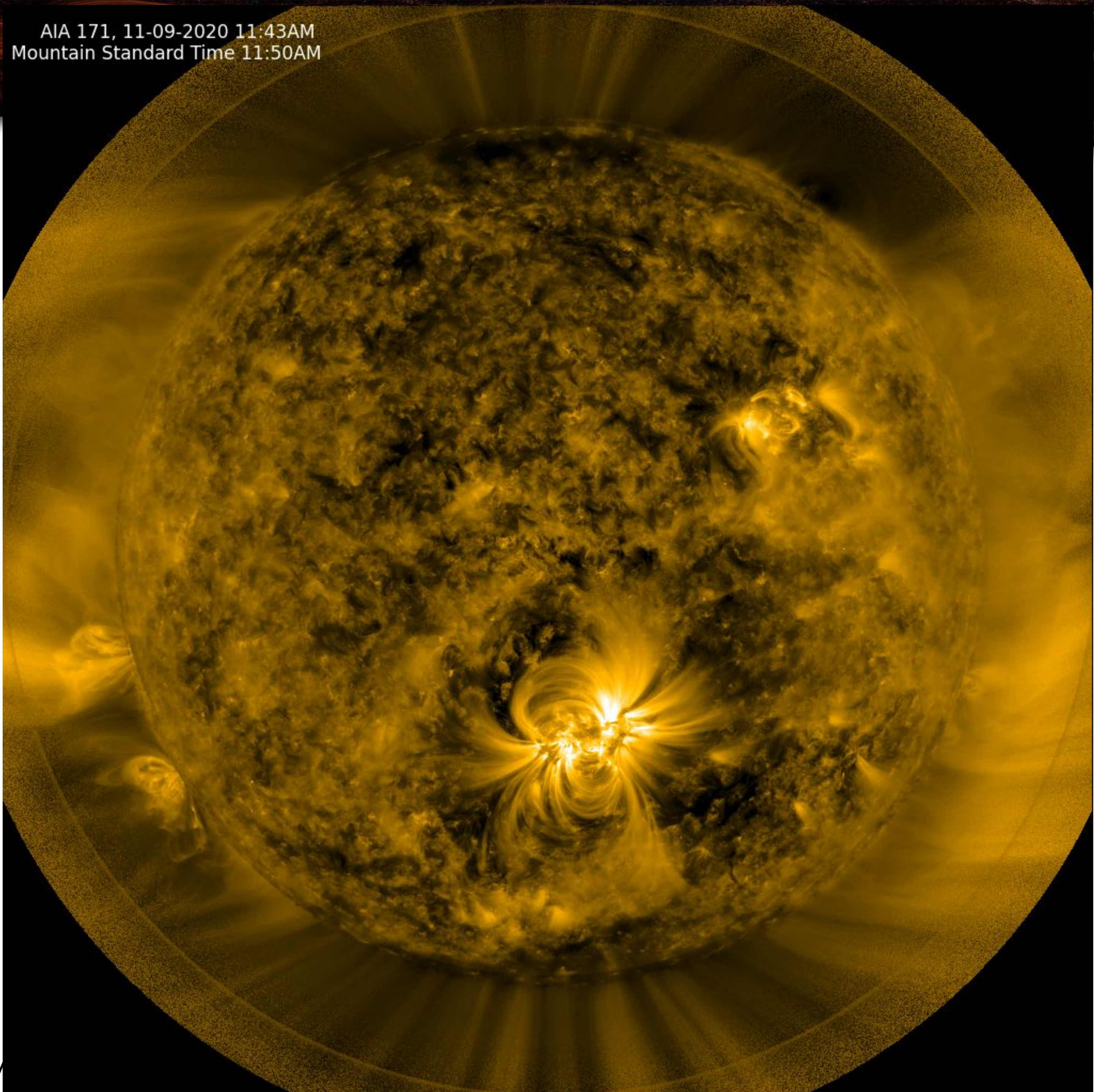


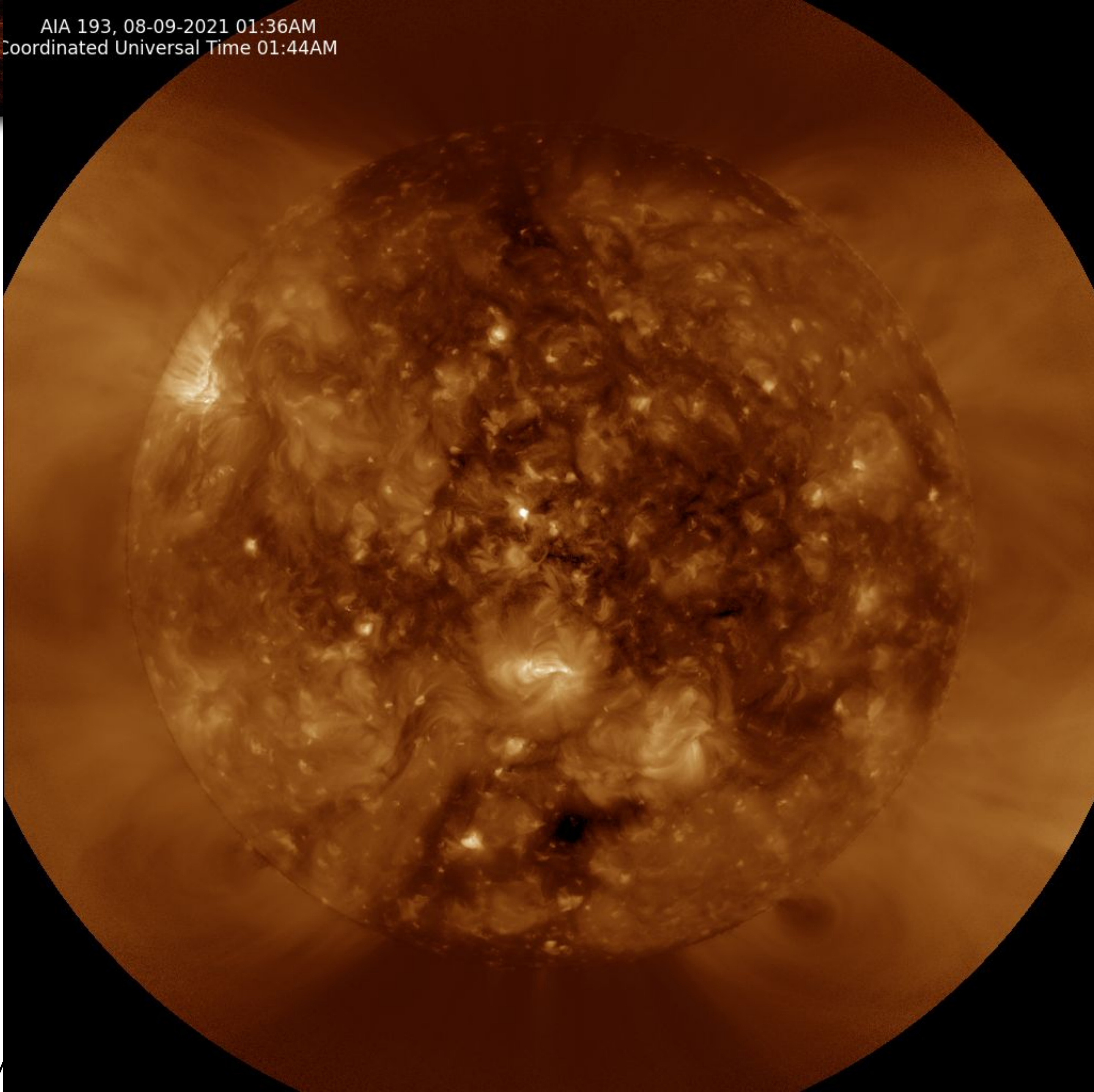


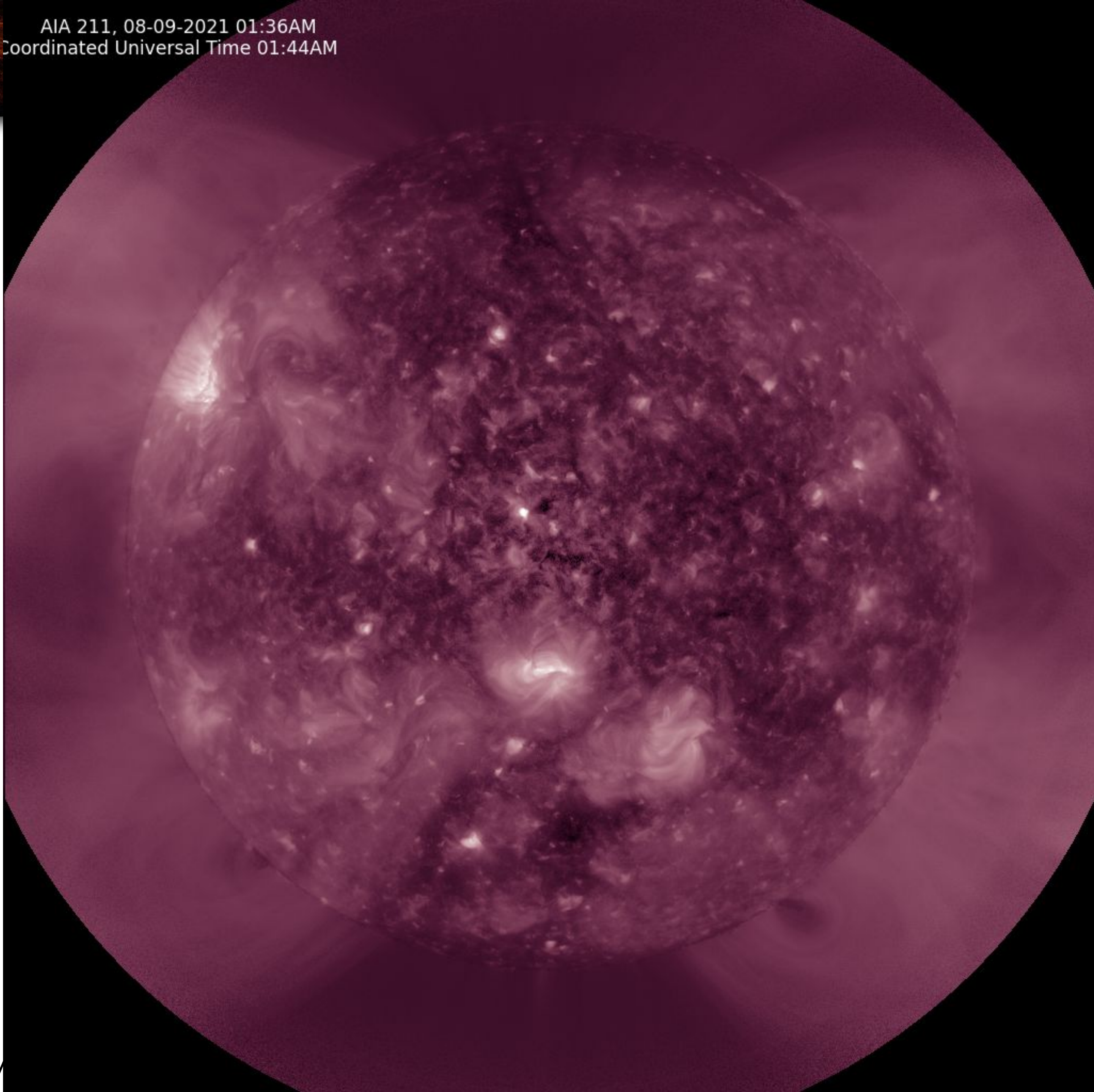
Normal



SRN

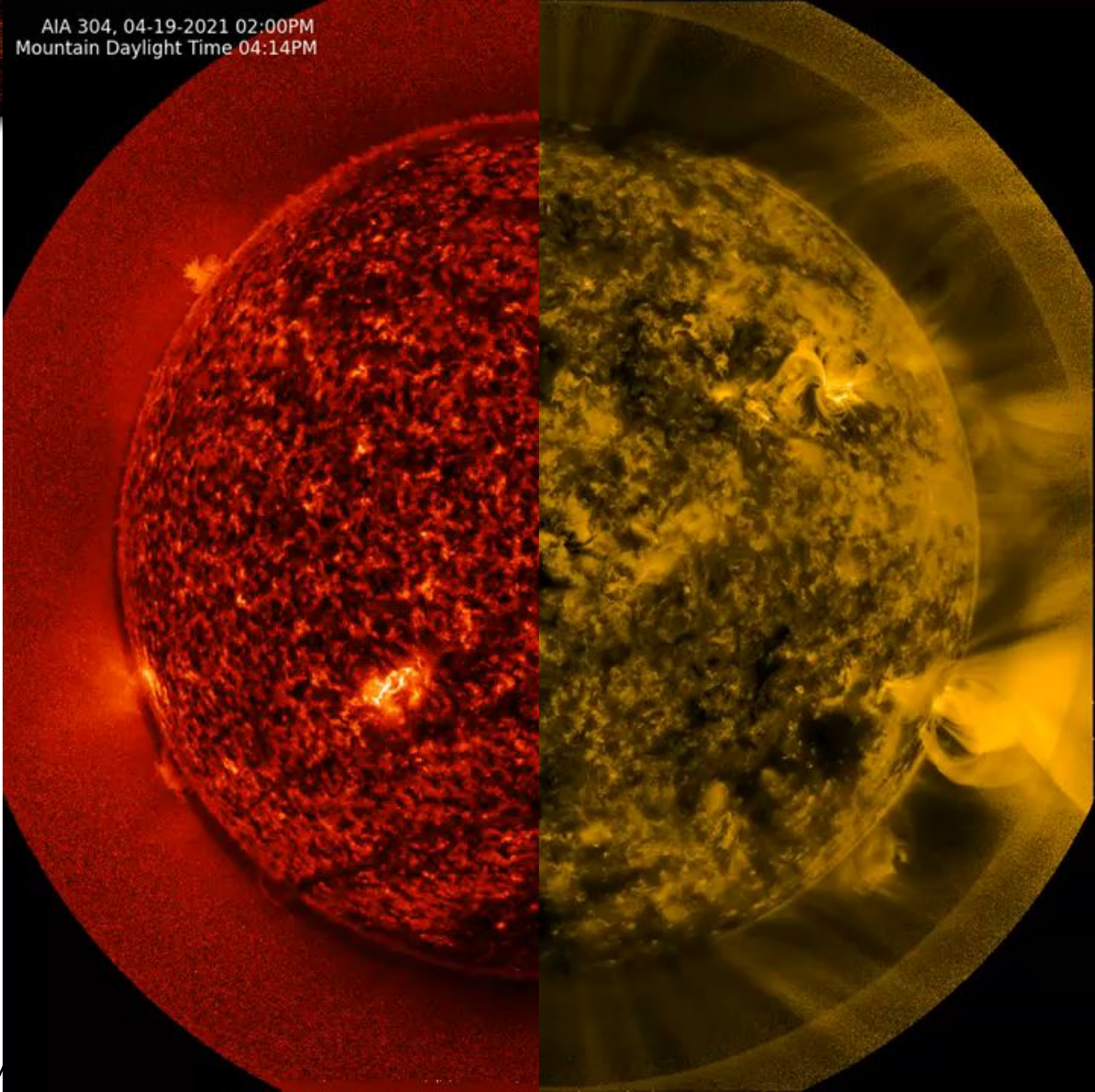



AIA 193, 08-09-2021 01:36AM
Coordinated Universal Time 01:44AM


AIA 211, 08-09-2021 01:36AM
Coordinated Universal Time 01:44AM

I have lots of ideas about where to disseminate these

- My Website
- Planetaria
- SWx Model Stage Platform
- PanHelio
- Etc.
- Contact me if you want access to the imagery!
- There’s a lot more science that can be done with this!



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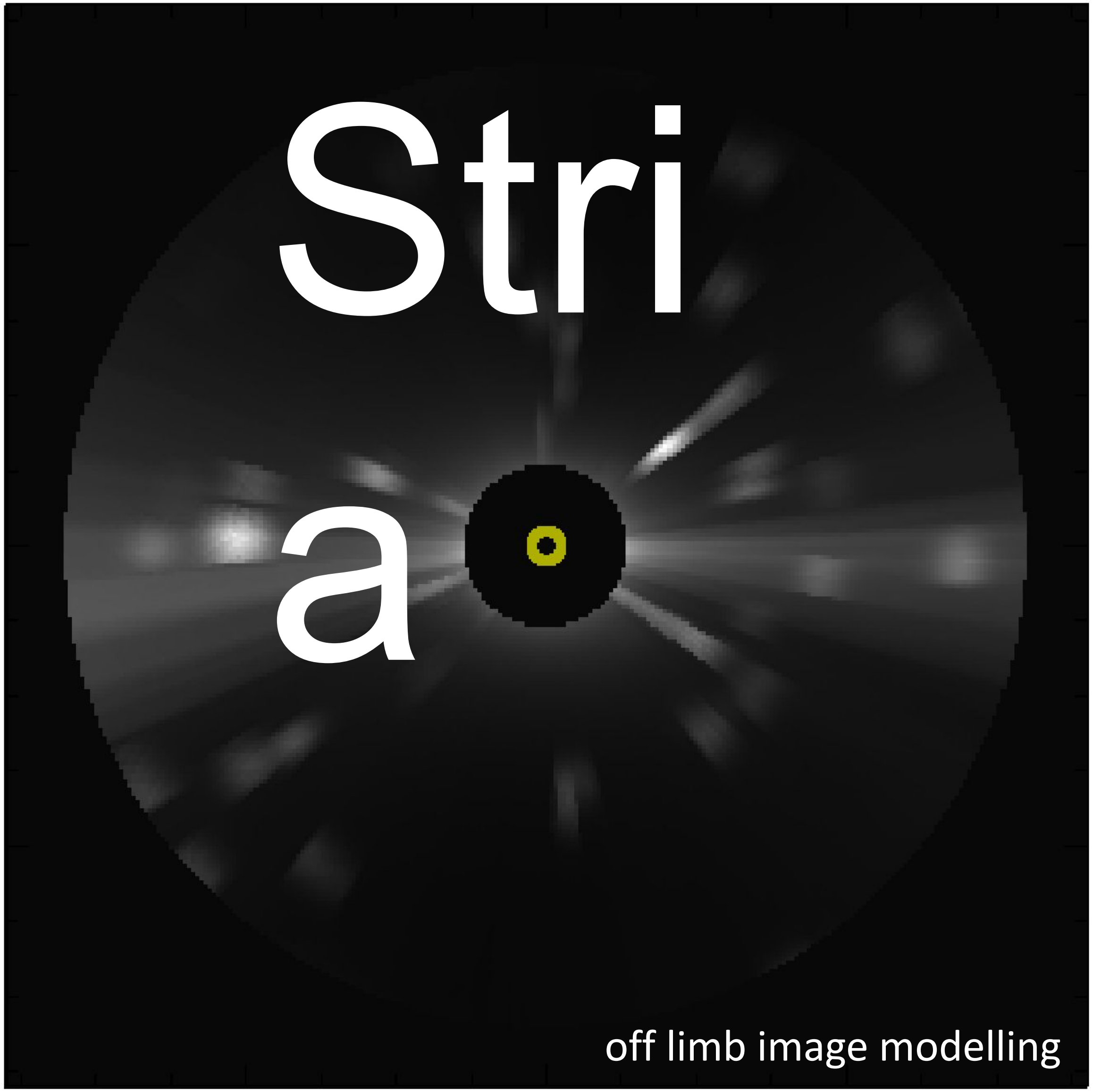

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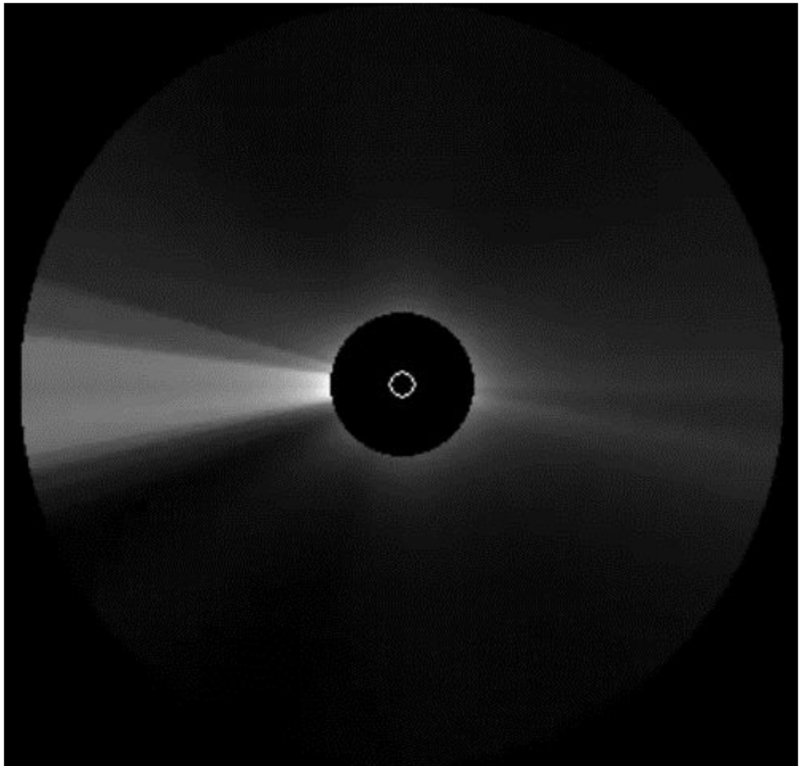
What is STRIA?

- **FORWARD** is a radiative transfer code managed by Sarah Gibson
  - **STRIA** is a module within **FORWARD**
  - **FORWARD/STRIA** is written in **IDL**
  - **STRIA** provides plasma parameters to **FORWARD**
  - **FORWARD** produces images of Polarized Brightness

- **STRIA** is essentially analytic and vectorized, as opposed to the discrete, rasterized nature of typical 3D simulations. It uses magnetograms to determine the density of radial flux tubes.
- It's also a testbed – now I have FORWARD working.

- **STRIA_PY** is an analysis suite I'm writing in **Python.**

  Because **yuck**, IDL. ;)



FORWARD/STRIA

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- Some of the Science Questions we want to answer

Static STRIA

- How does solar rotation contribute to time variability in pB?
- If we treat the striation density contrast as a free parameter, how does the overall level of "pB noise" (i.e., hour-to-hour variability at any single point) depend on that density contrast?
- How does this variability signal differ at different points in the solar cycle?

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Example "synoptic" image

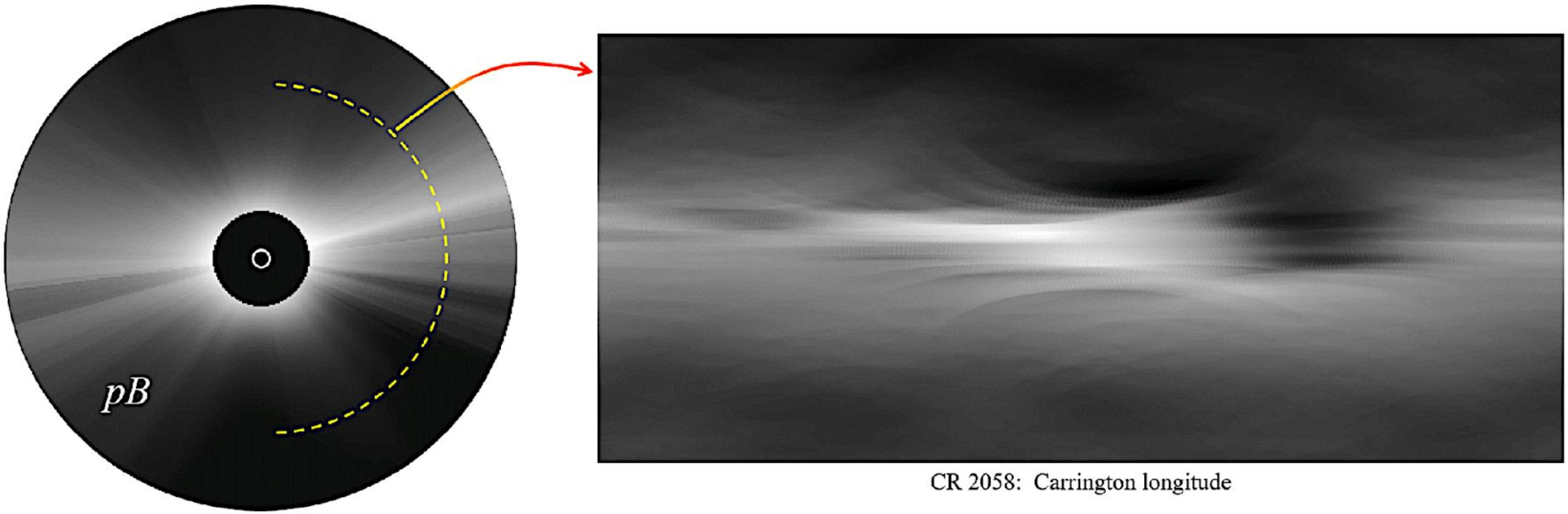
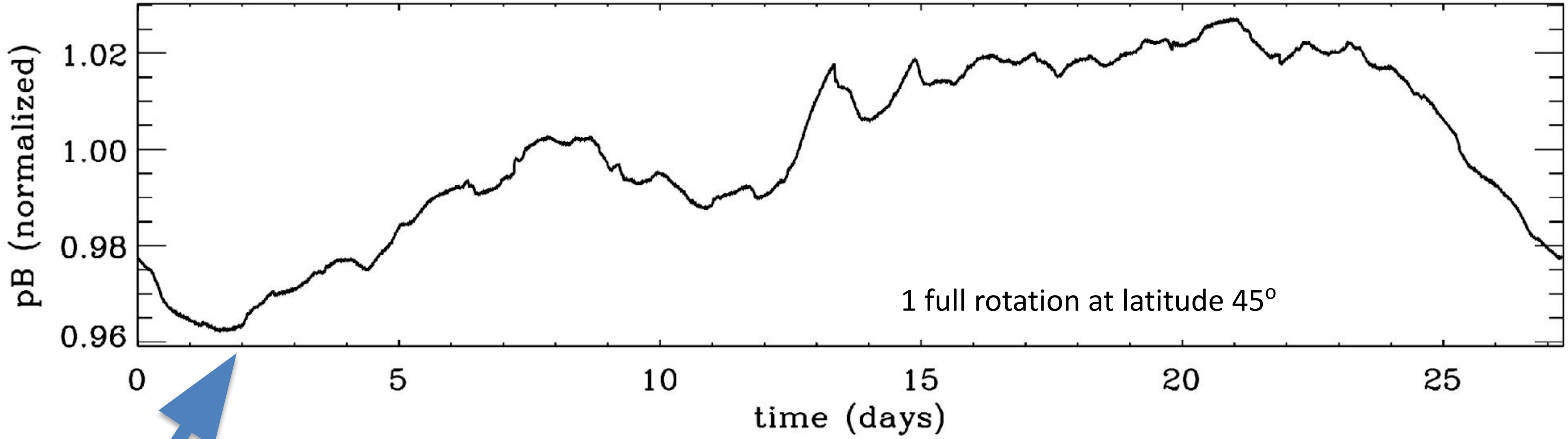
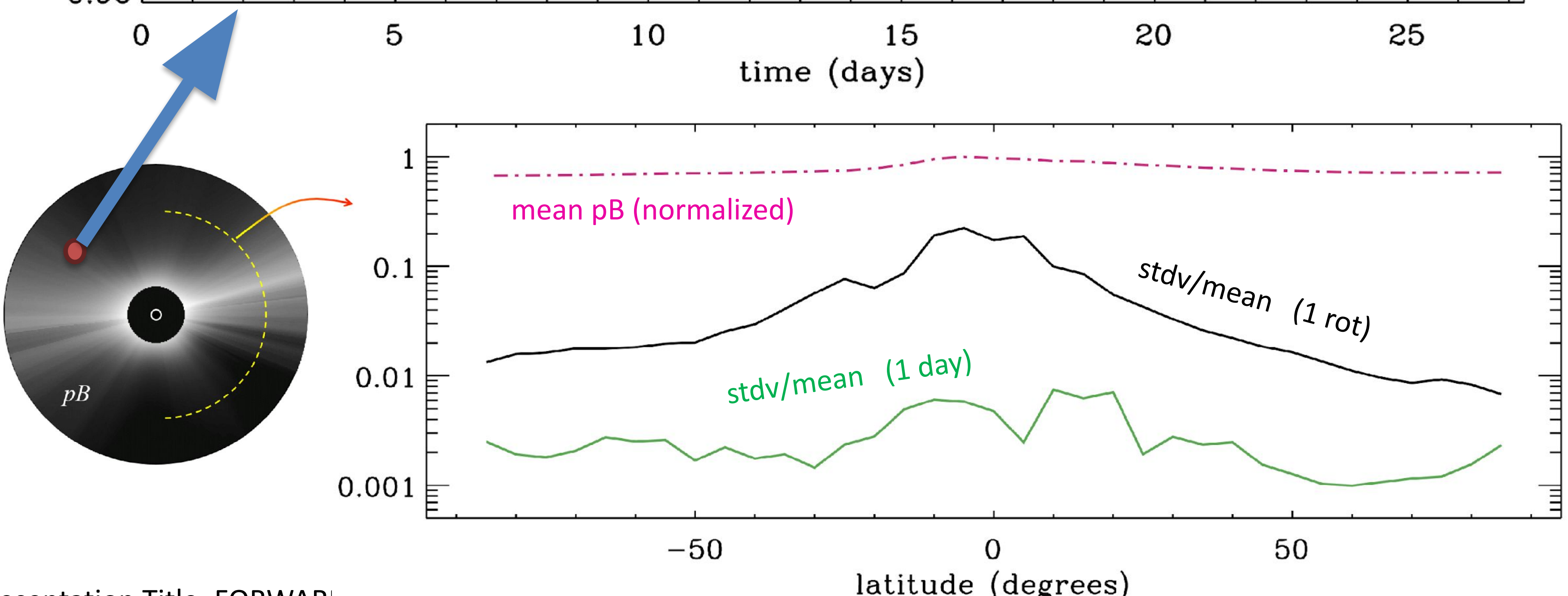


Figure 3: *Simulated pB image (with some radial-gradient image processing to bring out fine details) for Carrington Rotation 2058. Left: single-time snapshot of the PUNCH NFI field of view. Right: One solar rotation's worth of pB data extracted at a radial distance of 20 $R_\odot$, with time mapped to longitude (x-axis) and latitude sampled off the west limb (y-axis).*

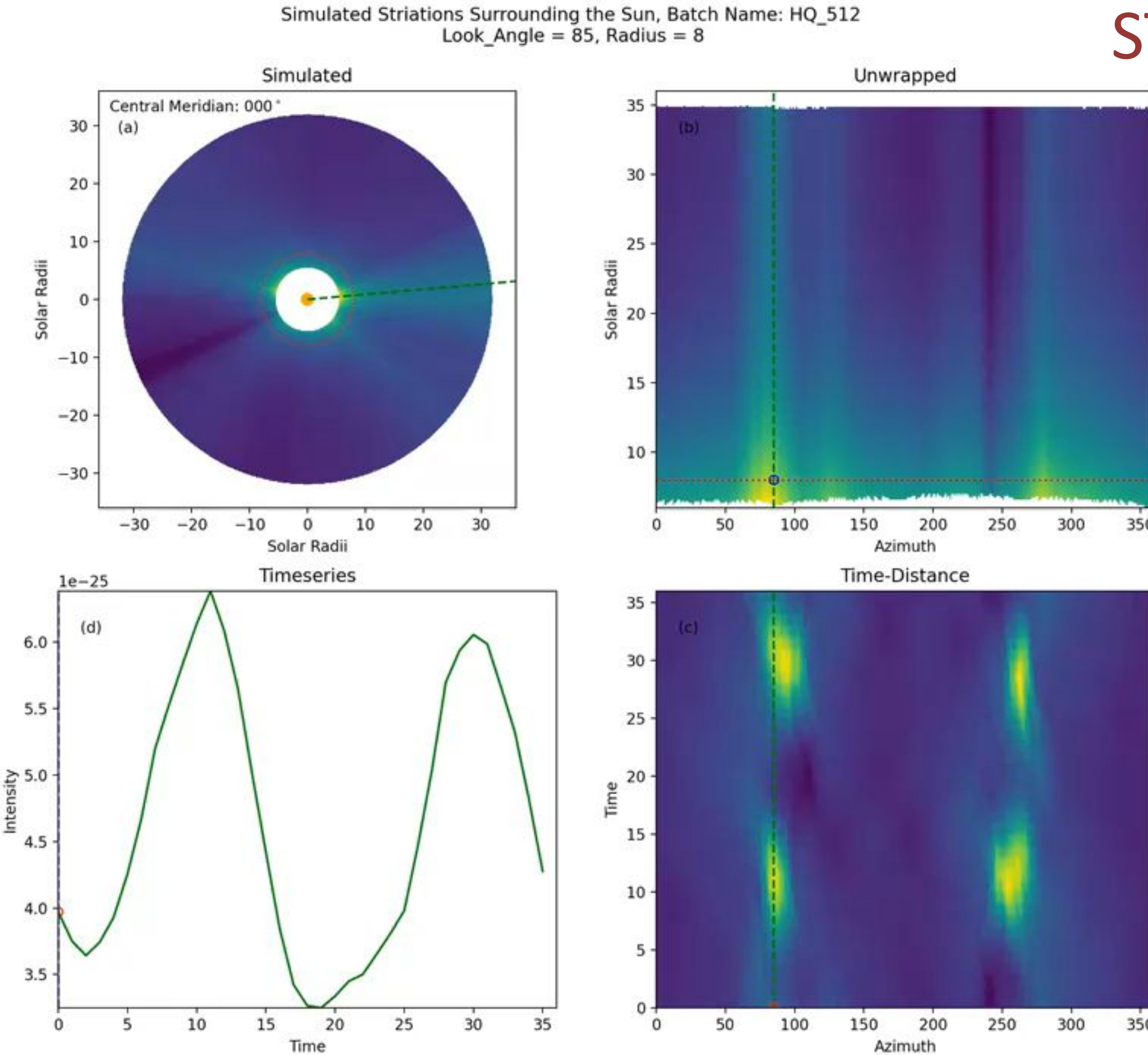
Rotational variability

- Choose 1 radial distance (at different latitudes) & examine time variability:

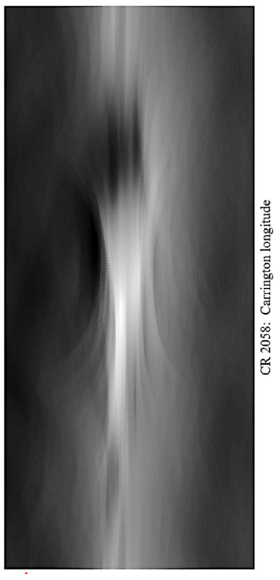




STRIA_PY



Simulated Striations Surrounding the Sun, Batch Name: HQ_512
Look_Angle = 85, Radius = 8
Simulated
Central Meridian: 000°
(a)
Solar Radii
Solar Radii
Unwrapped
(b)
Solar Radii
Azimuth
Timeseries
1e−25
(d)
Intensity
Time
Time-Distance
(c)
Time
Azimuth



CR 2058: Carrington longitude

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FORWARD/STRIA

- Some of the Science Questions we want to answer

Static STRIA

- How does solar rotation contribute to time variability in pB?
- If we treat the striation density contrast as a free parameter, how does the overall level of "pB noise" (i.e., hour-to-hour variability at any single point) depend on that density contrast?
- How does this variability signal differ at different points in the solar cycle?

Blob STRIA

- How does the presence of blobs affect the overall time variability of pB?
- How must we deal with LOS/projection effects to measure the true 3D radial speeds of blobs using flow-tracking?
- How large or dense do the blobs need to be in order to use polarimetry to deduce whether they are in the foreground or background (like CMEs)?
- Does it become difficult to accurately measure the properties of blobs when the number of blobs along the LOS grows too large? (i.e., do they start to cancel each other out?)

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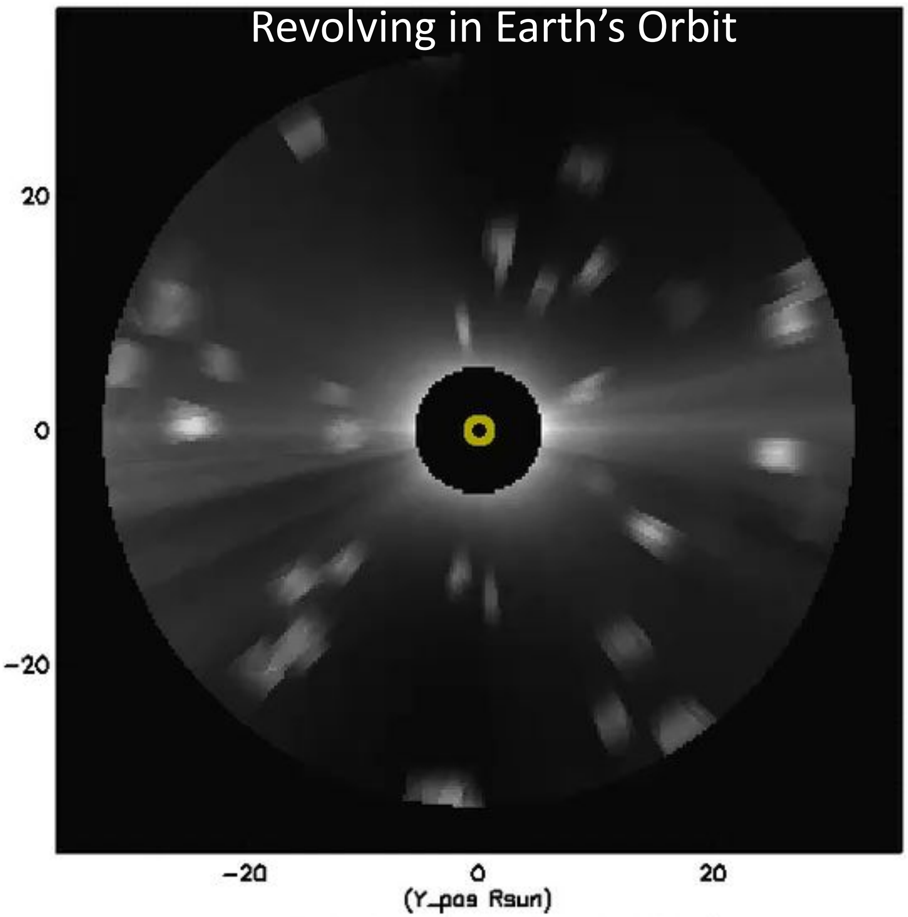
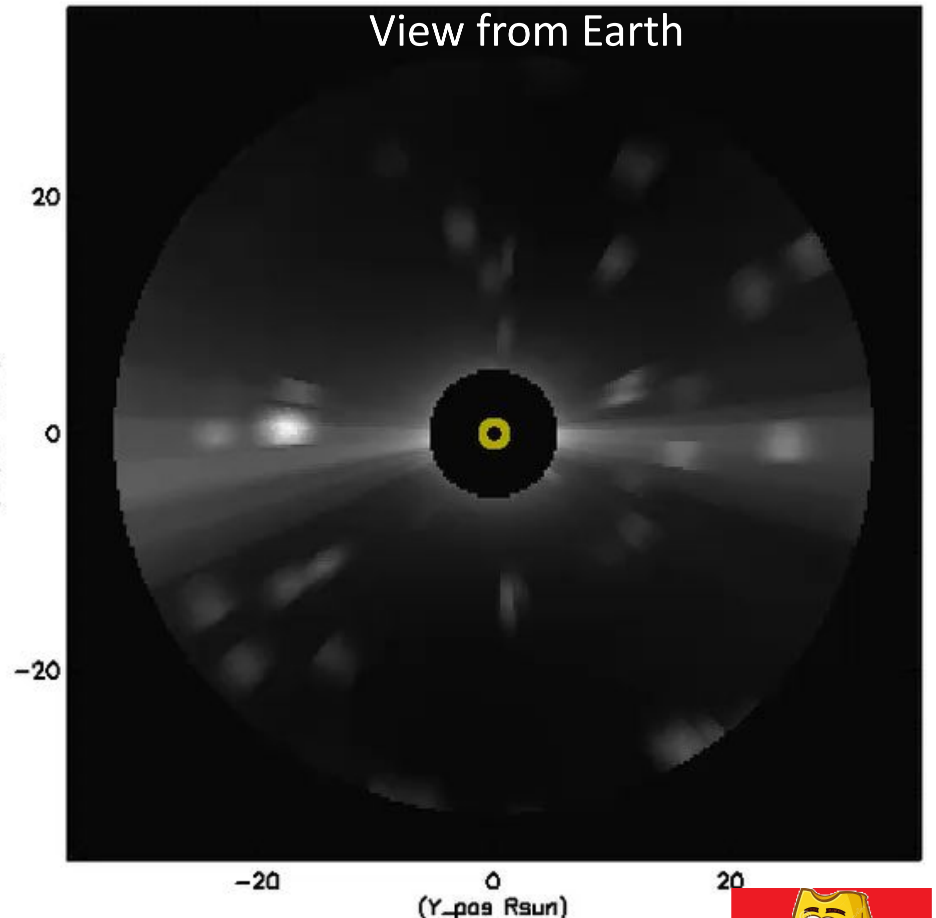
Bleeding Edge (for me)

Static Blobs

Flowing Blobs





Tune in next time for "*Why these blobs don't know about object permanence*!"

Bleeding Edge (for me)

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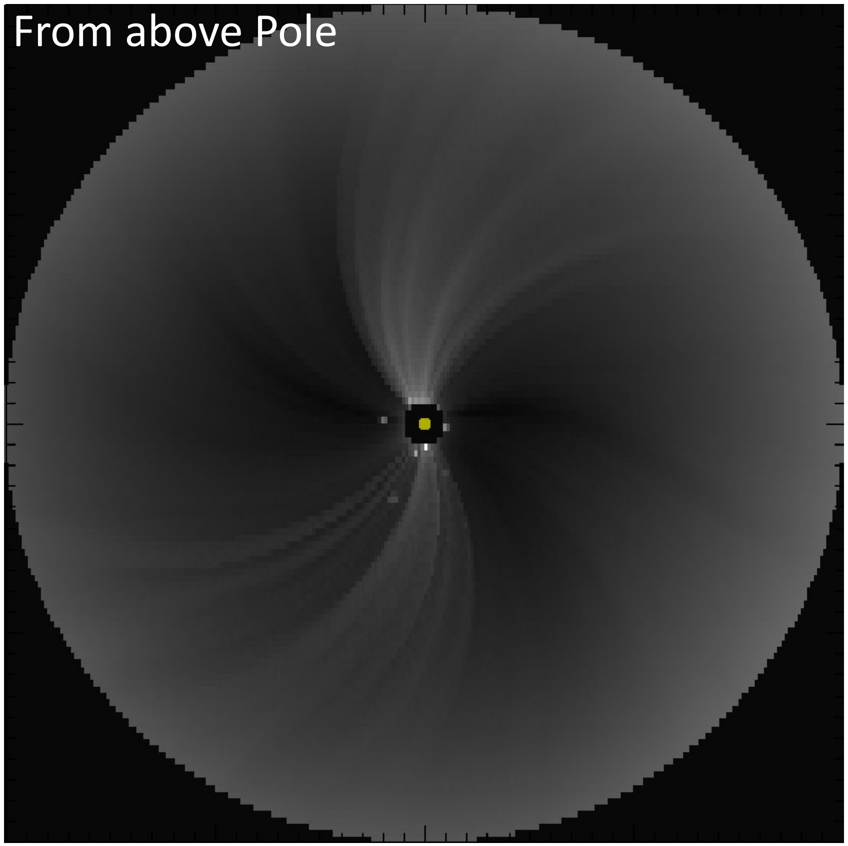
Effect of the Parker Spiral



Collaborations

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- (Active) **Steve Cranmer**
  - Graduate Advisor, GHOSTS Science
- (Active) **Sarah Gibson**
  - SSW/Forward and PUNCH Science with STRIA
- (Starting) **Barbara Thompson** and **Valmir Moraes Filho**
  - Forward Modelling and Flow Tracking for PUNCH
- (Future) **Ben Boe**
  - Predictions of ion freeze-in heights for Eclipse Observations
- (Future) **Yeimy Rivera**
  - Discussing Non-Equilibrium Ionization in the Corona
- (Active) (Many Authors) Middle Corona Review Paper
- (Active) (Many Authors) Outreach White Paper

- Want to see your name here? Email me!

Summary

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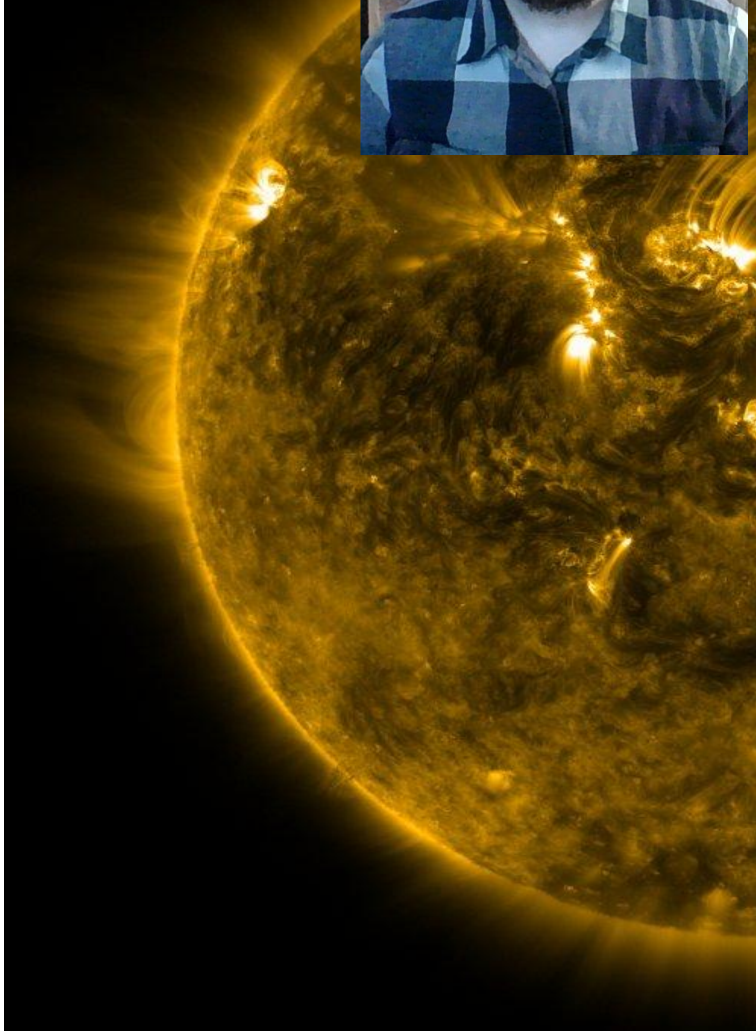
Contact Me!

- I'm **Gilly**, one of the 4 new PUNCH AIs
- I do optically-thin line-of-sight science
  - Forward Modeling
    - Spectroscopy (GHOSTS)
      - NEI coronal ion modeling
    - WL Imaging (STRIA)
      - PUNCH project
  - Image Filtering
    - Statistical Radial Norm (SUNBACK)
- I love doing **outreach**!
- **Defending** my dissertation sometime in **2022**.



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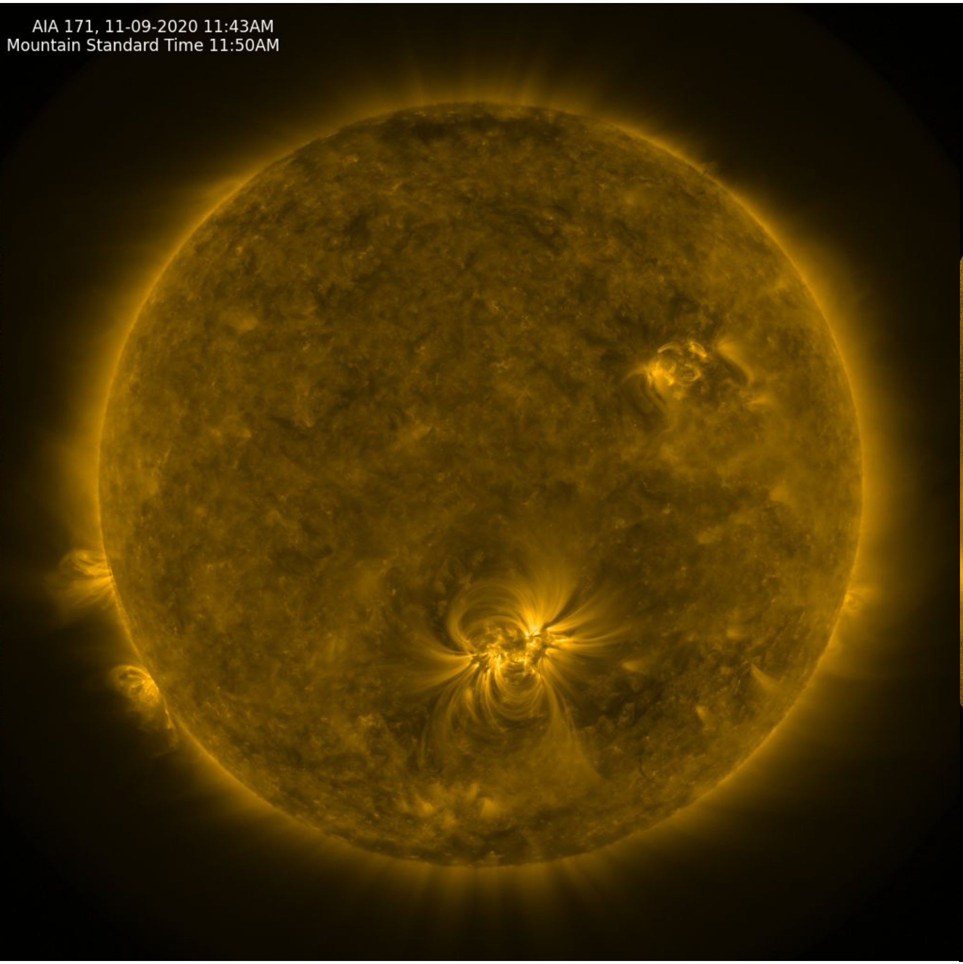
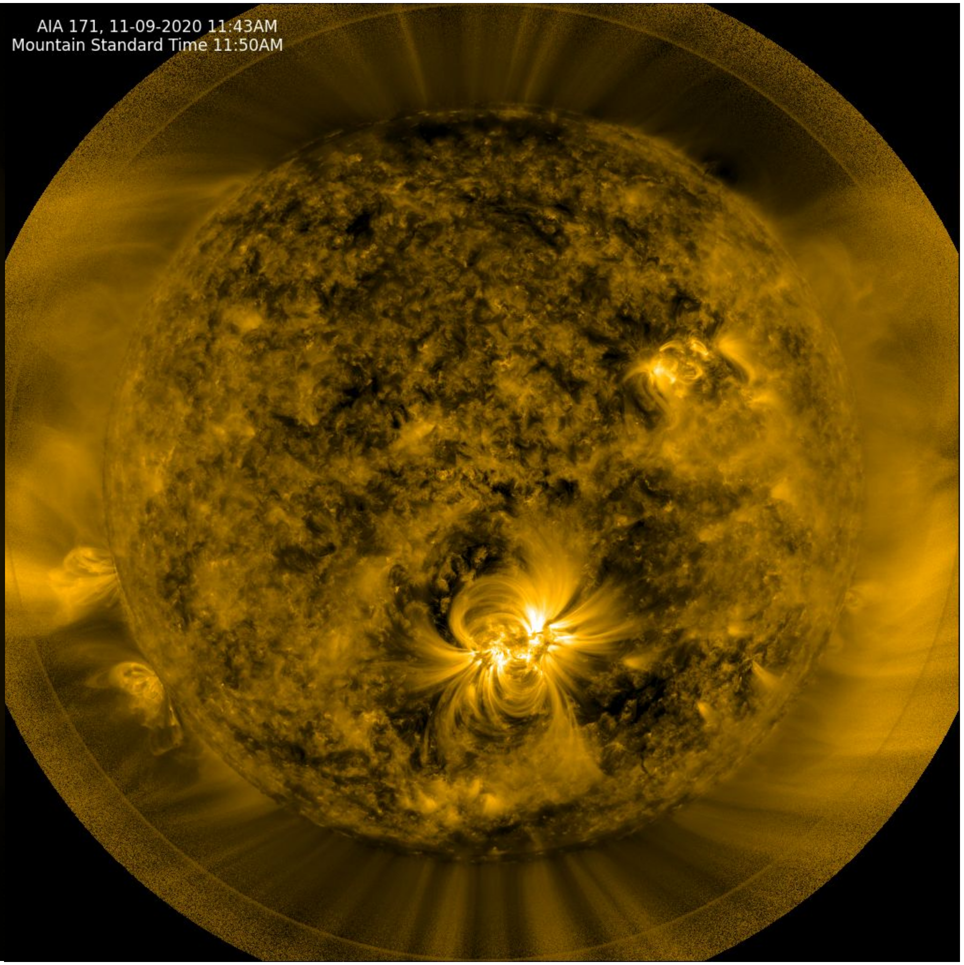
Extra Slides





Dynamic Spectra

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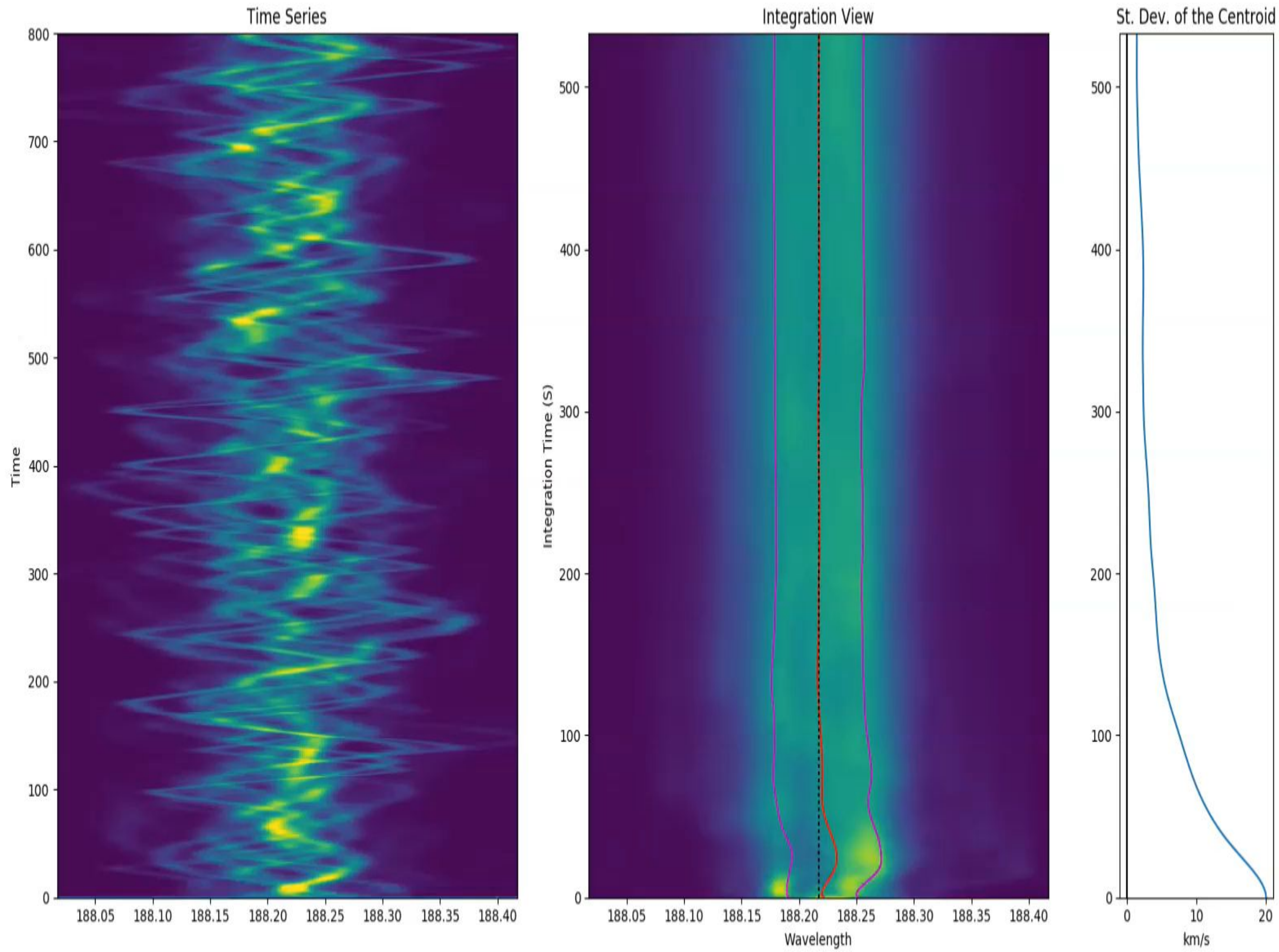
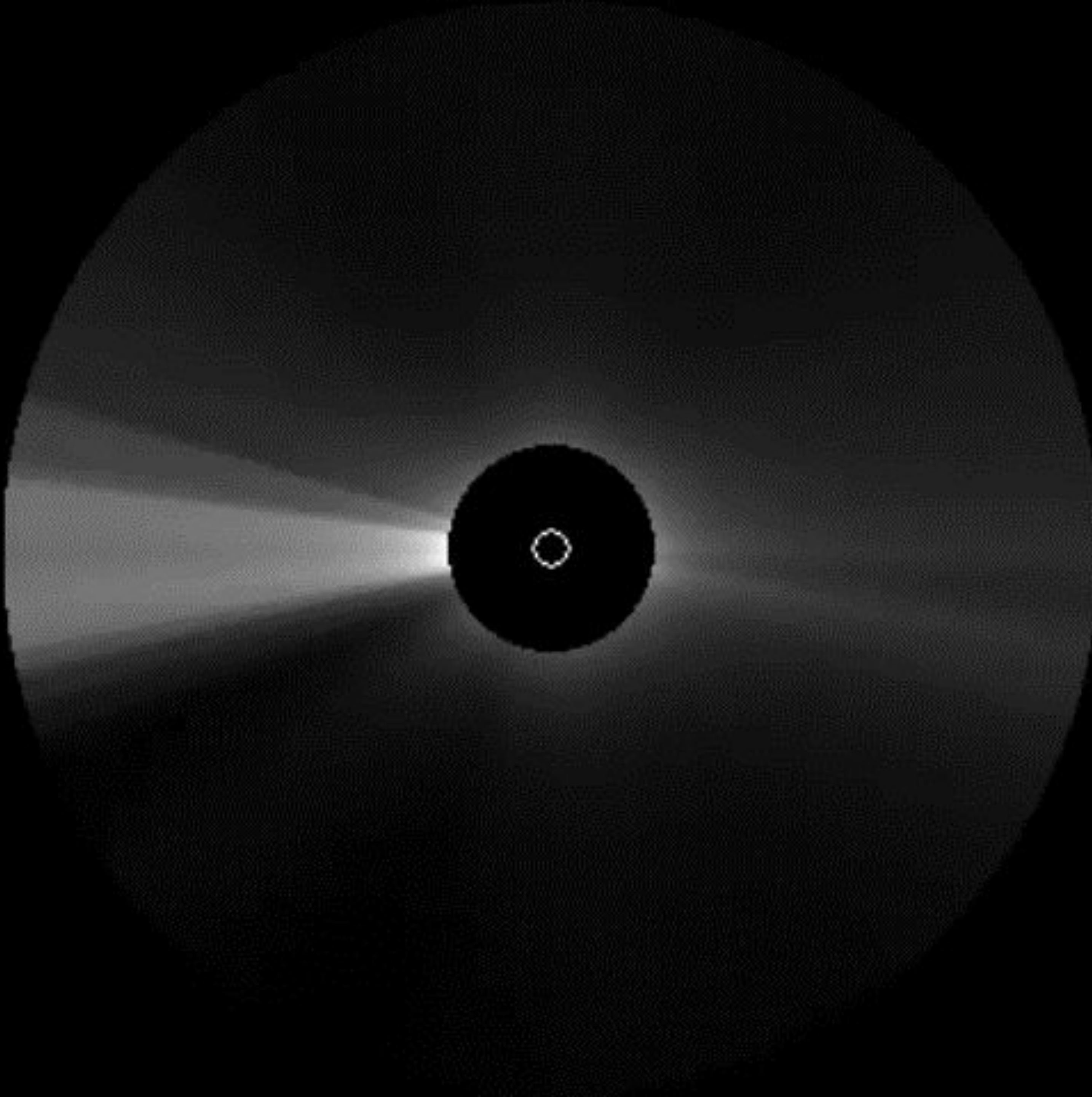
With short cadence, we can track the centroid motion.

With long exposures, we must look at the line width





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Personal Data Pipeline

- Modular Image Pipeline Constructed

```python
def run_background(delay=5, debug=False, do_one=False, stop=True):
    p = Parameters()
    p.delay_seconds(delay)
    p.do_one(do_one, stop)
    p.stop_after_one(stop)
    p.is_debug(debug)

    # p.fetcher(WebFetcher(p))       # Gets Fits from JSOC Most Recent
    p.fetcher(AwsFetcher(p))         # Gets PNGs from S3 Daemon
    # p.fetcher(LocalFetcher(p))       # Gets Fits from Disk

    # p.executor(RadialFiltProcessor(p)) # Makes the PNGs from Fits
    p.executor(LocalExecutor(p))     # Gets the PNGs from Disk

    # p.putter(AwsPutter(p))         # Uploads the PNGs to AWS
    p.putter(LocalPutter(p))         # Runs the Desktop Background Sequence
    # p.putter(NullPutter(p))        # Does Nothing with the PNGS

    run.Runner(p).start()


f __name__ == "__main__":
    # Do something if this file is invoked on its own
    run_background()
```

```python
def __process(self):
    """Use the provided fetcher, executor,
    and putter to do the thing"""

    self.params.fetcher().fetch()

    print("Processing Images...", flush=True)
    for proc in self.params.processors():
        proc.process()

    self.params.putter().put()
```

Computing density from magnetic field

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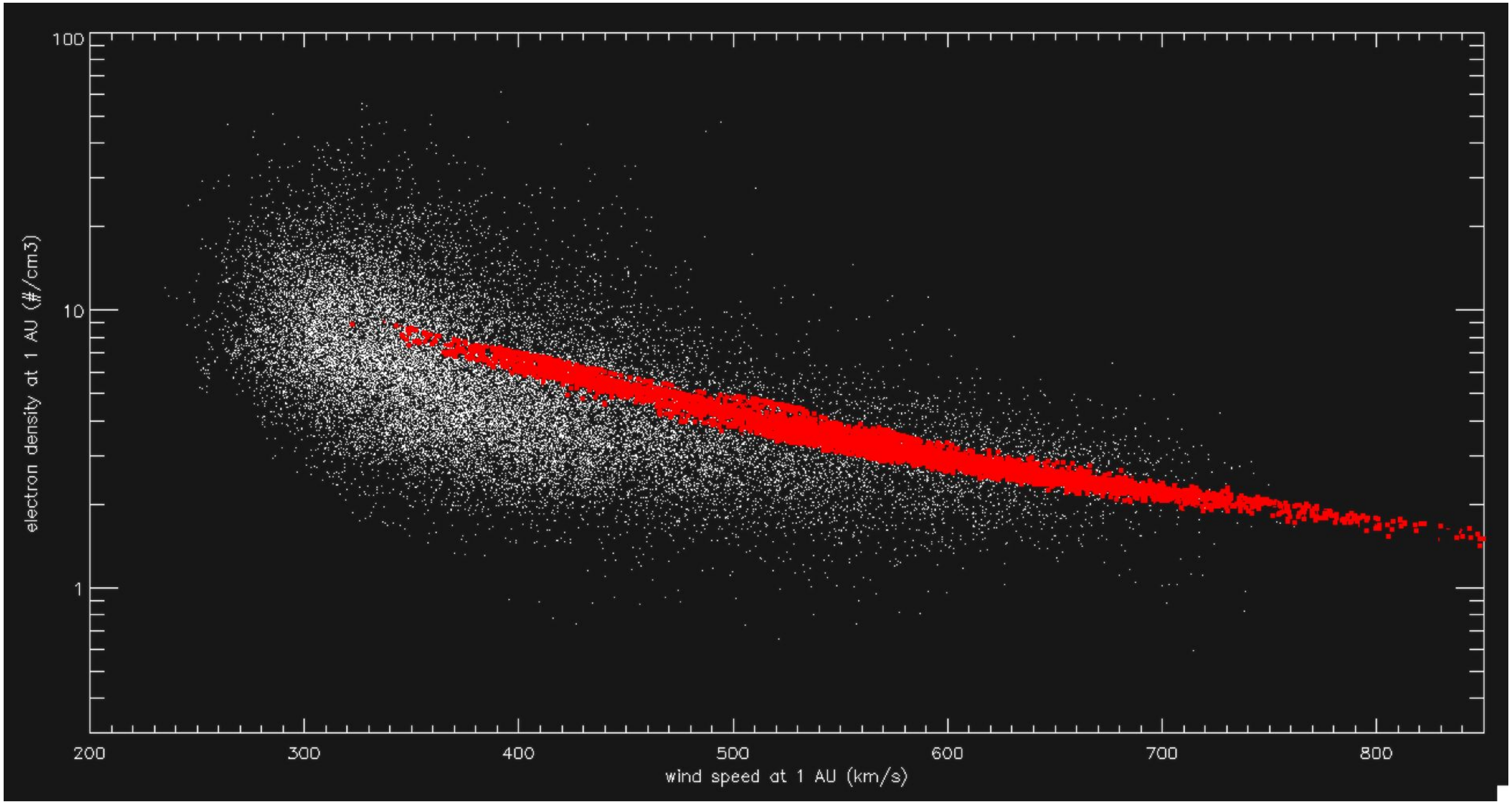
Comparing results for a sampling of a solar cycle with OMNI data at 1 AU…



We will determine whether better choices for the parameters exist, but we caution that the 1 AU data has undergone lots of stream-stream interaction.

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Computing density from magnetic field

There are 2 effects that appear to determine solar-wind density:

1. For quiescent phases of the solar wind (i.e., where the wind appears to be rooted in large coronal holes or the legs of large streamers), there is a well-known anticorrelation between f_{ss} and the wind speed u at 1 AU (Wang & Sheeley 1990). Also, the fast wind tends to have low density and the slow wind tends to have high density. These trends are approximated as

$$u = \frac{900 \text{ km/s}}{f_{ss}^{0.165}} \qquad \text{and} \qquad n_{\text{quies}} = \left(\frac{1150 \text{ km/s}}{u}\right)^{1.7} \tag{6}$$

2. For times when the solar wind appears to be rooted in active regions, the wind speed tends to be slow and the density appears to be high. Models that employ MHD turbulence tend to find an inverse correlation between an active-region-like basal field strength and the solar wind speed (see, e.g., Figure 10 of Cranmer et al. 2013). Thus, there is a positive correlation between $B_\odot$ and density, which we model as

$$n_{\text{active}} = 1.7 \left(\frac{B_\odot}{1 \text{ G}}\right)^{0.42} \tag{7}$$

Gilly & Cranmer (2021, in prep) will be providing additional references and equations about this scaling, which can also be applied to polar plumes.

Thus, we combine these two effects together by setting the electron density at 1 AU as

$$n_{1\text{AU}} = n_{\text{active}}^{\beta}\, n_{\text{quies}}^{1-\beta} \tag{8}$$

and we chose a value of $\beta = 0.25$ for the blending constant.

Rotational variability

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- Over 1 rotation (near solar min), the rotation of "static" structures contributes to as much as a **10% to 20%** pB variability baseline.
- Over 1-day timescales, this reduces to **~0.3 %.**
- Over only 2 hours, this reduces to **~0.08 %.**
- Seems small, but with all the background subtraction required to resolve velocity-tracing "blobs," it may be important.
- Note: 2 hours ≈ { 1 degree of solar rotation; time for a parcel to flow ~1 R_s at 100 km/s }

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Also to do:

At a given radial distance, compare & contrast **power spectra,** computed as a function of position angle, for:

- density fluctuations in plane of sky
- pB fluctuations computed from LOS integrals

Zephyr 2007

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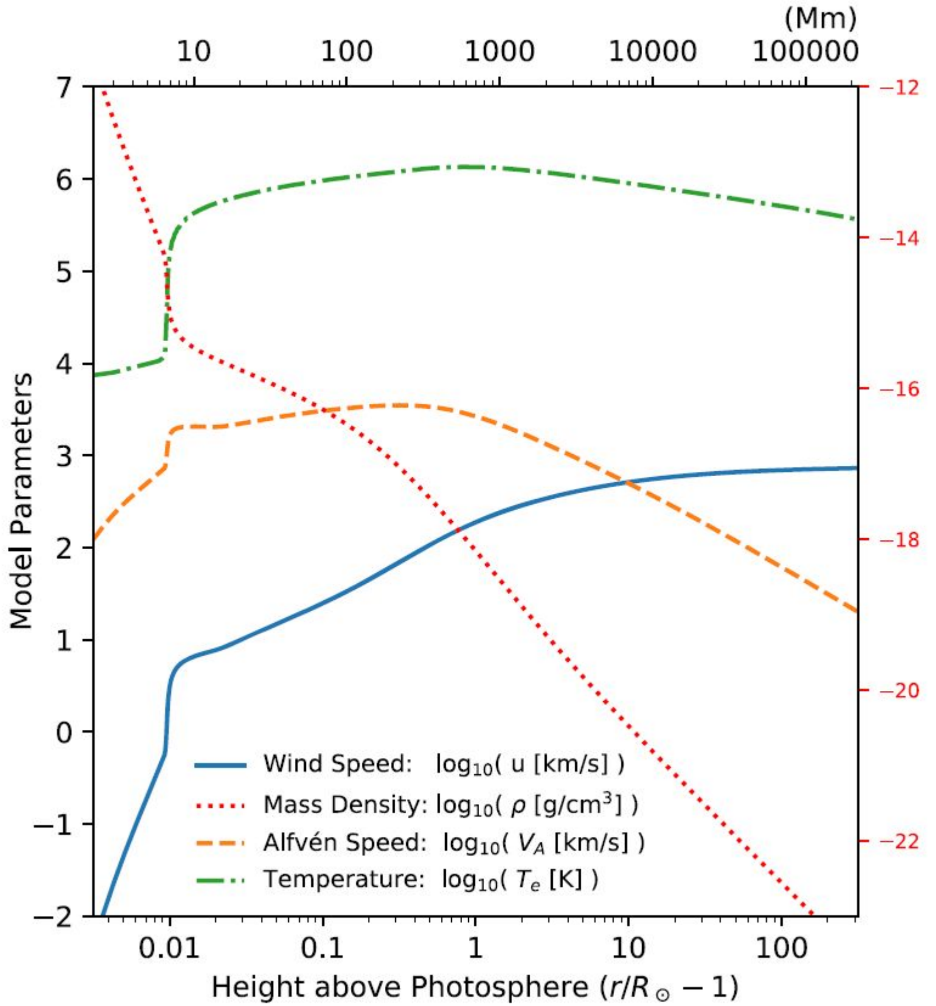

Figure 1. Tabulated output from ZEPHYR showing steady-state background plasma parameters. All lines use the left scale bar except for density, which uses the right scale.

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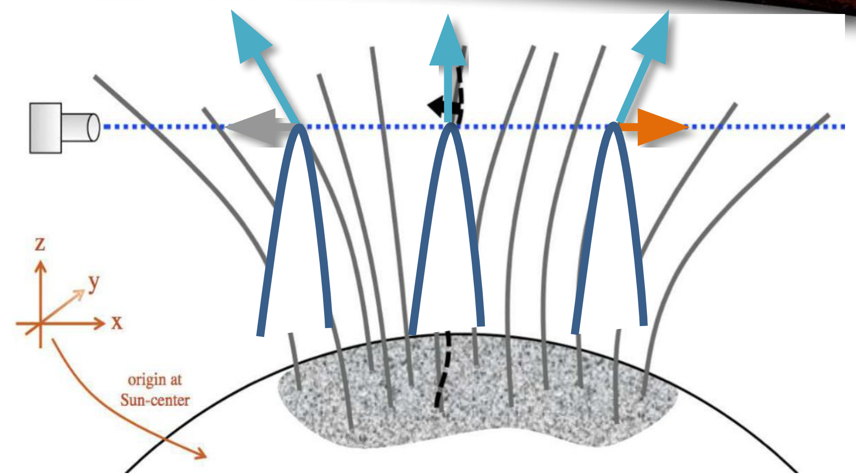
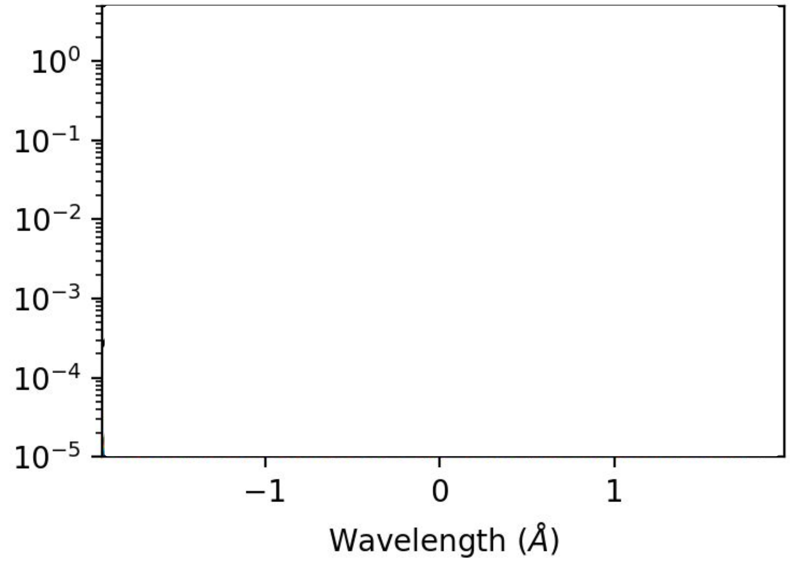
What Factors cause line broadening?z



In this work, observations are simulated using semi-empirical forward modeling. This means the physics must be manually added to the model.

- Physics that Contribute to Line Width:
  - Natural Thermal Width
  - Solar Wind Outflow Doppler Broadening
  - *Alfvén Wave Doppler Broadening (in prep!)*
- Other important physics:
  - Density Variation along Line-of-Sight
  - Rapid Ionization State Changes with Height



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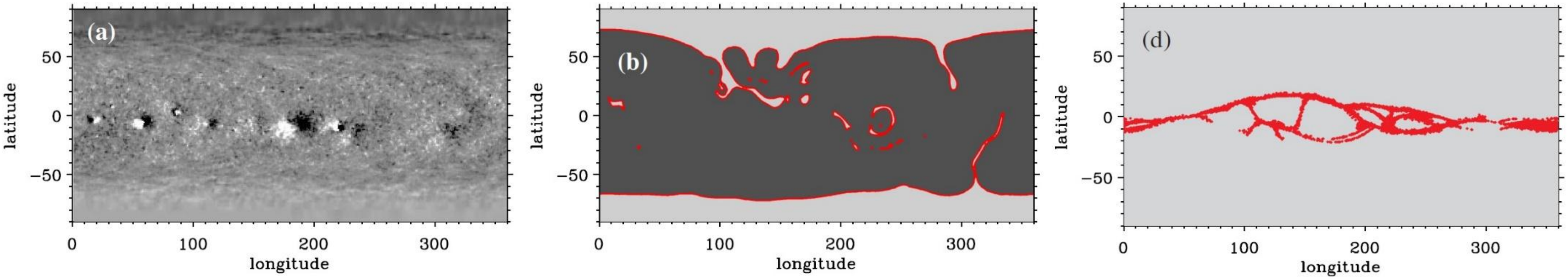
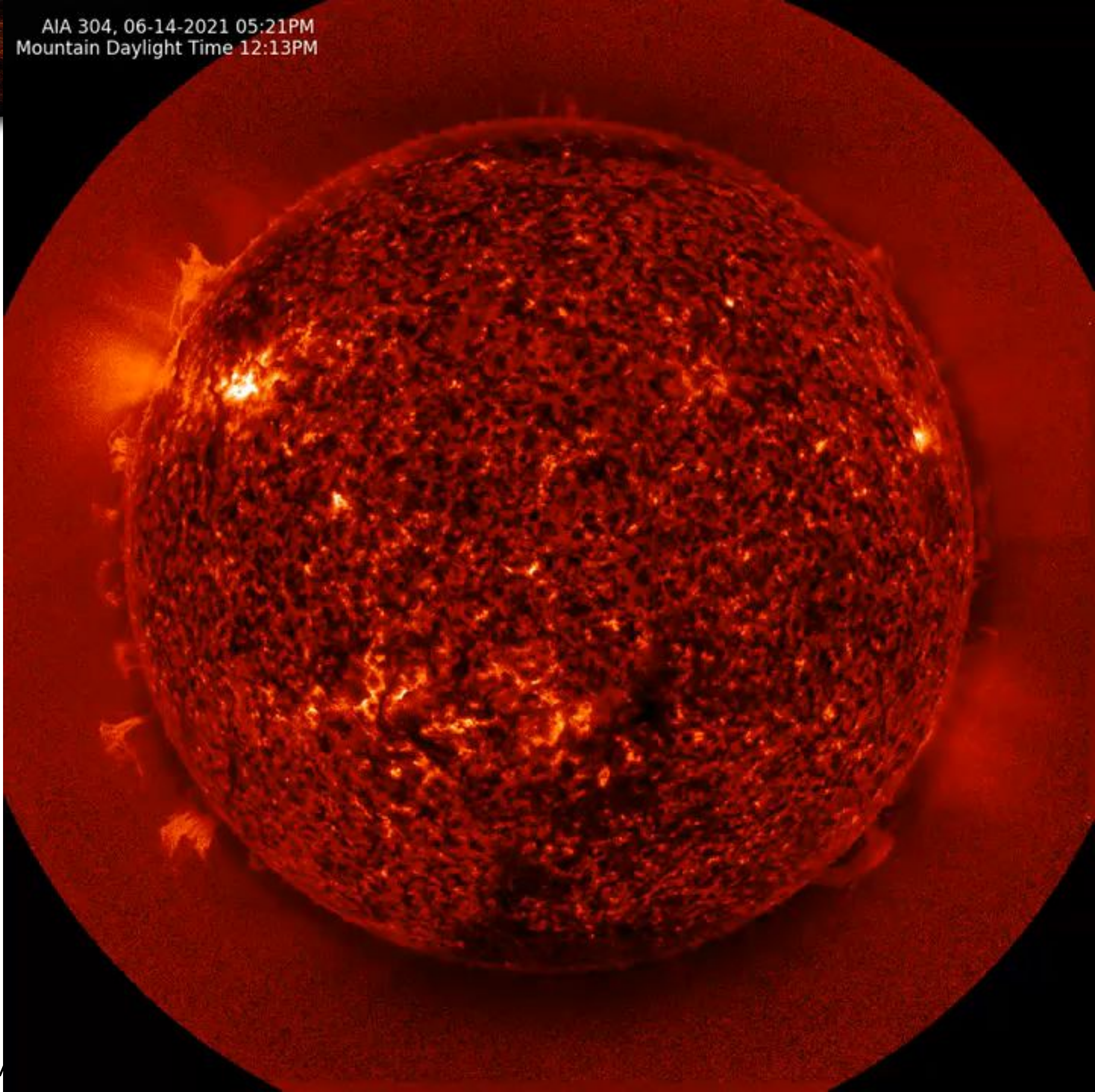
3D description of corona & heliosphere

- Rather than use a 3D simulation (limited by grid resolution), we define an "infinitely resolved" set of flux tubes assumed to be separated by rigid walls.
- Number/width of flux tubes: each maps down to ~1 supergranule.
- GONG synoptic magnetograms are extrapolated using SWPC's operational version of PFSS (we call it the SMCS technique: "Schatten [1971] & McGregor et al. [2008] Current Sheet").
- The central axis of each flux tube is mapped from r >> R_s down to the photosphere, and we compute both the WS90 expansion factor f_{ss} and the photospheric magnetic field strength.
- Example: one full rotation of CR 2058, with open regions shown in light gray; closed in dark gray; regions of likely S-web interchange reconnection in red.



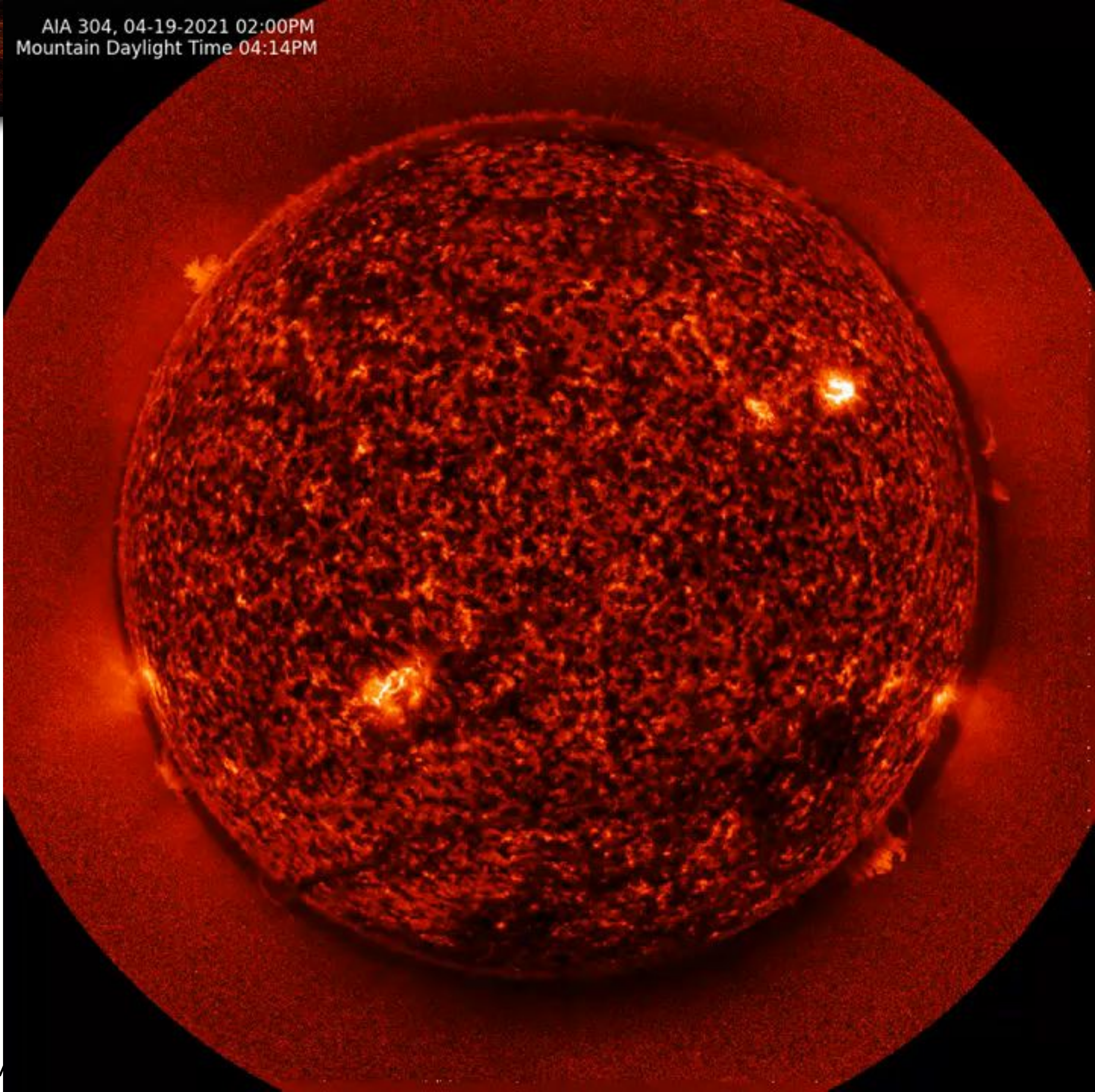
Video

6-14-21



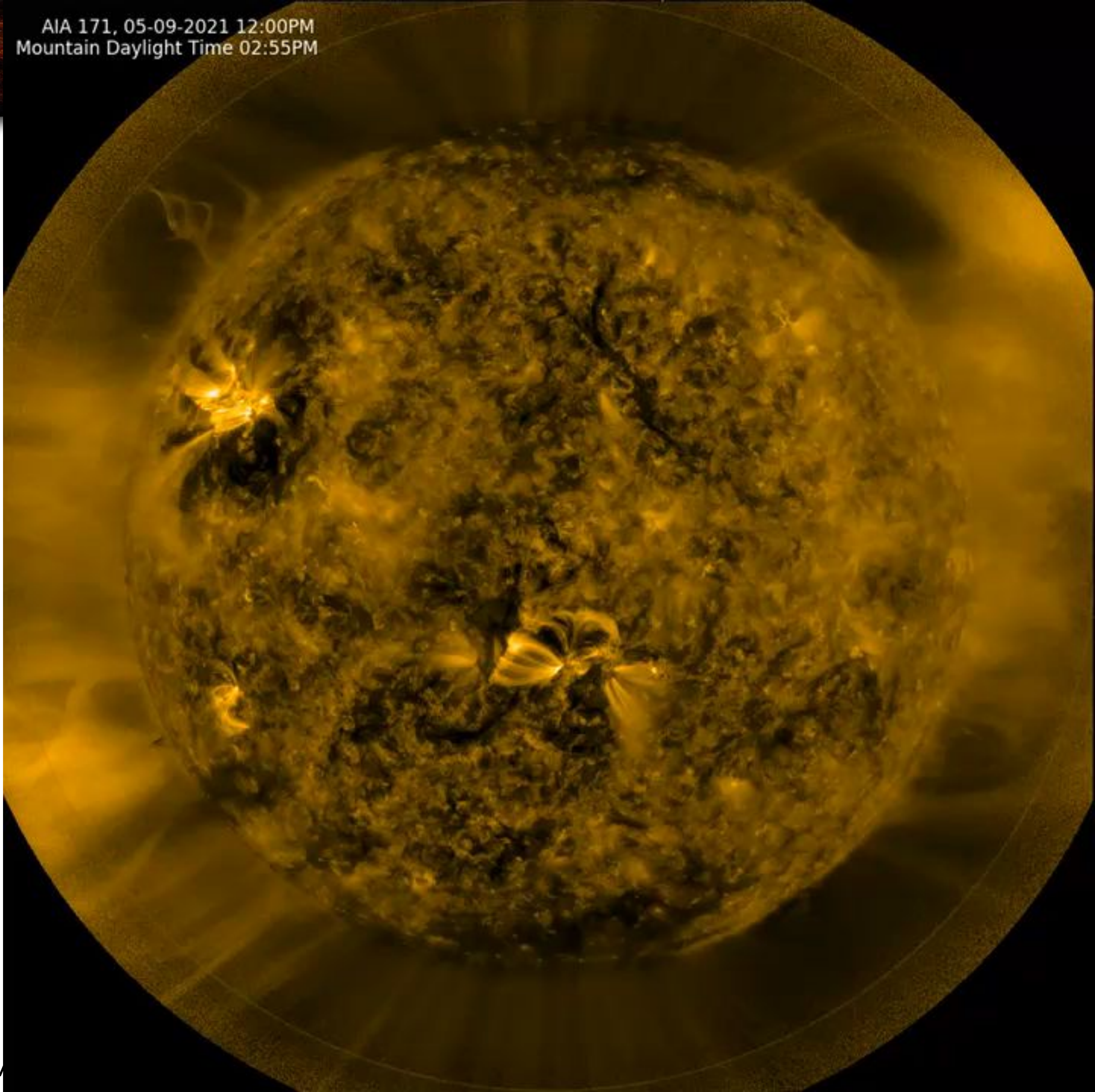
Video

4-19-21



Video

5-9-21



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Forward Modeling PUNCH-like Observations of Faint Plasma Blobs

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ABSTRACT

With the upcoming launch of the PUNCH satellite constellation, it is important to begin simulating the type of observations that will be made by this mission. The primary data product we will examine is the polarized brightness observed in an annulus around the Sun, with an inner and outer radial distance from sun center of 6 and 36 solar radii, respectively. The mission will provide this product at a three minute cadence, with faster products available for sub-fields of the image. In this work, we simulate this same type of observation and examine some preliminary features of the timeseries. We utilize the FORWARD model platform provided by the SolarSoft suite of IDL code to produce simulated imagery. The output of that code is then analyzed using python.

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- FIN

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