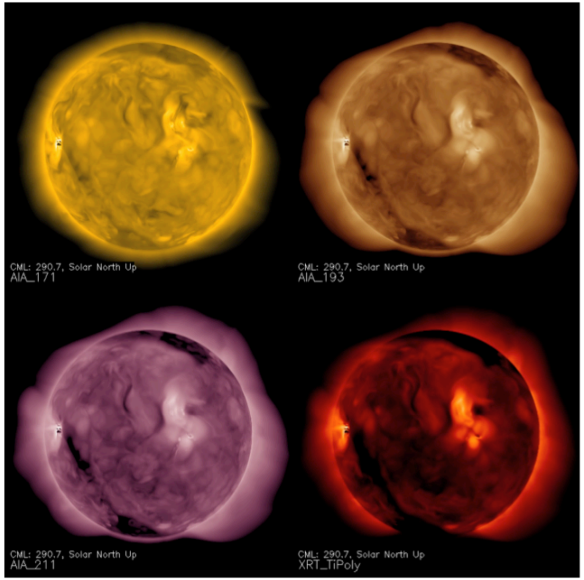
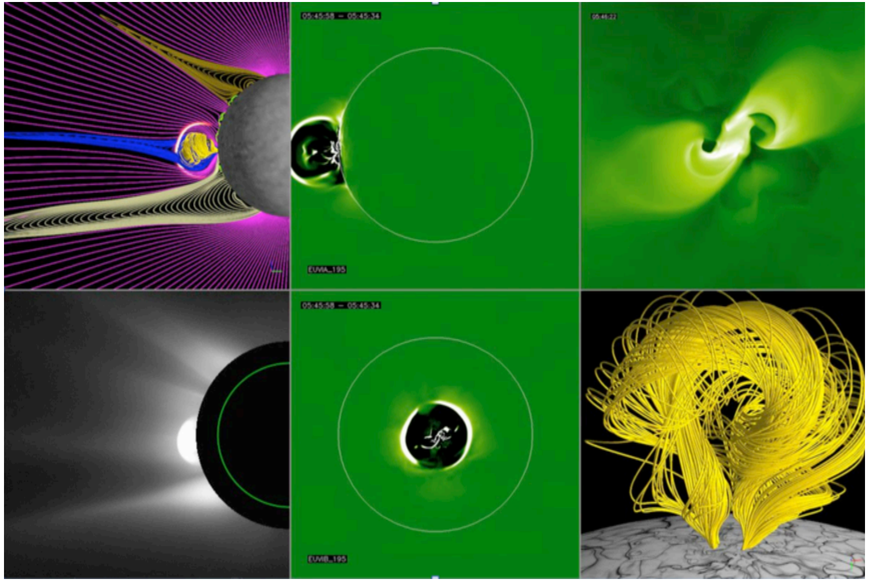
Global Coronal Models and Forward Modeling:

Connecting Observables to the Underlying Physical State of the Corona





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Predictive Science, Inc.

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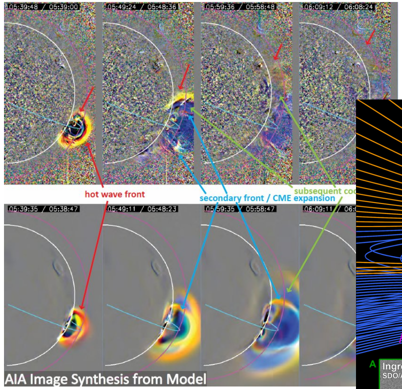
Research supported by NASA HSR and LWS and programs, AFOSR, and NSF.

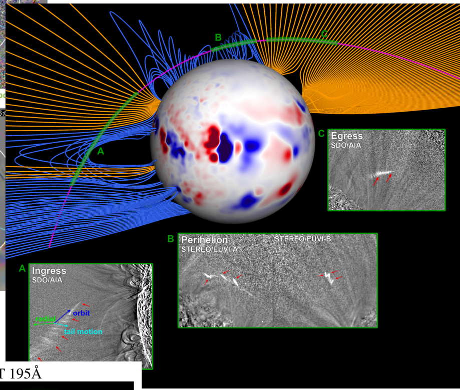
Why am I here?

- **My primary interest: understanding the thermal-magnetic structure and dynamics of the corona.**
  - Eruptions and their observational signatures (energy storage, onset, EUV waves, coronal dimming).
  - Coronal Heating (Alfvén waves, empirical models).
  - Global structure (mag connectivity/complexity, solar wind).

- **Magnetic and thermal states of the corona are closely related.**
  - The plasma state of corona (rho, t, v) strongly influences observables. (i.e. coronal line-emission / resonant scattering)
  - But it is the magnetic field that largely structures the plasma and loop geometry plays a crucial role in the hydrodynamics.
  - With models acting as a "digital laboratory" we can directly test our physical assumptions and interpretations of observations.



Downs et al. 2012



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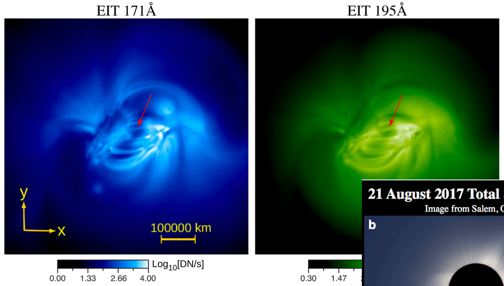
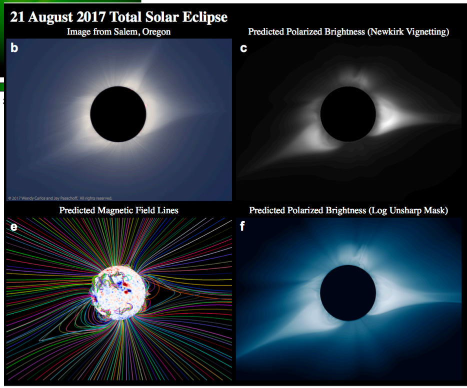


Mok et al. 2016

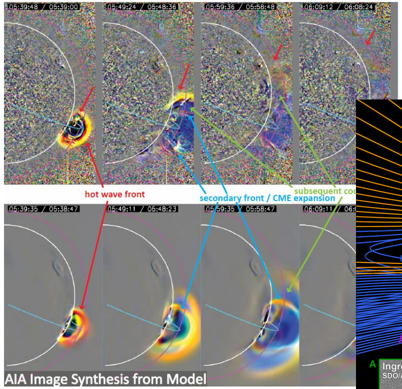


Mikić et al. 2018, under review

Why am I here?

- **Forward modeling observables from the models is key:**
  - This connects the physical parameters and/or evolution of rho, t, v, B (what we want to know) to remote sensing diagnostics (what we can observe).
  - We can test inversion methods using forward modeled data.
- **Advantages of 3D Modeling:**
  - With proper boundary conditions, we can simulate the global corona at a particular time.
  - It is “volume filling”. Can sample large dynamic range in plasma and magnetic field complexity along any LOS.
- **Why is this relevant to DKIST Observations and Planning?**
  - DKIST will provide new observations of magnetically sensitive coronal IR lines -> new insights and constraints!
  - Interpreting these signals will likely be very complicated, modeling can help disentangle things.

Goal of this talk: Give a tangible example of how we do “realistic” coronal modeling and a perspective on how this fits with the capabilities of DKIST



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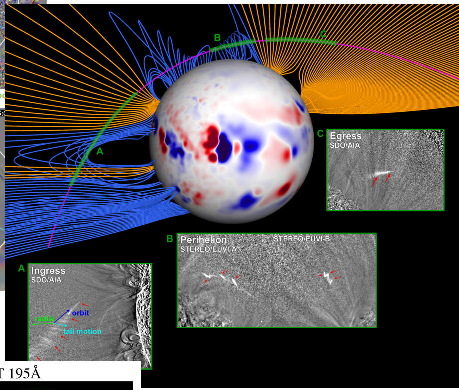

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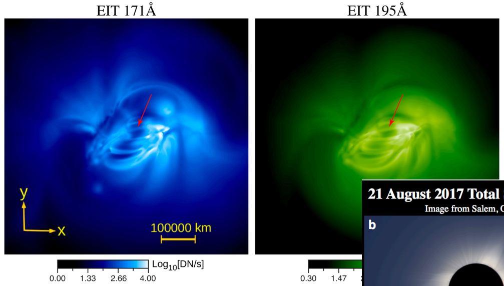
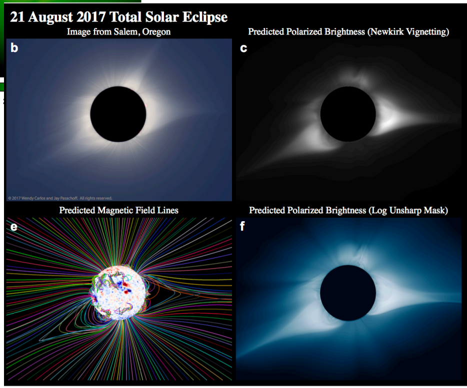


Mok et al. 2016



Mikić et al. 2018, under review

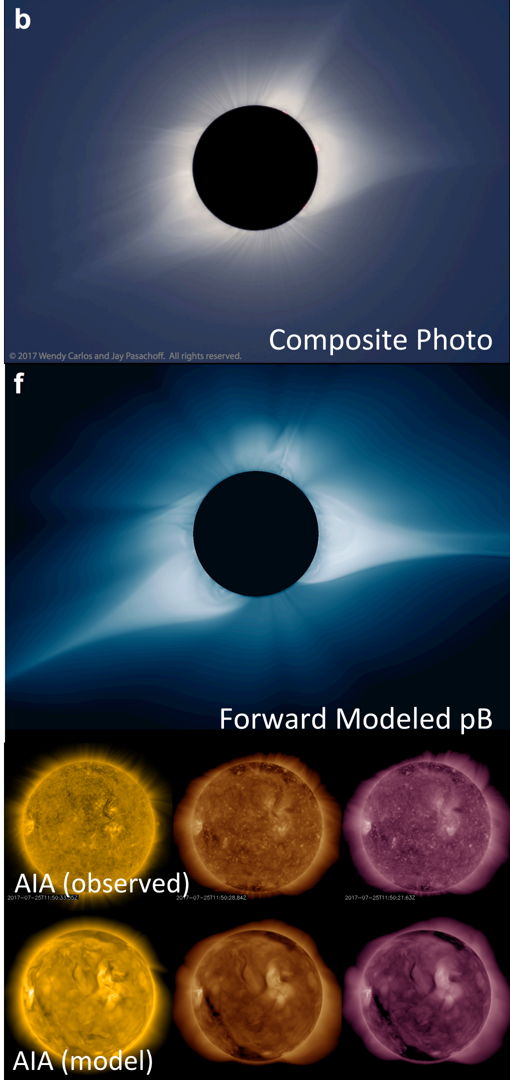
Global Corona Modeling Example

- One of our major efforts in 2017 was making a coronal prediction model for the August 21, total solar eclipse.

- An opportunity to test out our latest and greatest methods for a time period where there was a lot of scientific interest.
  - **Heating:** Test our new Wave-Turbulence-Driven (WTD) coronal heating model in 3D at high resolution.
  - **Magnetic Energization:** Study how energizing the global corona (shear/twist) may change the global structure of the corona.

- A chance to see where we are in terms of predictive capability.
  - Want to model the corona 2 weeks out, how well can we do?

- Forward modeling and comparing to observations was a key part of vetting the model before hand.



Mikić et al. 2018, under review

MAS: a Thermodynamic MHD Model

MHD Equations

$$\nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{J}$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

$$\mathbf{E} + \frac{1}{c}\mathbf{v} \times \mathbf{B} = \eta \mathbf{J}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = \frac{1}{c}\mathbf{J}\times\mathbf{B} - \nabla p - \nabla p_w + \rho \mathbf{g} + \nabla\cdot(\nu\rho\nabla\mathbf{v})$$

$$\frac{\partial p}{\partial t} + \nabla\cdot(p\mathbf{v}) = (\gamma - 1)(-p\nabla\cdot\mathbf{v} - \nabla\cdot\mathbf{q} - n_e n_p Q(T) + H)$$

Thermodynamic Terms

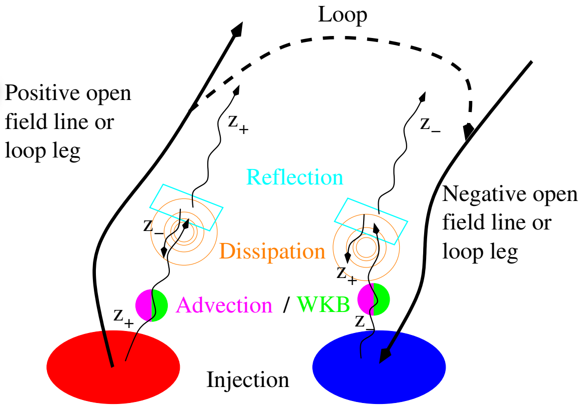
Heating Specified by WTD Model + weak isotropic exponential (heat floor)

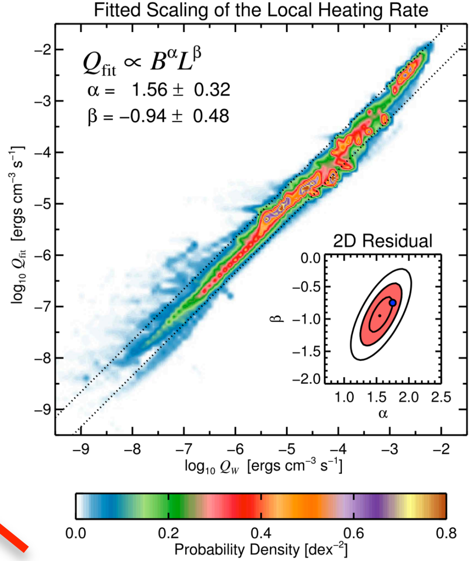
$$\gamma = 5/3$$

$$\mathbf{q} = -\kappa_{\parallel}\hat{\mathbf{b}}\hat{\mathbf{b}}\cdot\nabla T \quad \text{(Close to the Sun, } r \lesssim 10R_S\text{)}$$

$$\mathbf{q} = 2\alpha n_e T\,\hat{\mathbf{b}}\hat{\mathbf{b}}\cdot\mathbf{v}/(\gamma - 1) \quad \text{(Far from the Sun, } r \gtrsim 10R_S\text{)}$$

+ WKB equations for Alfvén wave pressure p_w evolution

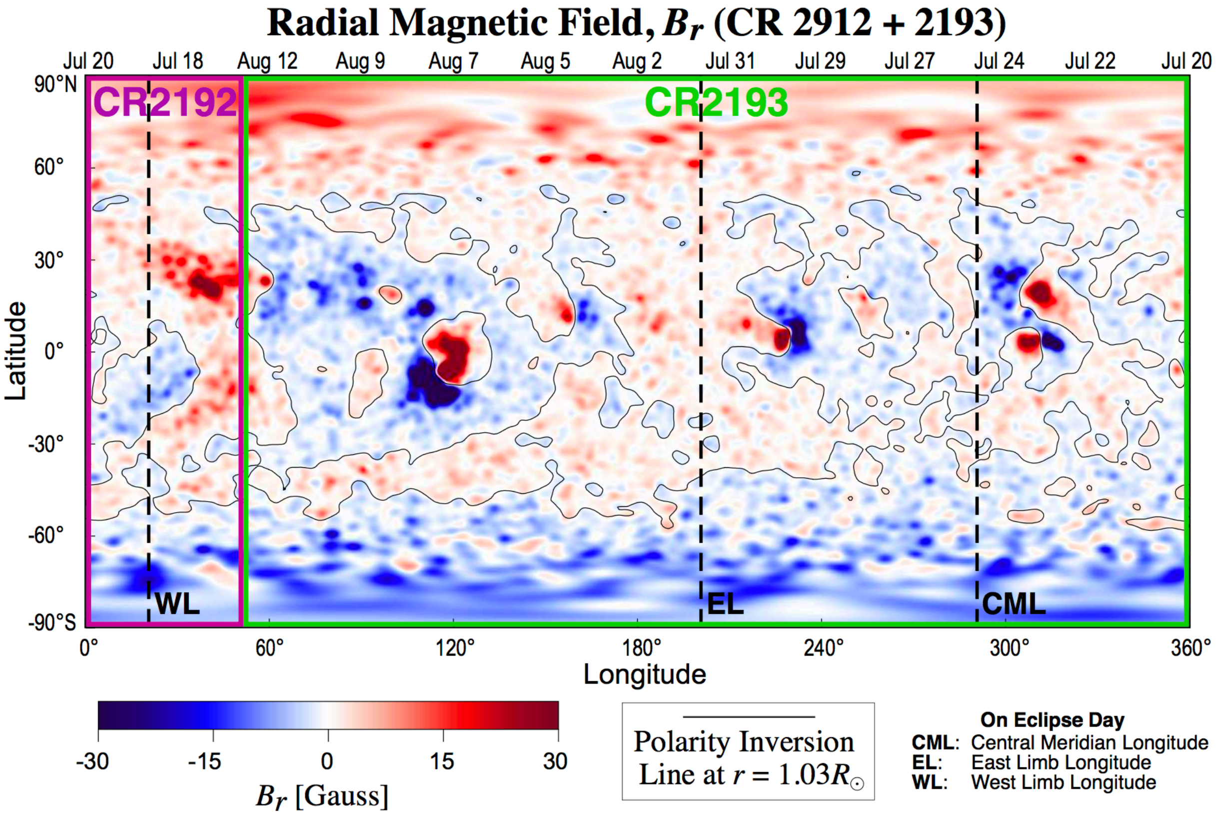




(see Lionello et al. 2009 for more details on MAS, and Downs et al. 2016 for details on WTD heating)

Boundary Conditions

- Need a full-sun map of the radial magnetic field.
- How you calculate and/or map Br from observations (and which ones) is a crucial input.
- Here we use near real time HMI synoptic maps with data up to 8/11 (mix of CR2193/2192).
- Can also use surface flux transport models (e.g. ADAPT or AFT) but this has its own set of tradeoffs.



Energization Summary

- Active filament channels are identified by inspecting AIA movies and a magnetofrictional (MF) model run by Duncan Mackay.

- An electric field profile is built to emerge shear along the neutral lines of the selected channels.

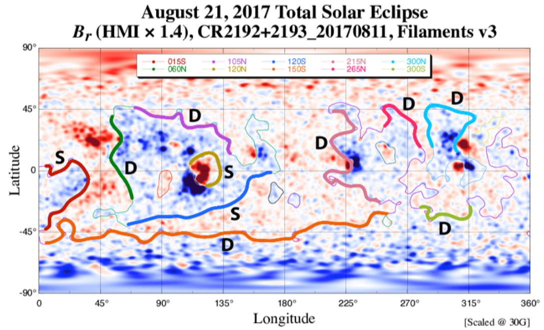
$$\mathbf{E}_t^0 = \boldsymbol{\nabla}_t \times \psi\hat{\mathbf{n}} + \boldsymbol{\nabla}_t\phi \quad \rightarrow \quad \frac{1}{c}\frac{\partial B_n^0}{\partial t} = \nabla_t^2\psi$$

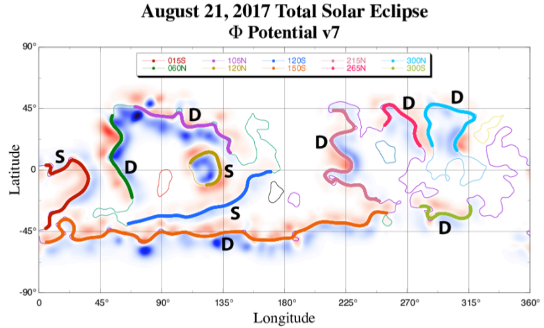
- The MF model informs the choice of handedness for the shear.

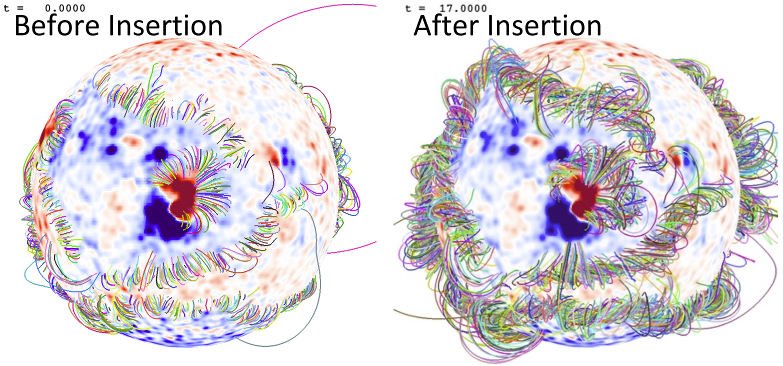
- Additional flux along each NL is added at the beginning and cancelled after the shear phase.

- The energized field is constructed in a simple zero-beta MHD model:
  - Start with a potential field, then emerge shear via E_t from Φ.
  - Stop shear, cancel added flux via E_t from Ψ.
  - End up with energized field (flux-ropes/highly sheared NLs)

- Insert the energized field into the thermodynamic MHD model by adding only the energized part of the vector potential ($A_E = A_{total} - A_{pot}$), and relax for 8hrs physical time.

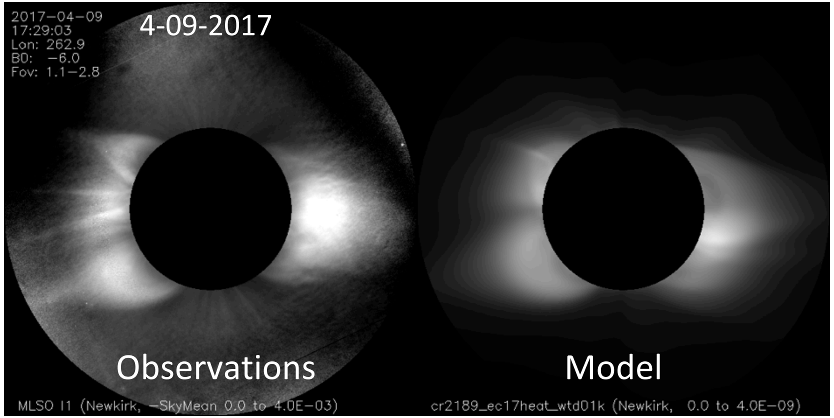




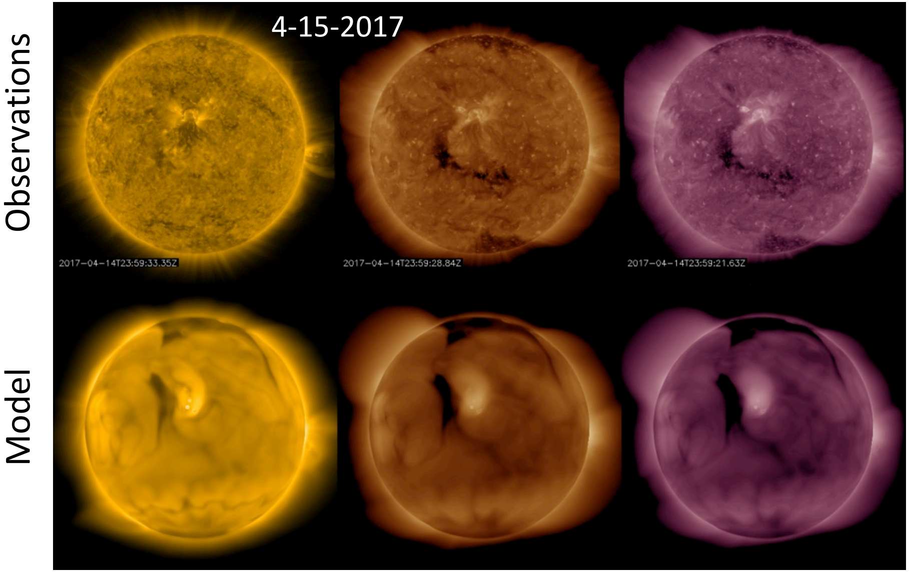


Observational Benchmarking

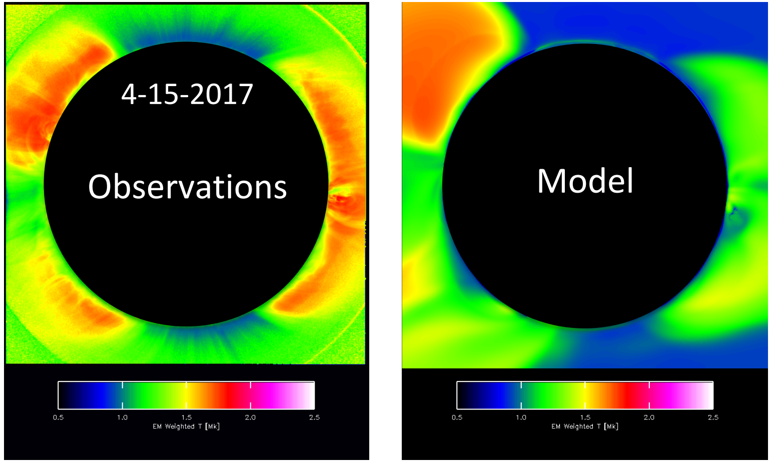
- 15 test runs for CR 2189 (medium resolution).
- Vary free heating parameters (z_0, λ_0).
- Vary B scaling by a factor of 2 (HMI to MDI ~1.4, Y. Liu 2013).
- Use 3 diagnostics: EUV images, off-limb Te, MLSO White Light.
- Main Point: Even our most sophisticated model still needs fine tuning. Multiple observational metrics needed!



White Light Morphology in Polarized Brightness (MLSO/HAO K-Cor)



EUV Emission Comparison (AIA 171/193/211)



Off Limb Temperature
(EM weighted Te, derived from Hanna & Kontar DEM fit)

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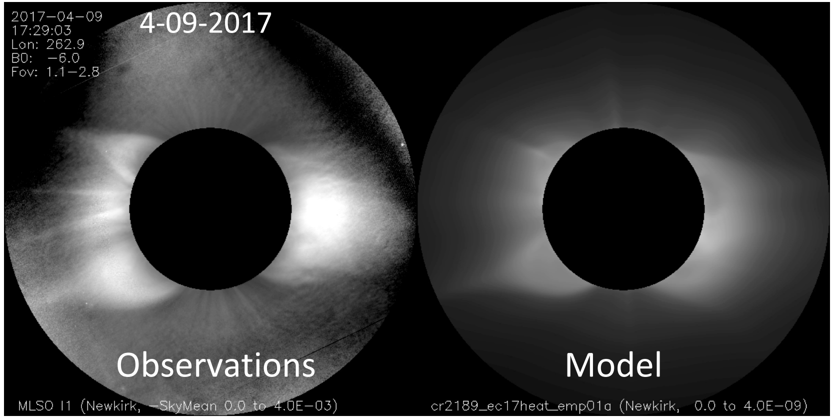

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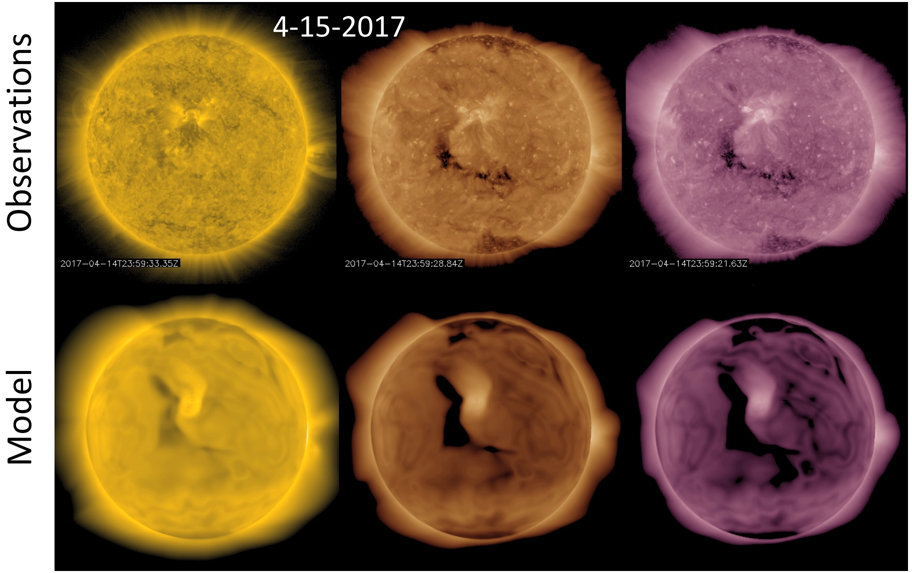

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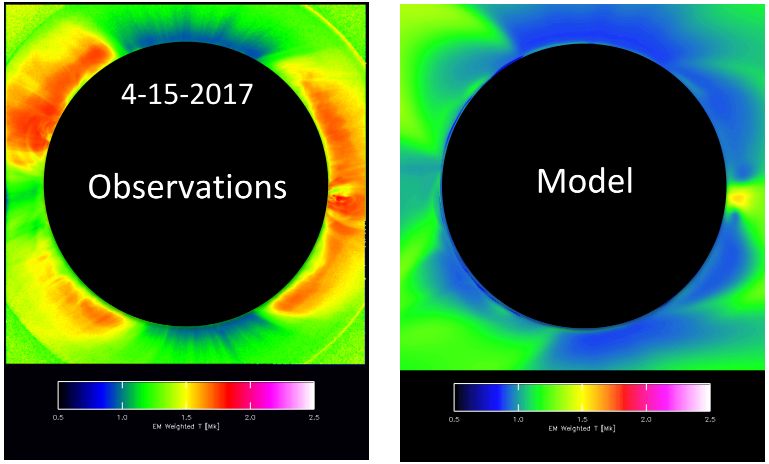

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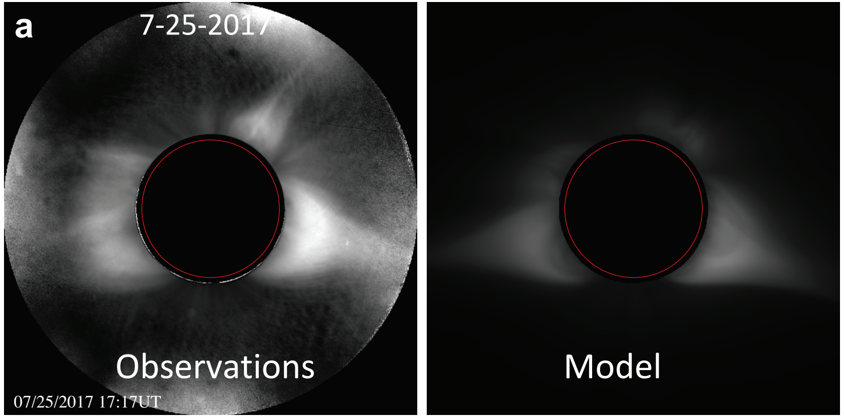
(EM weighted Te, derived from Hanna & Kontar DEM fit)

Observational Benchmarking

- **Final Prediction (posted 8/14)**
- Last chance was to compare to eclipse day 1 rotation earlier.
- Here, EUV images, temperature map, and white light look good.
- Interplay between heating/energized fields bumps up the heating temperature a last little bit.



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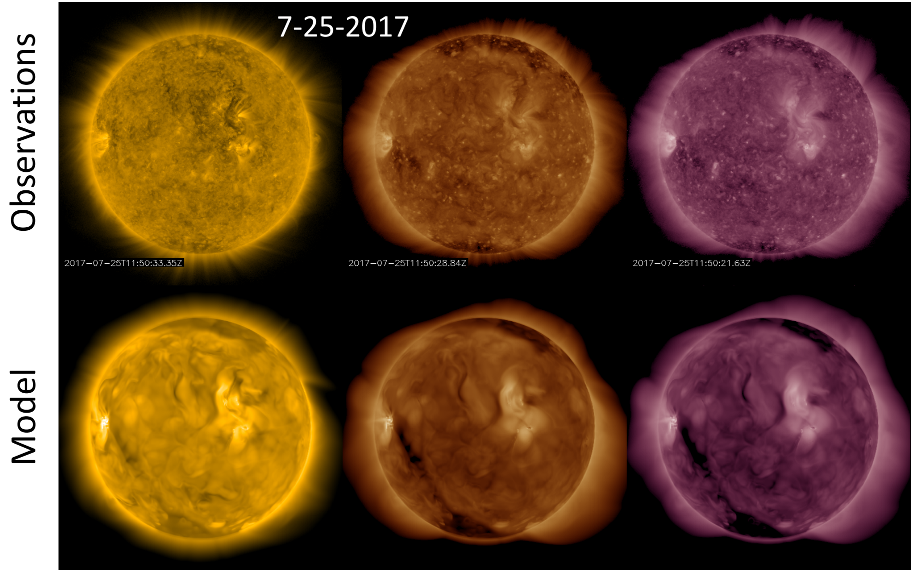

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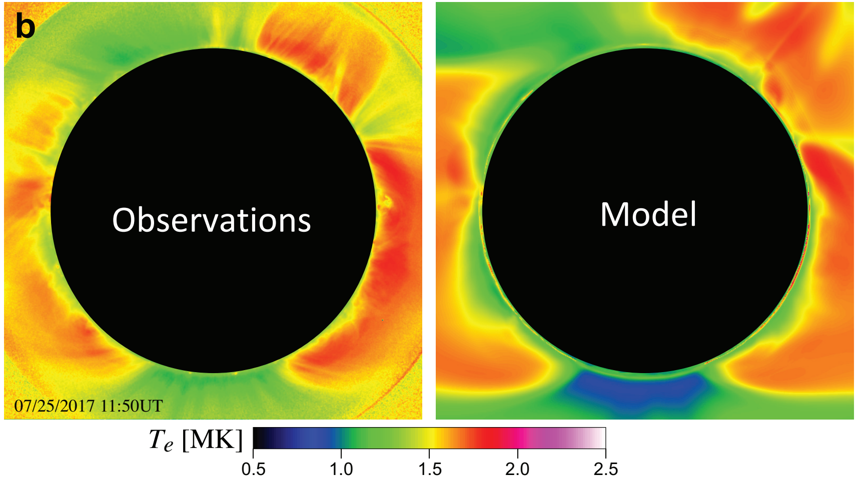
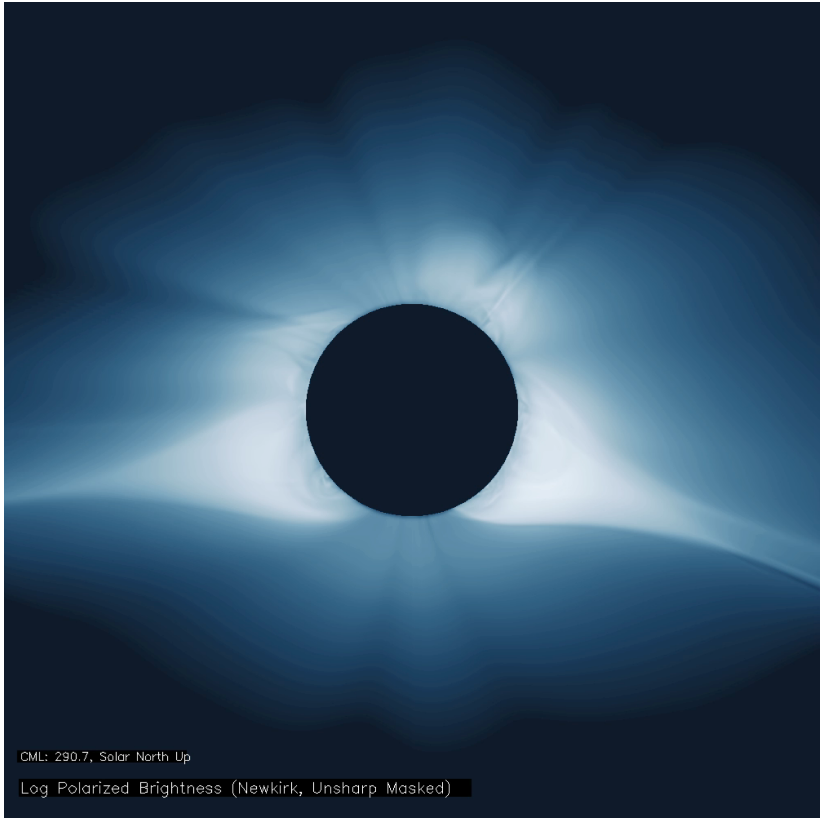
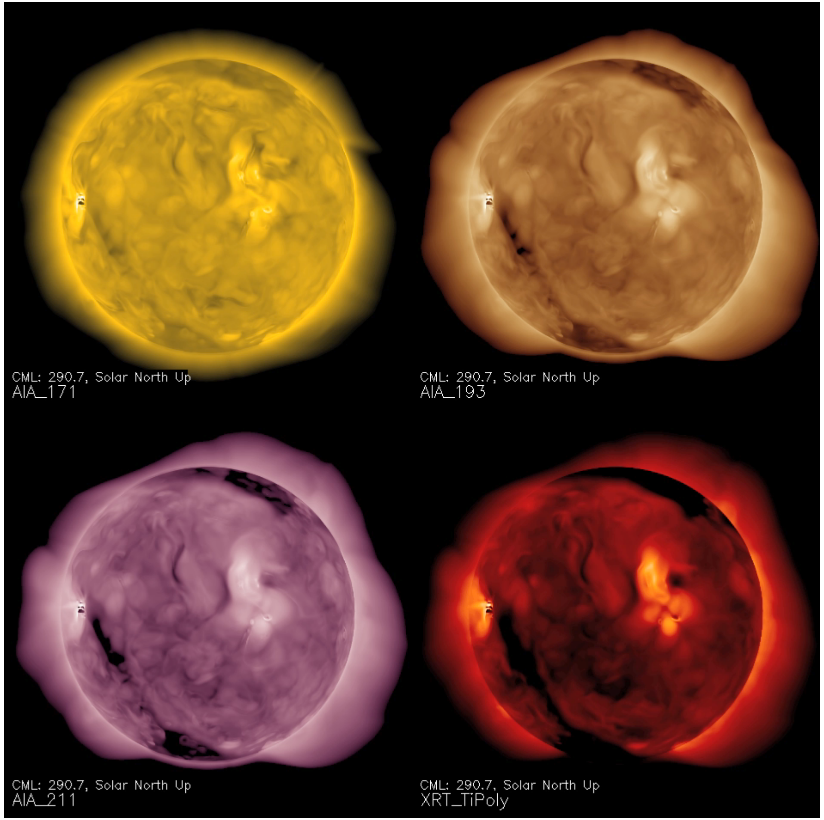


Off Limb Temperature
(EM weighted Te, derived from Hanna & Kontar DEM fit)

Final Prediction Movies (Observables)

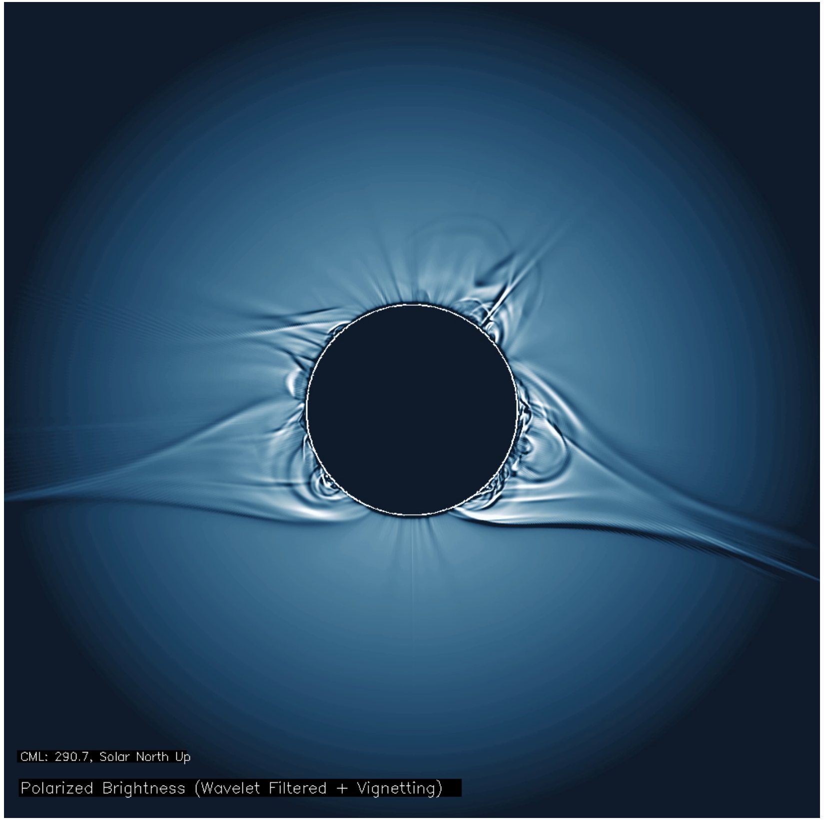


Log$_{10}$ Polarized Brightness, Newkirk Vignetting

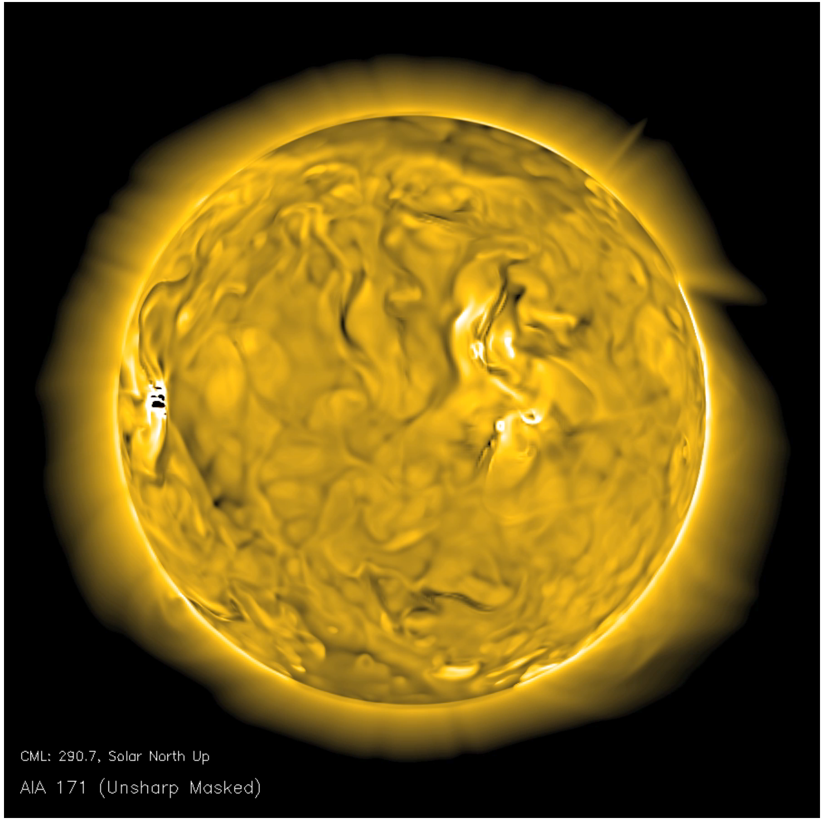


EUV/soft X-Ray Images (AIA 171,193,211, XRT Ti-Poly)

Final Prediction Movies (Observables, Processed)

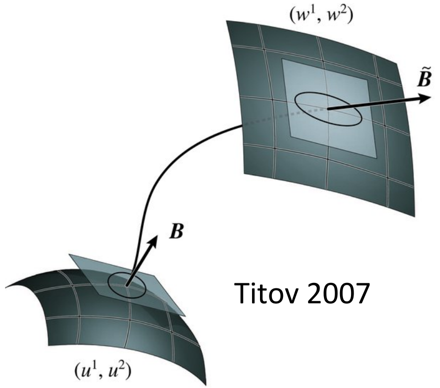


Wavelet Filtered Polarized Brightness



Unsharp Masked AIA 171

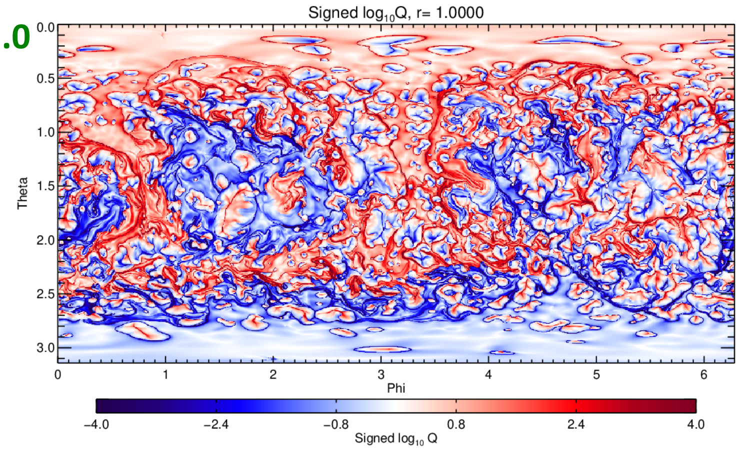
3D Field Line Mappings: Squashing Factor Q



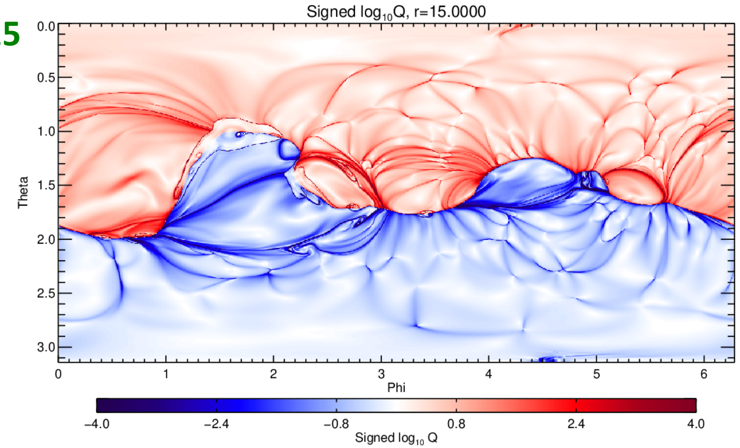
Titov 2007

Basically map field lines on the boundary from the starting to end point.

R=1.0

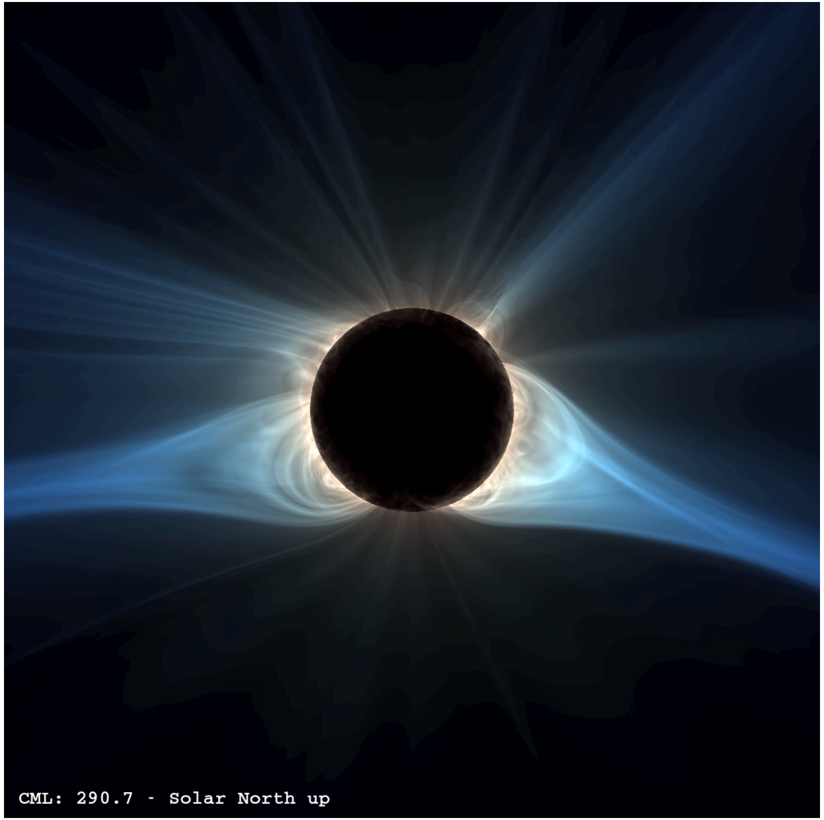


R=15

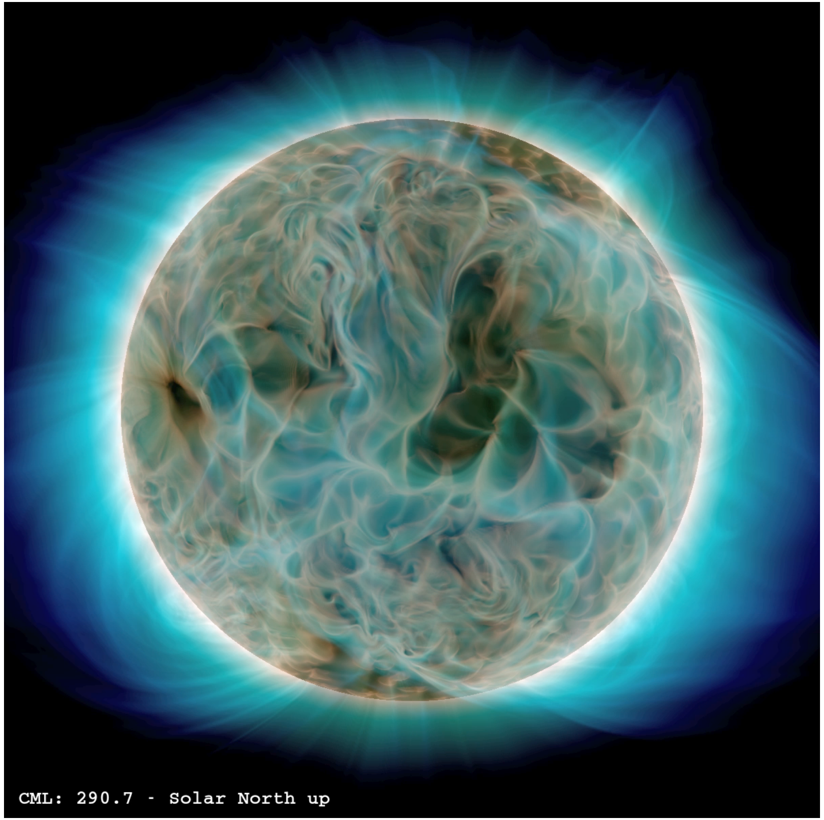


- Q is related to the deformation of an infinitesmal flux tube (i.e. derivatives of the mapping).
- Extremely useful diagnostic for mapping interesting regions of the magnetic field.
- Q becomes infinite in the presence of separators (i.e. distinct flux-systems).
- Q is large at quasi-separatrix layers (QSLs).

Final Prediction Movies (Q Renderings)

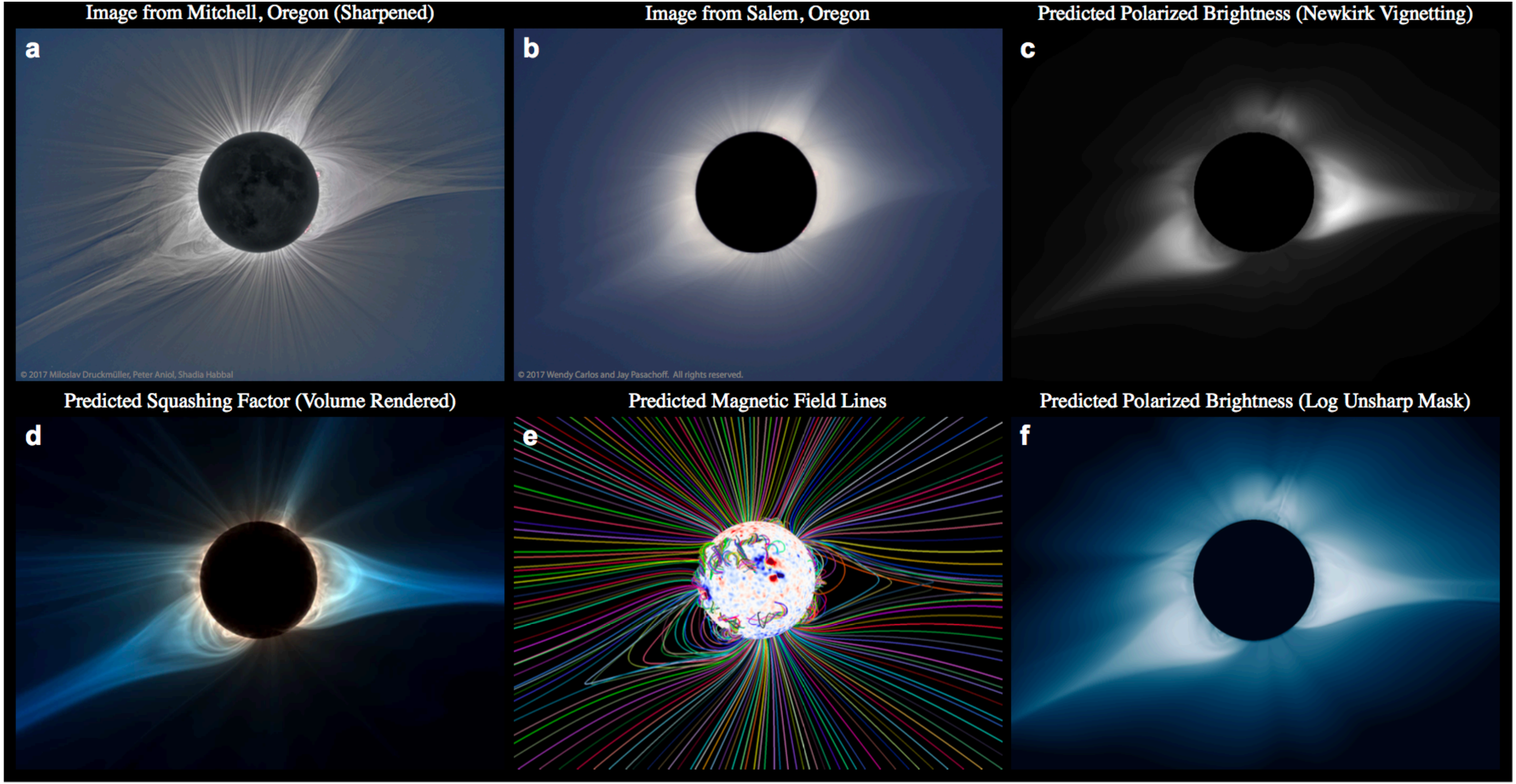


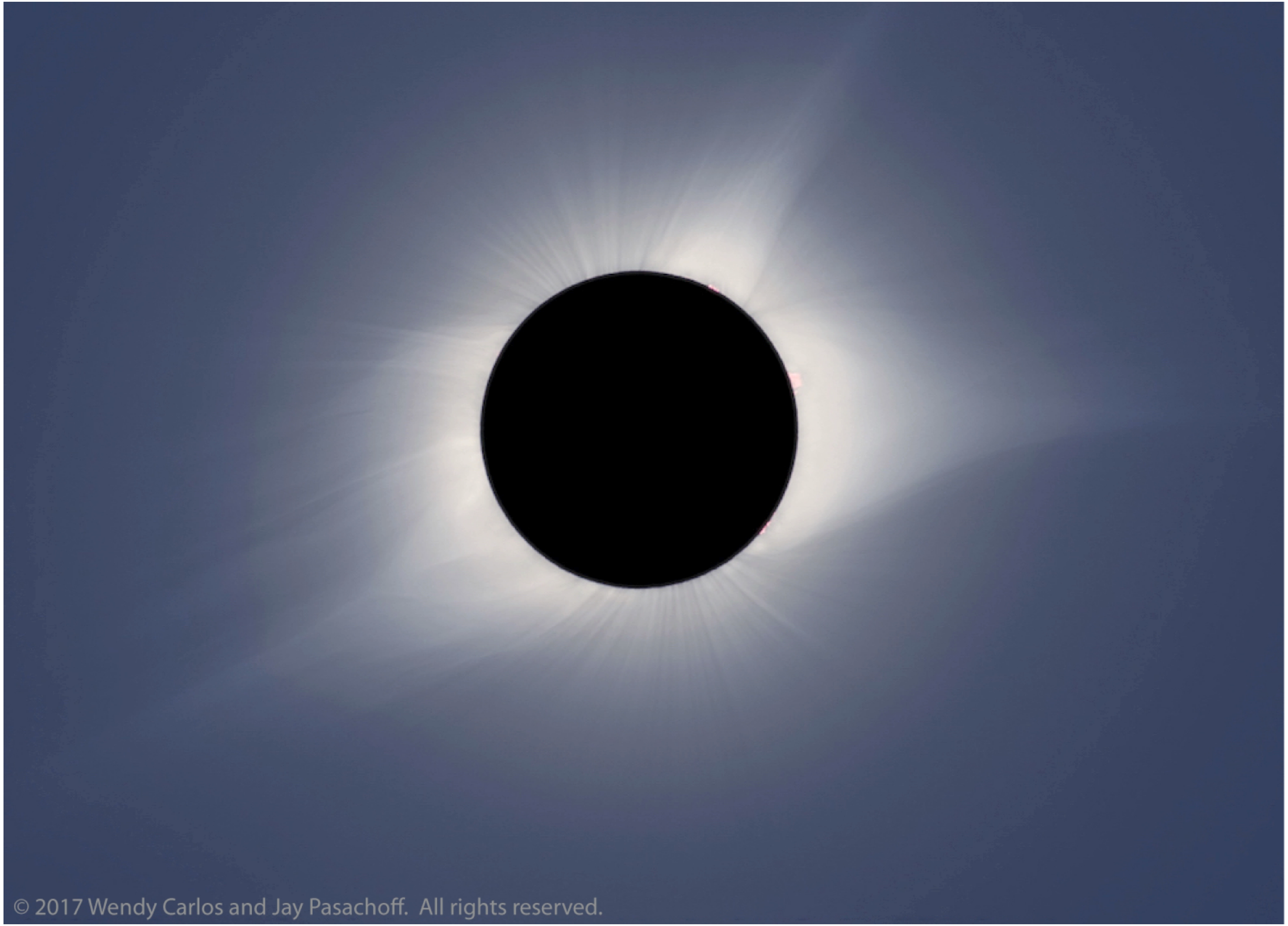
Volume Rendered Q (RGB Composite, POS/radial weights)



Volume Rendered Q (RGB Composite, exp weights)

Comparing to the actual Eclipse



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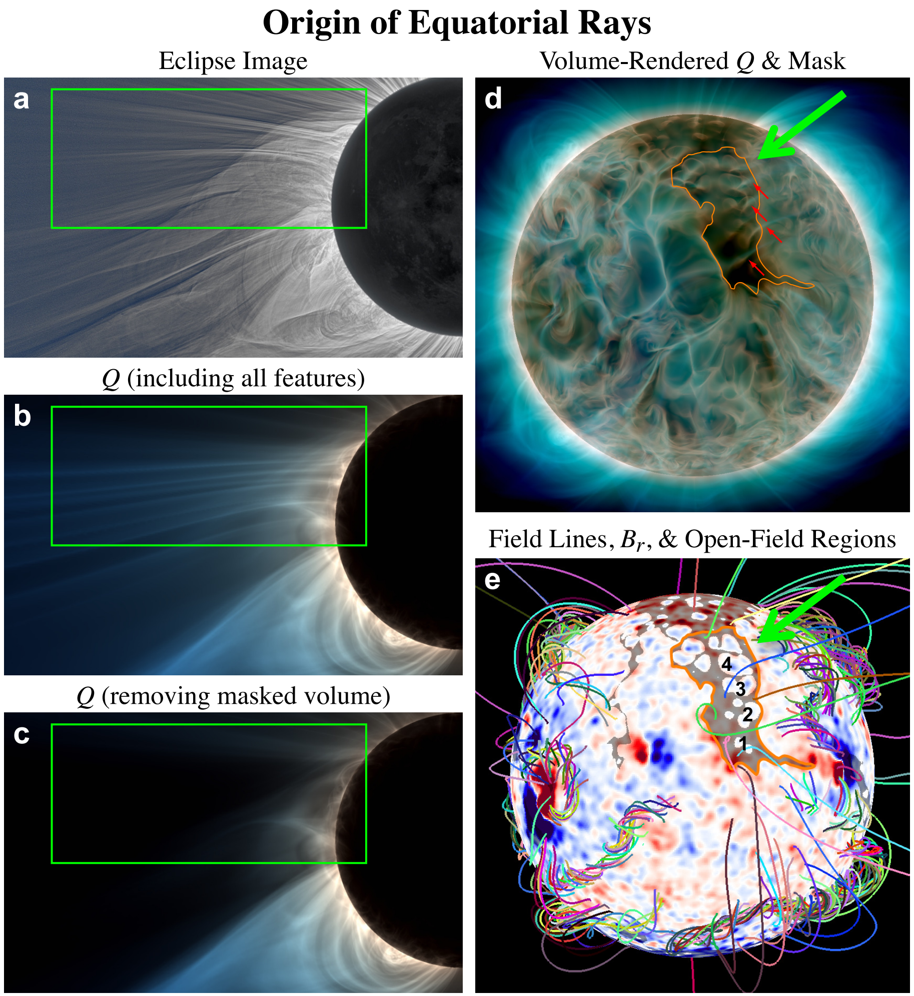
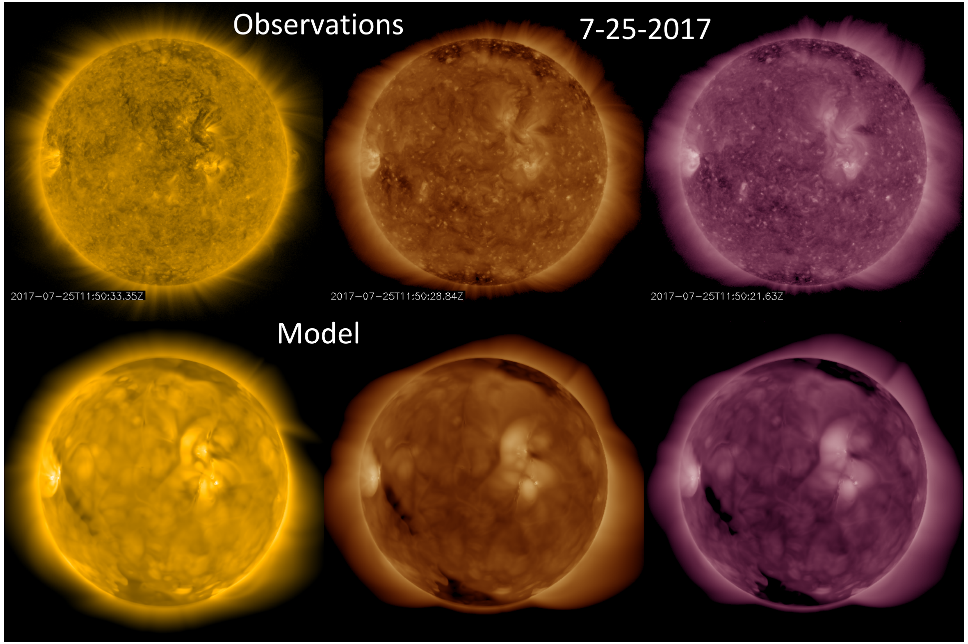
Analysis Example I

Overlapping Structures in the Corona

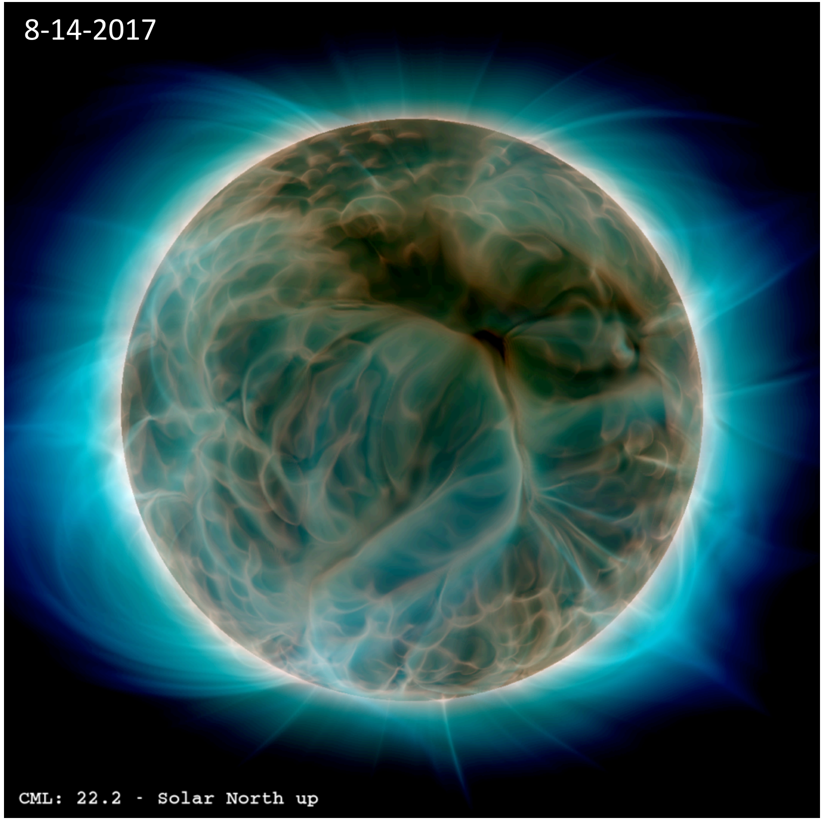
- Examine the origin of the fine equatorial rays visible in the highly sharpened image (a).
- We see the rays in the 3D Q rendering coming from the equatorial coronal hole near the east limb on eclipse day (b, d).
- Mask out this region from 3D mapping, they disappear! (c).
- These rays map to the separatrix domes of parasitic polarities embedded inside the coronal hole (Panel e)



Analysis Example II: Low Coronal Effect of Energization



SDO AIA 171, 193, 211 Comparison (Before Energization, 7/25)



Volume Rendered Q Composite (Before Energization, 8/14)

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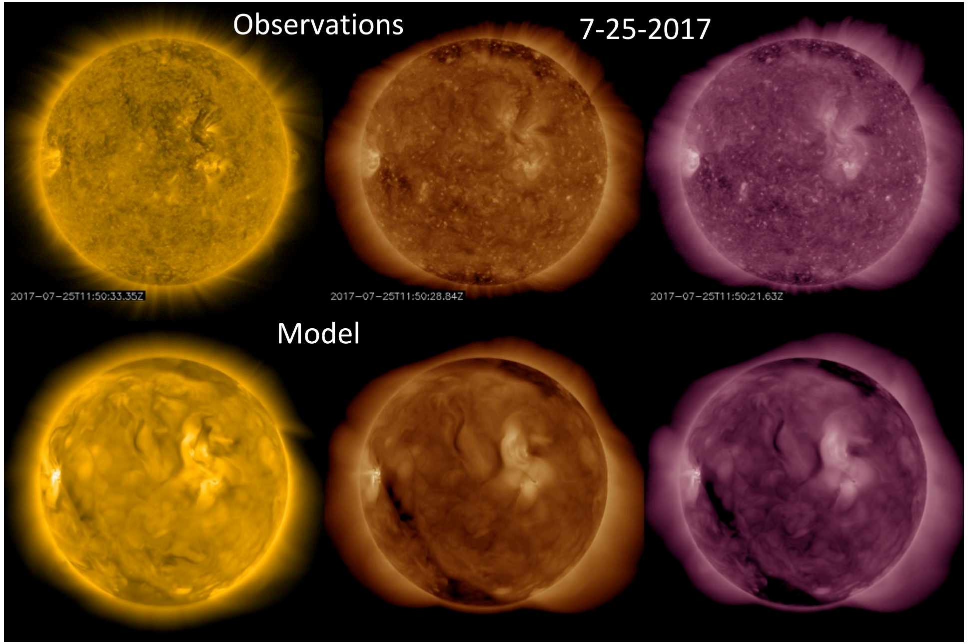

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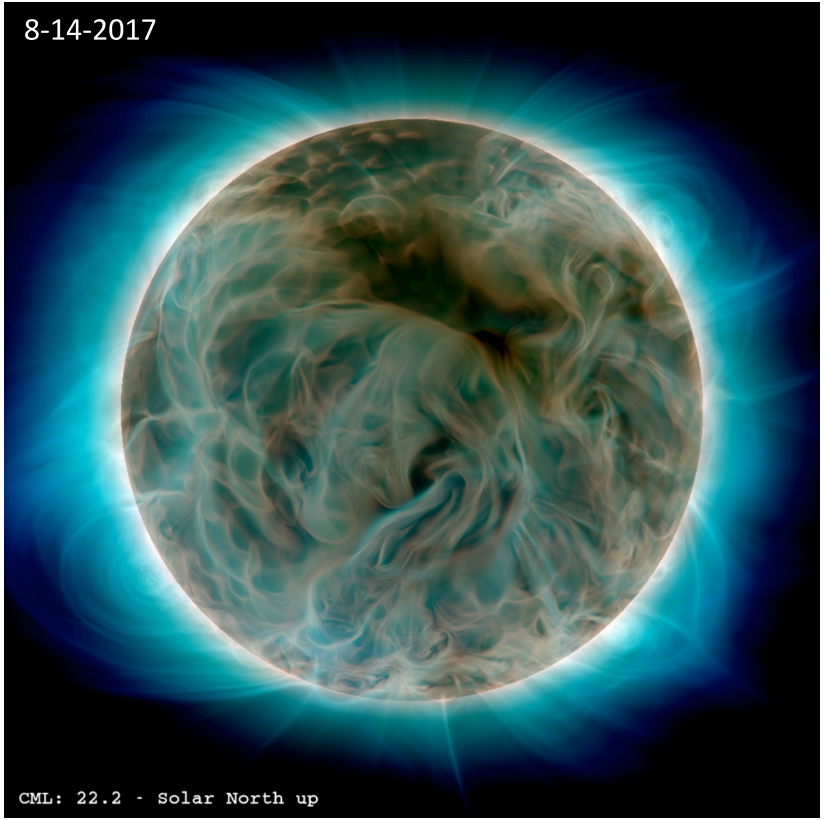
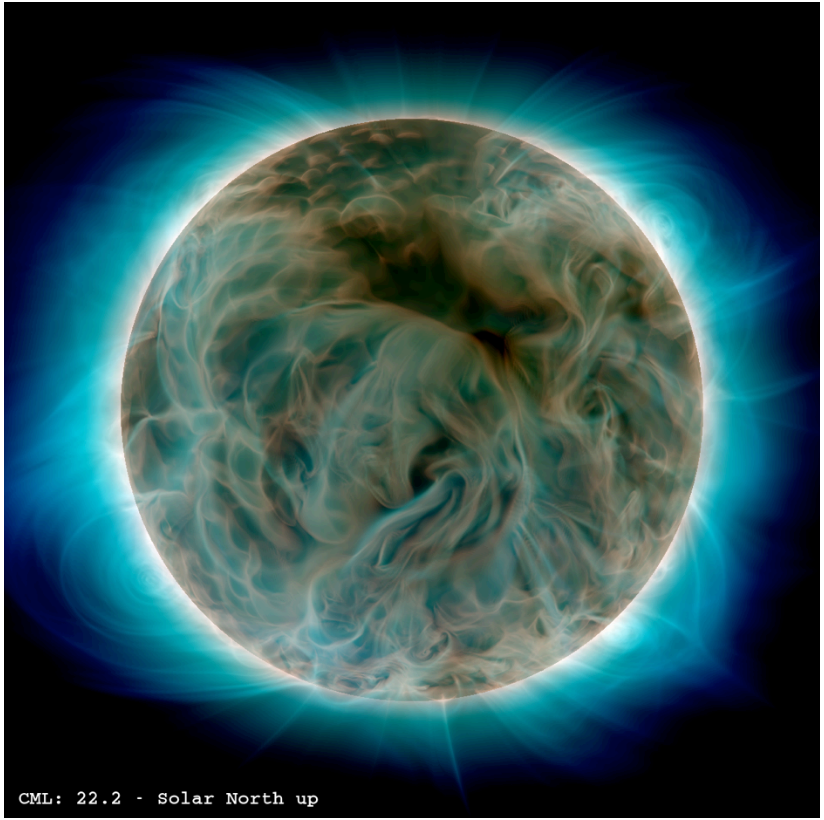


Volume Rendered Q Composite (After Energization, 8/14)

Analysis Example II: Low Coronal Effect of Energization

COMP Fe XIII 1074nm Enhanced Intensity (MLSO/HAO)



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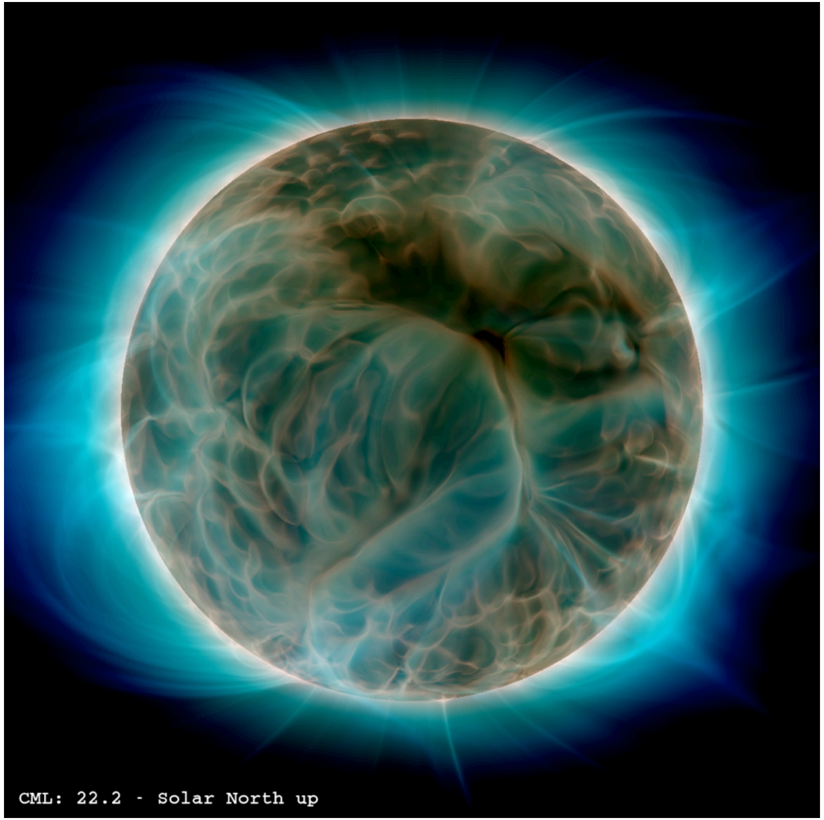


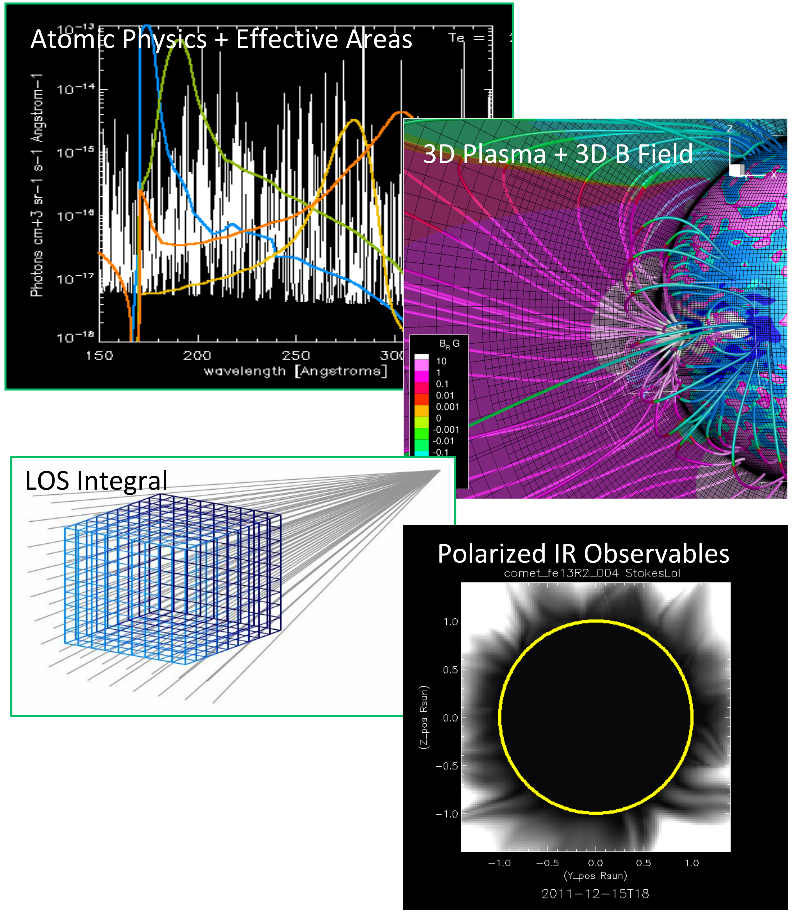
Volume Rendered Q Composite (Before Energization, 8/14)

So how can Coronal Modeling Complement the interpretation of DKIST Observables?

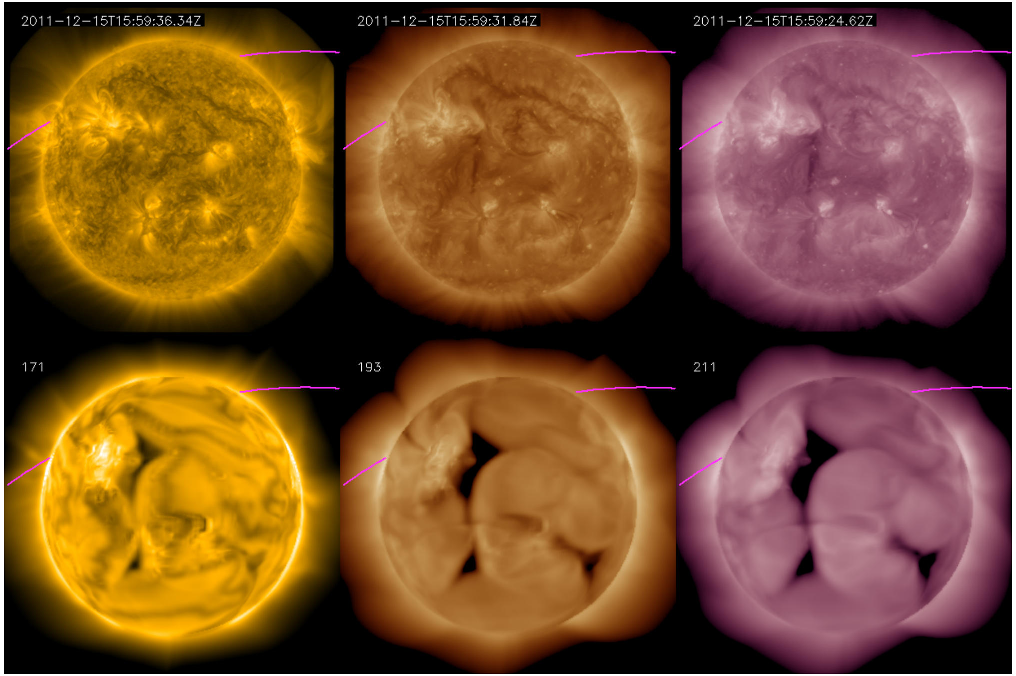
Some Thoughts/Examples

Example 1: Characterizing LOS effects and Model Choices

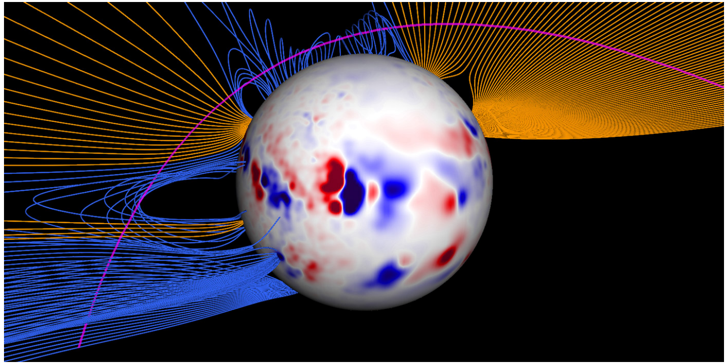
- Polarization signature of corona is a unique diagnostic of magnetic field and thermodynamic conditions.
- Similar to EUV images in the sense that they are a LOS convolution of thermodynamic variables.
- More complicated convolution this time: 3D Position, Vector B, N_e, T_e
- Can simulate FeXIII polarization signatures using SSW/ FORWARD (Gibson et al. 2016, Frontiers), which glues Phil Judge’s F77 code.

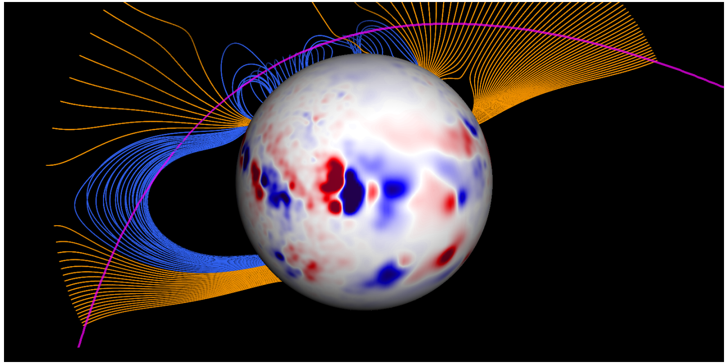


Coronal Case: Comet Lovejoy Perihelion 12/2012



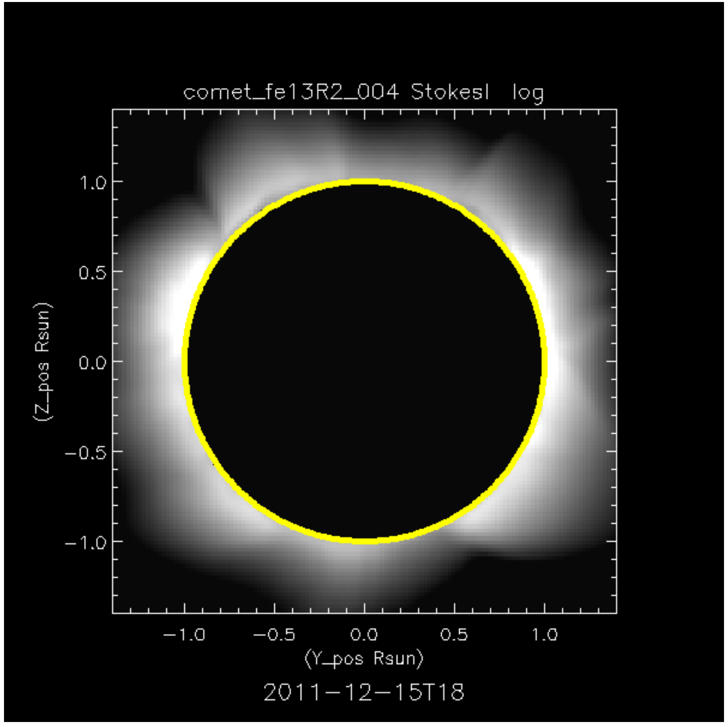
- Use thermo MHD state for Fe XIII Forward Modeling
- Disk is blurry because we lowered resolution there (not intersected by the comet orbit), off limb is good.



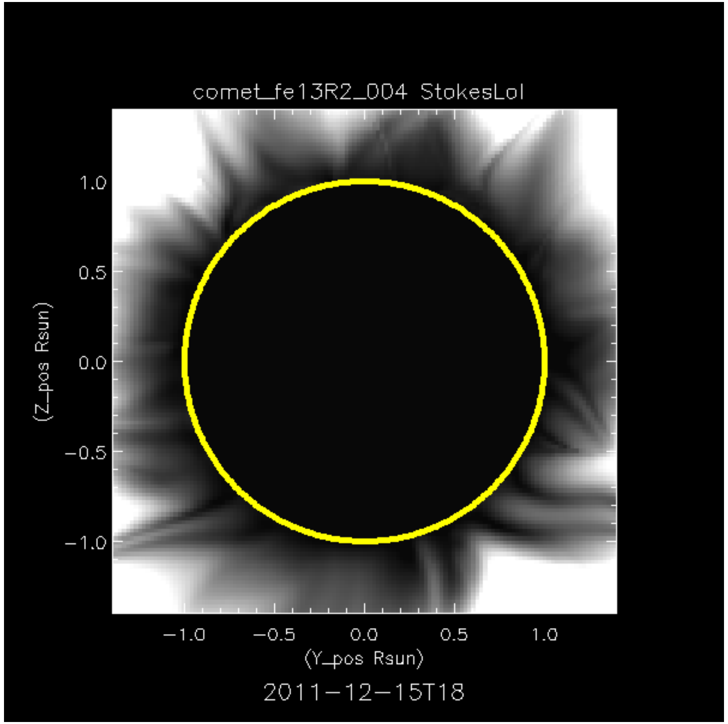


We compared MHD and PFSS magnetic field models along comet trajectory, can look at global properties here.

Fe XIII Signal From Solution

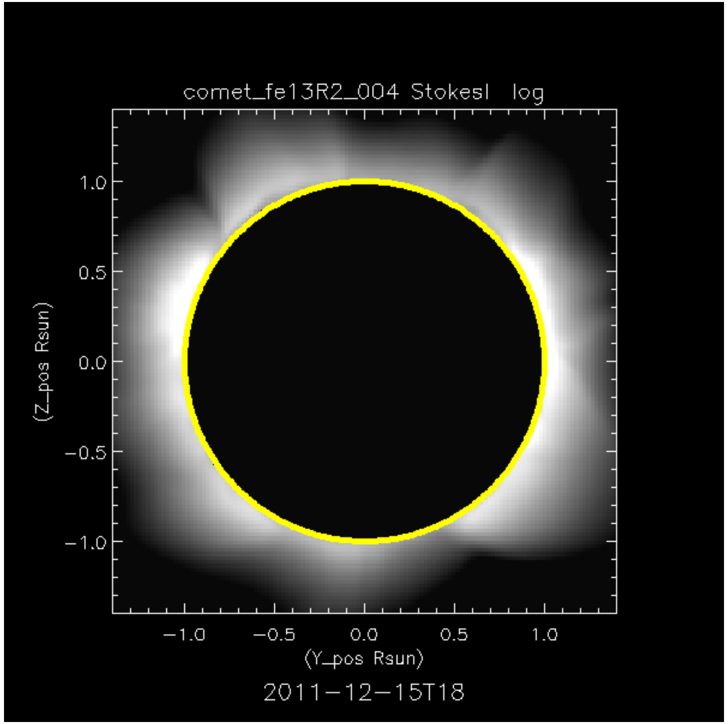


Stokes I (Intensity)

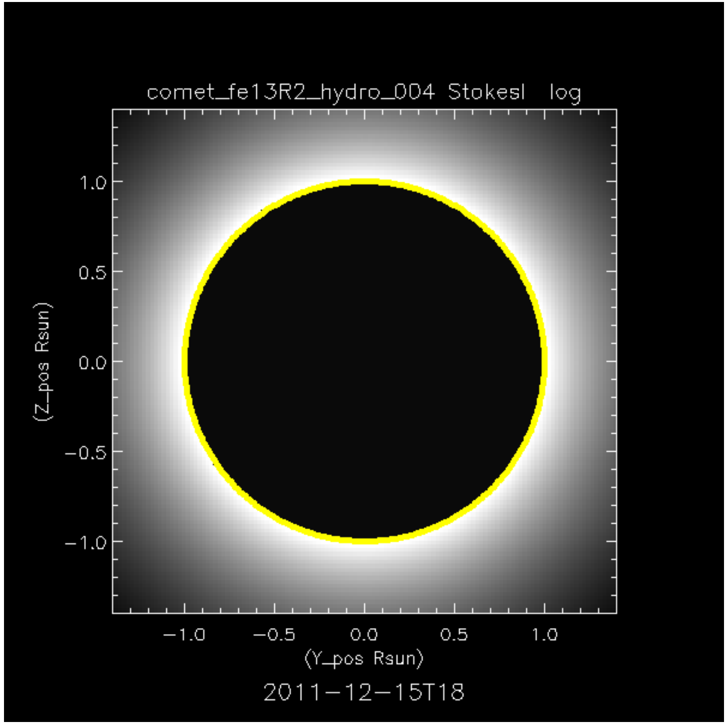


Stokes L/I (total linear over intensity)

Test 1: Spherical Symmetry

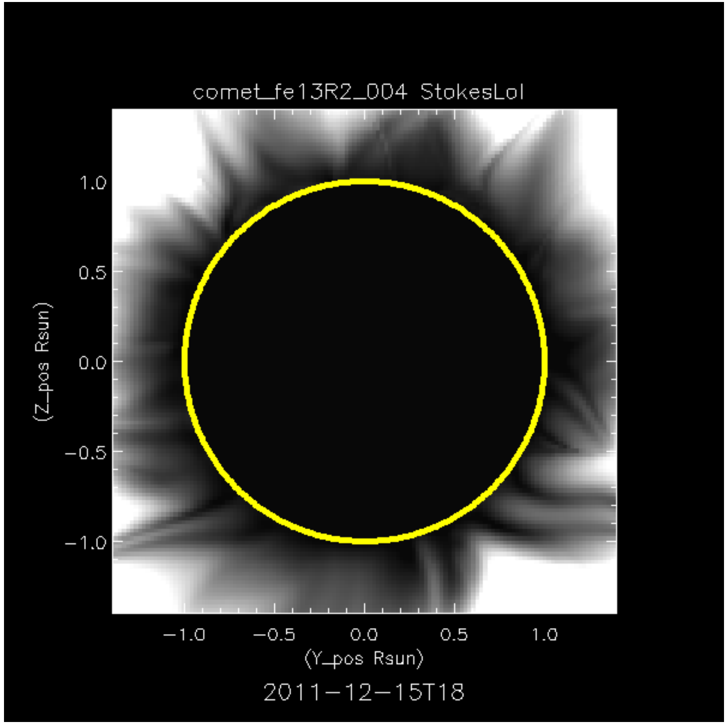


MHD Field + MHD Plasma

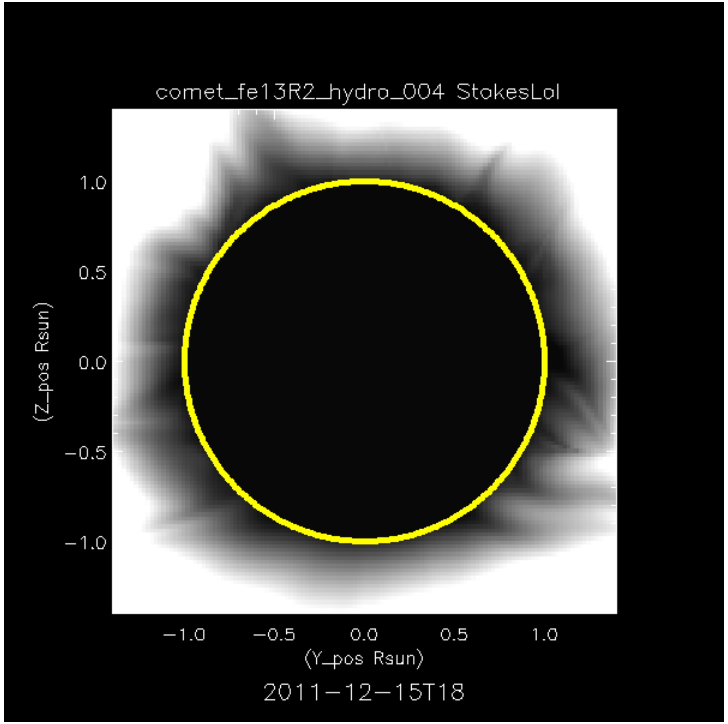


MHD Field + Symmetric Plasma

Test 1: Spherical Symmetry L/I

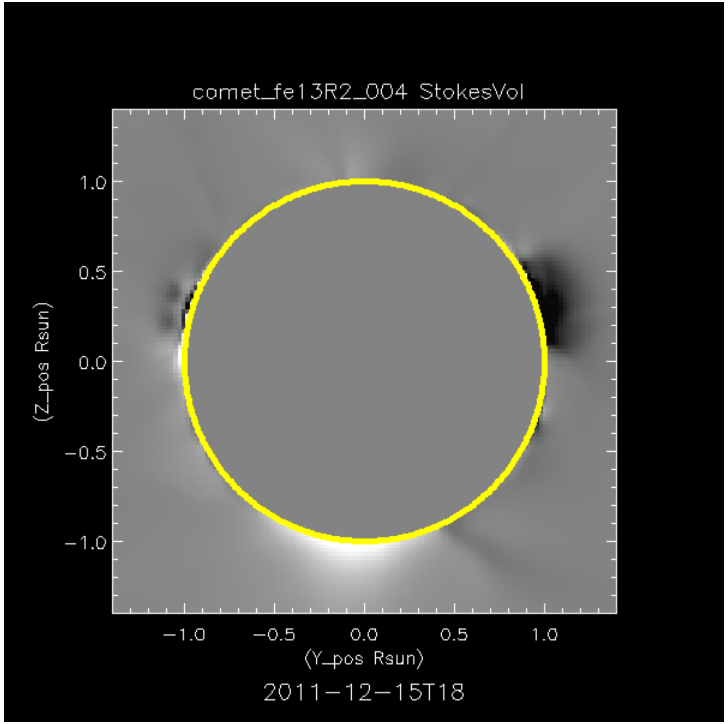


MHD Field + MHD Plasma

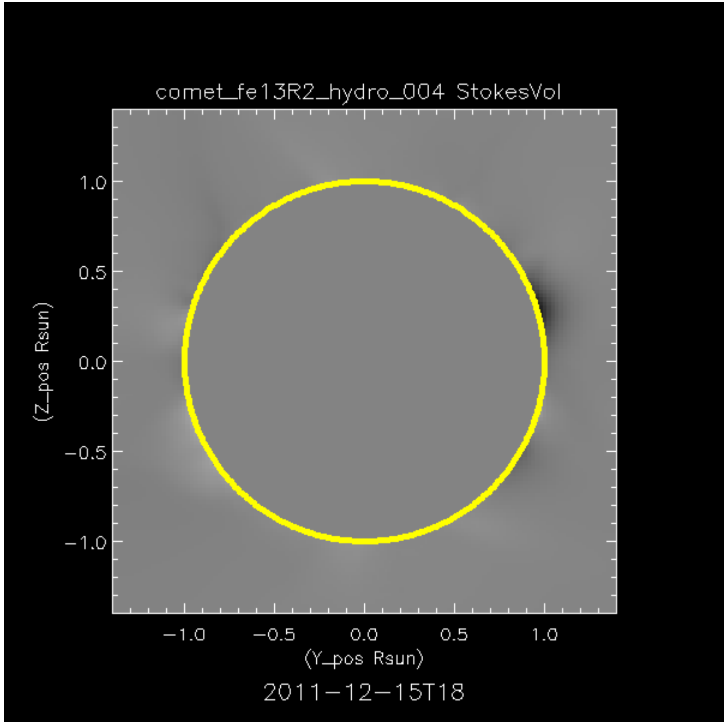


MHD Field + Symmetric Plasma

Test 1: Spherical Symmetry V/I

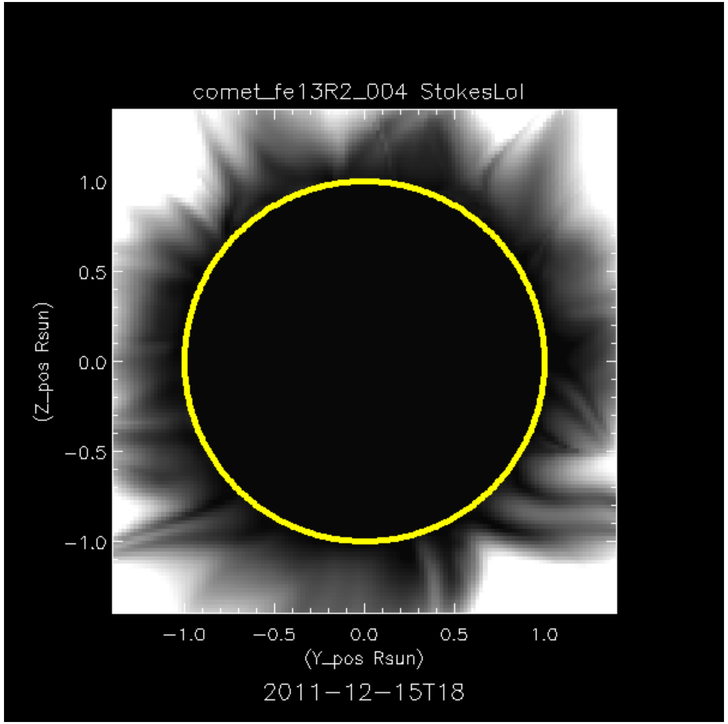


MHD Field + MHD Plasma

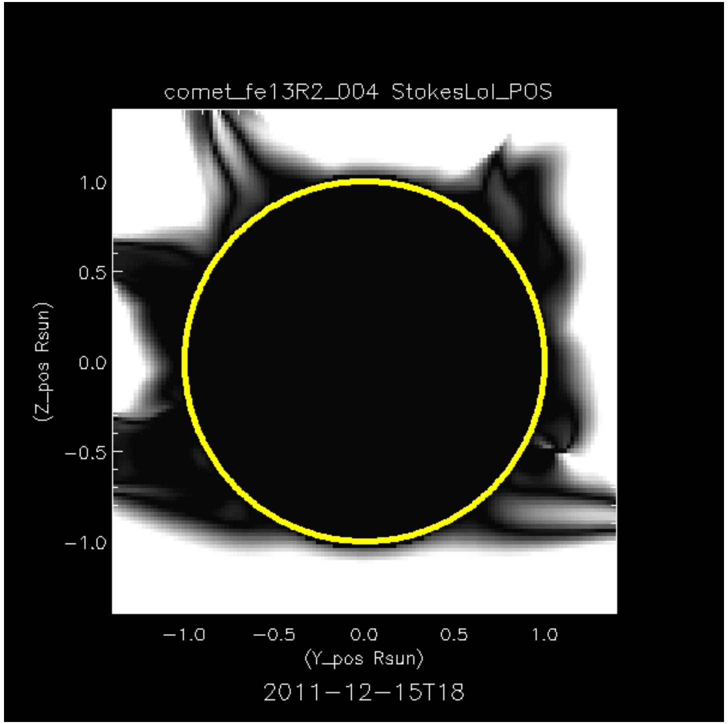


MHD Field + Symmetric Plasma

Test 2: Plane of Sky Vs. Full Integration

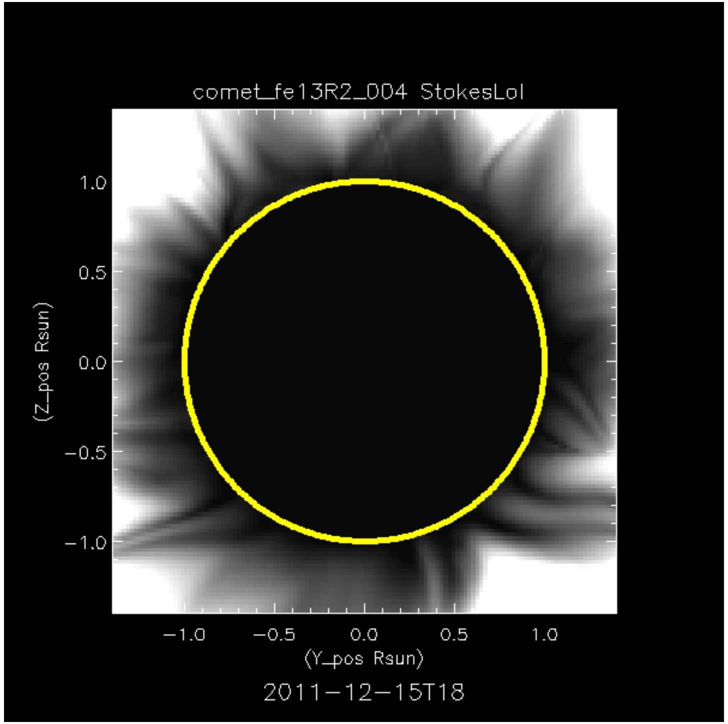


LOS integrated MHD Field + MHD Plasma

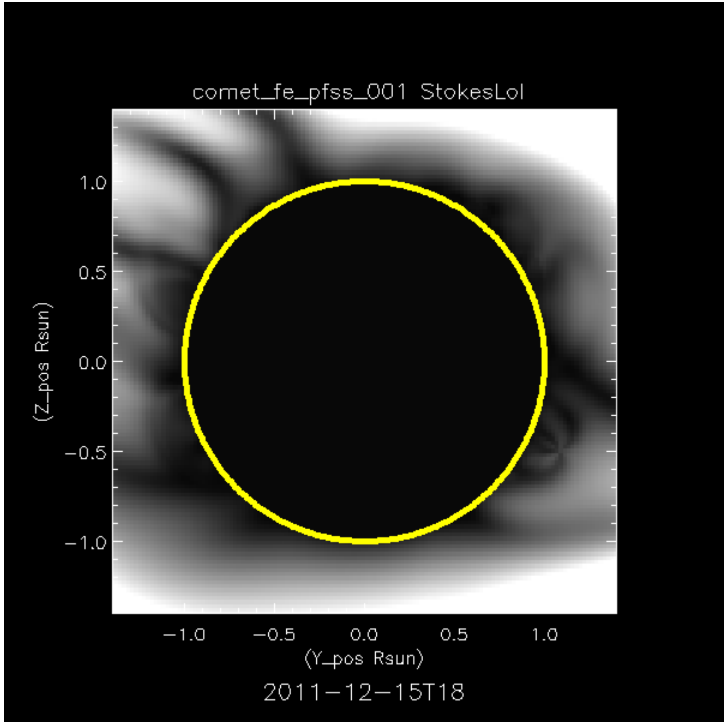


POS MHD Field + MHD Plasma

Test 3: MHD vs. PFSS



LOS integrated MHD Field + MHD Plasma

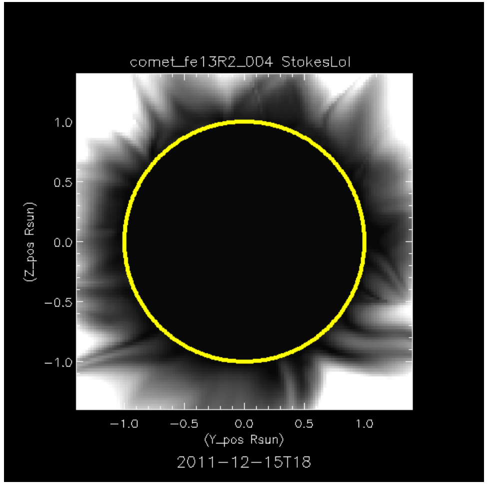


PFSS + Symmetric Plasma

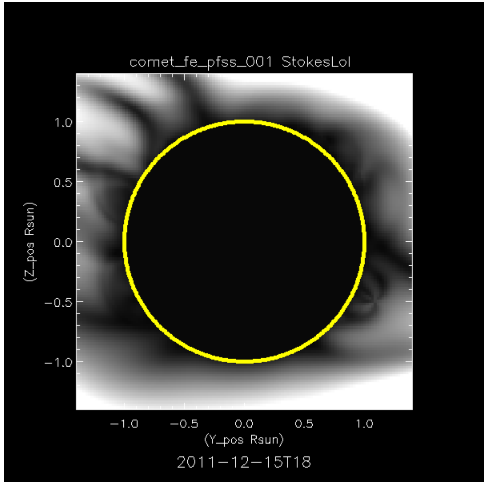
Some Quick Thoughts

- Fe XIII emission is density and temperature weighted → choice of plasma profile matters!
- Streamer density enhancements emphasize streamer polarization signals more than spherically symmetric choice.
  - I.e. signal won't necessarily be in POS because of density weighting
- MHD and PFSS solutions makes for significant differences in polarization signal.

→ Magnetically sensitive diagnostics can be used to vet models with observations, AND to explore the validity of the physics you are using to interpret observations.



LOS integrated MHD Field + MHD Plasma

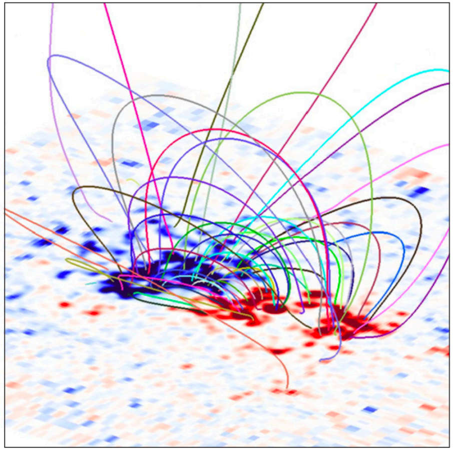


PFSS + Symmetric Plasma

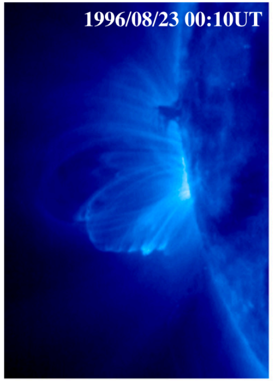
Example II: Time-Dependent Thermal Magnetic Signatures in an Active Region.

- Yung Mok and collaborators at PSI have studied AR 7986 (August 1996) extensively (Mok et al. ‘05, ‘08, ‘16).
- Current method is to freeze a NLFF state, and solve for the parallel plasma dynamics in time.
- This gives time-dependent snapshots of loop heating and cooling cycles.
- The time-dependent plasma state seems to agree well with observations.
- Ostensibly this work is about coronal heating, but this model provides a high-res, strong field AR with a self-consistent temperature and density background.

3D View of Magnetic Field Lines

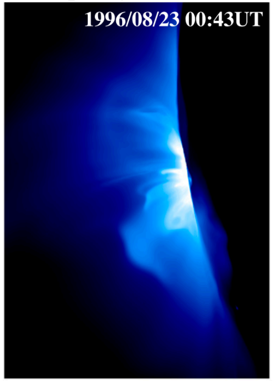


Observed Emission



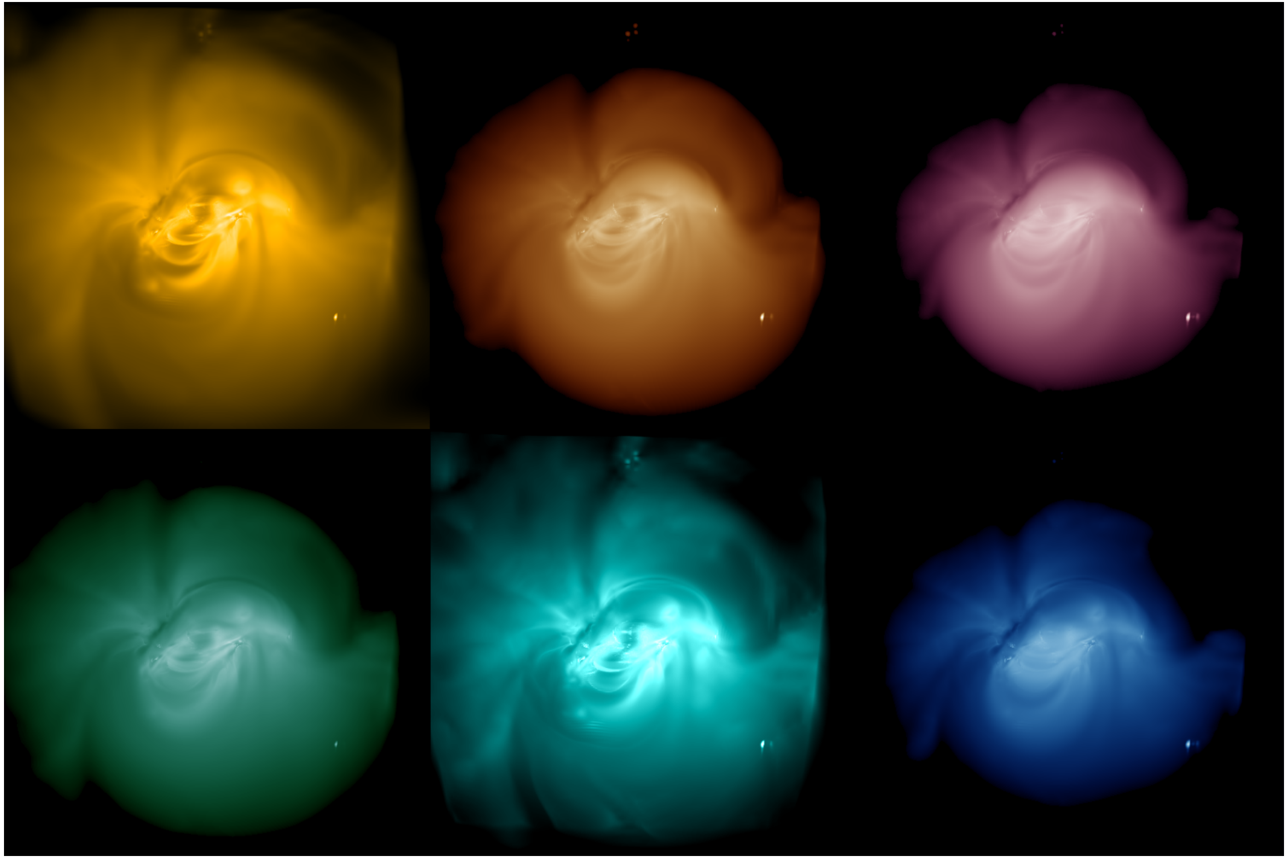
Simulated Emission

Opacity-Limited



Active Region Model

AIA Synthesis (Disk View)

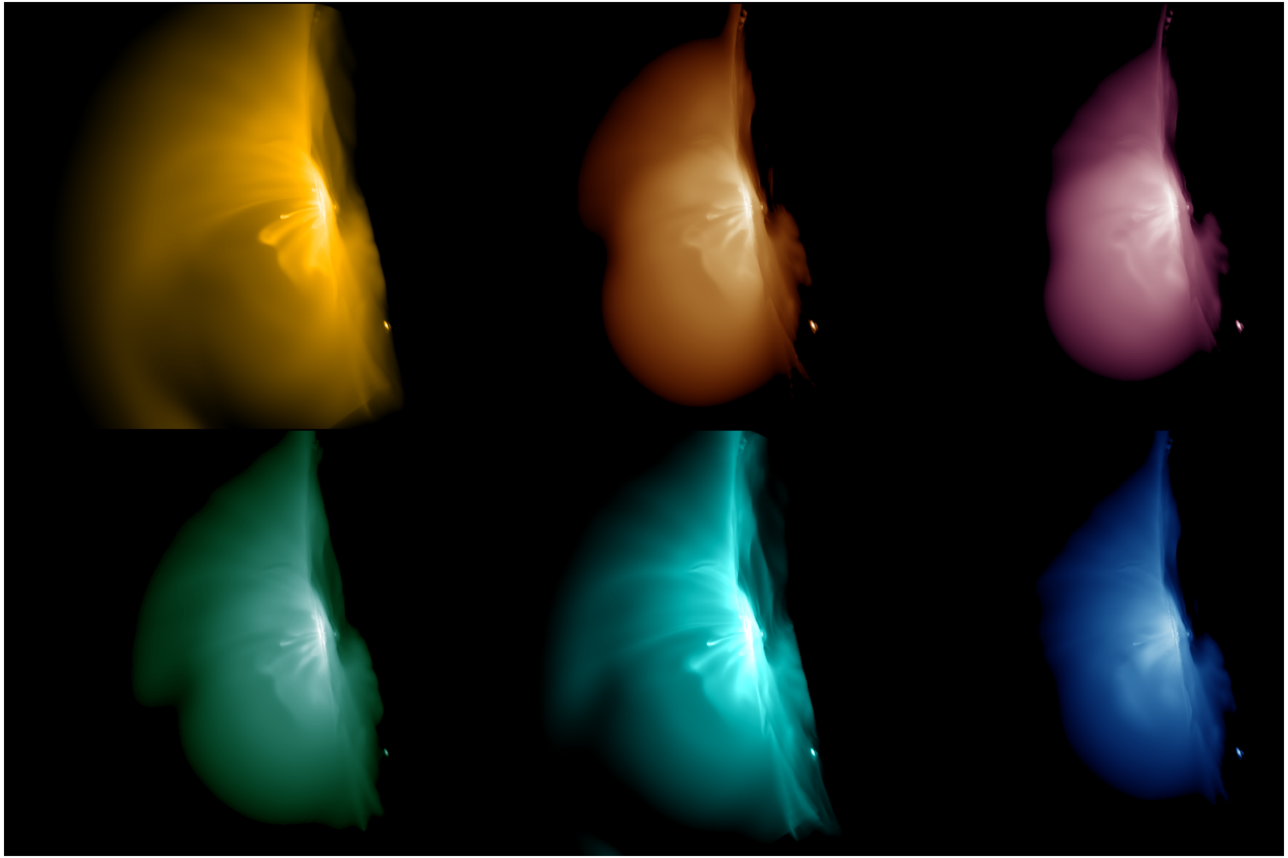


- Original paper compared to EIT observations in 1996, but can use time-dependent 3D datacube to forward model other bandpasses/observables.

- Here 6 Channel AIA images of AR emission.

Active Region Model

AIA Synthesis (Limb View)



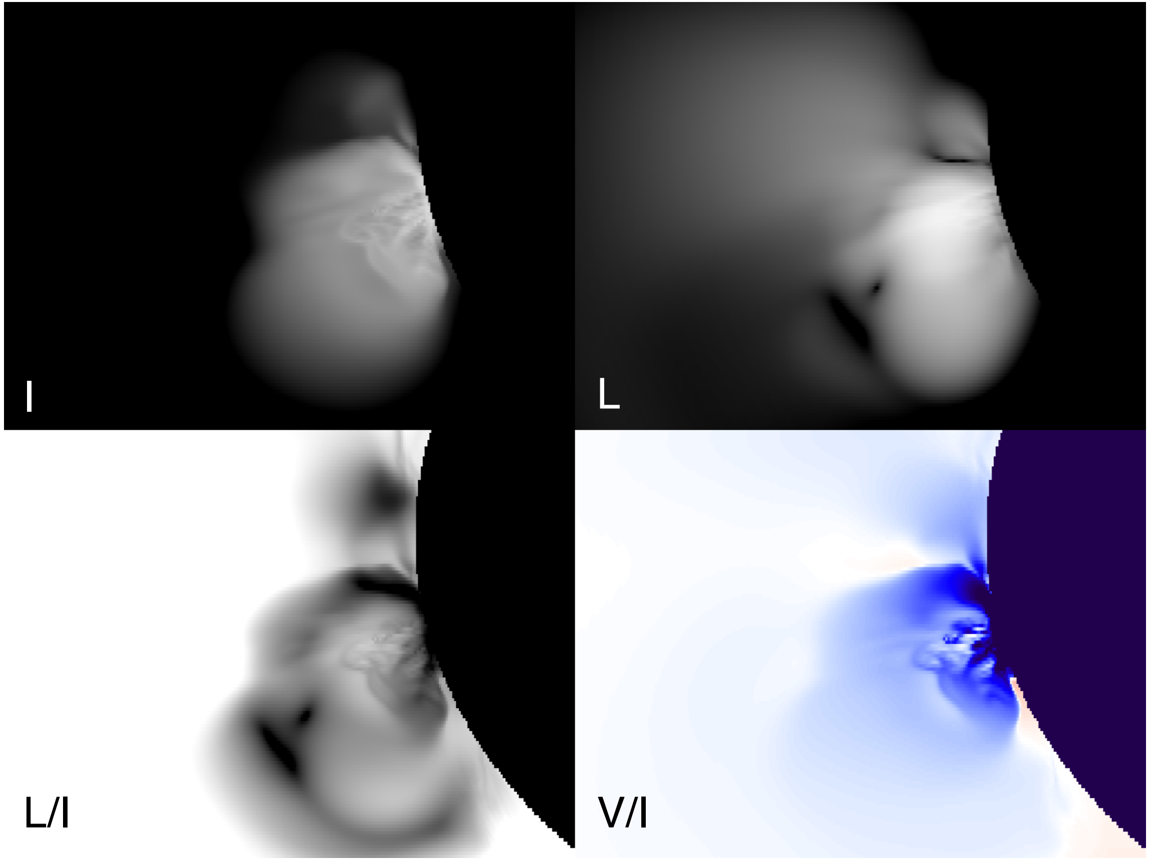
- Original paper compared to EIT observations in 1996, but can use time-dependent 3D datacube to forward model other bandpasses/observables.

- Here 6 Channel AIA images of AR emission.

Active Region Model

- Original paper compared to EIT observations in 1996, but can use time-dependent 3D datacube to forward model other bandpasses/observables.
- Here Fe XIII 1075 emission from SSW/FORWARD.
- Internal and overlying structure in polarized signatures.
- Coherent negative in V/I due to E-W orientation.

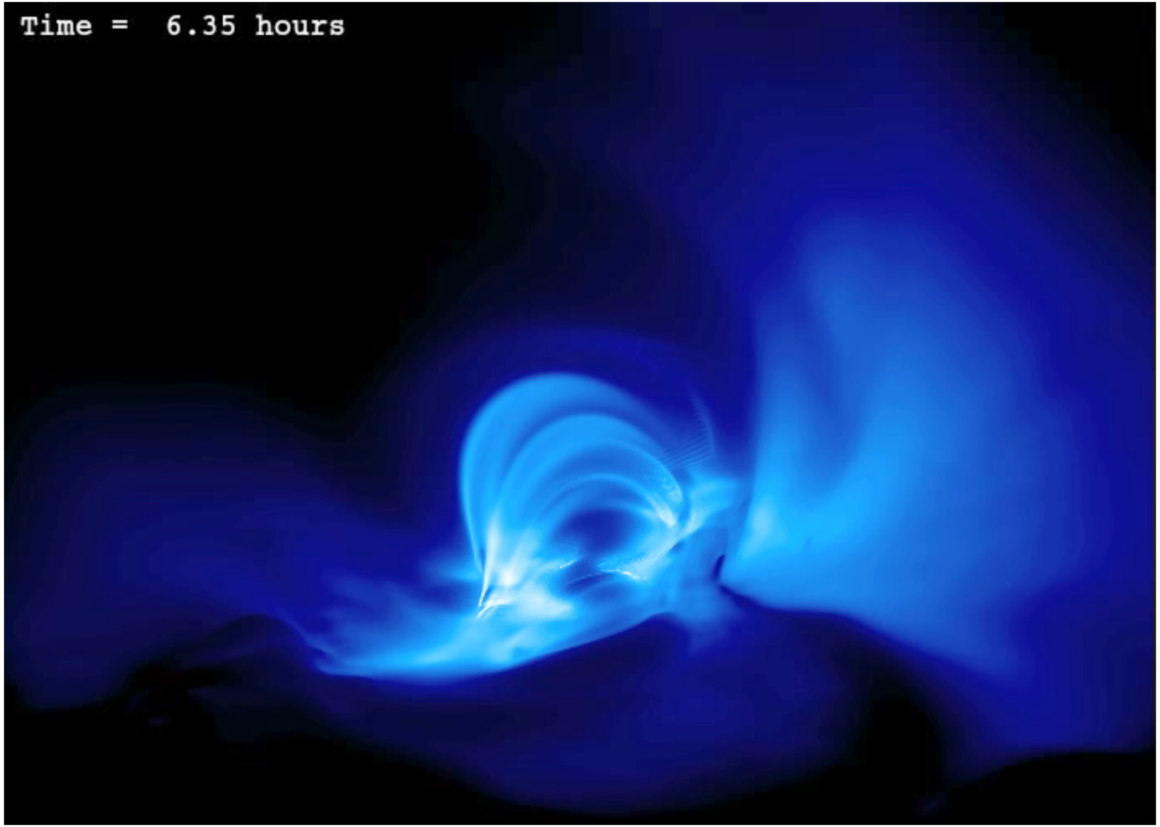
Example Fe XIII 1075 nm from FORWARD



Active Region Model

- Observe repeated cycles of thermodynamic evolution. This is due to thermal non-equilibrium induced by a stratified coronal heating profile
- What is interesting is that the field is FROZEN in time (no change).
- A magnetically sensitive (i.e. Si IX) might show B evolution due to changing plasma weighting along the LOS
- Main Point: Plasma evolution might be relevant when interpreting thermal-magnetic signatures.
- Time-dependent cool emission may let you sample different portions of a 3D magnetic field!

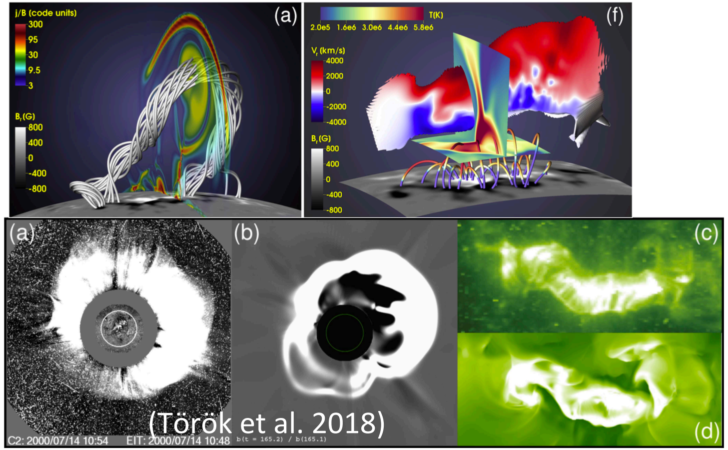
Thermodynamic Evolution (EIT 171, Fe IX)



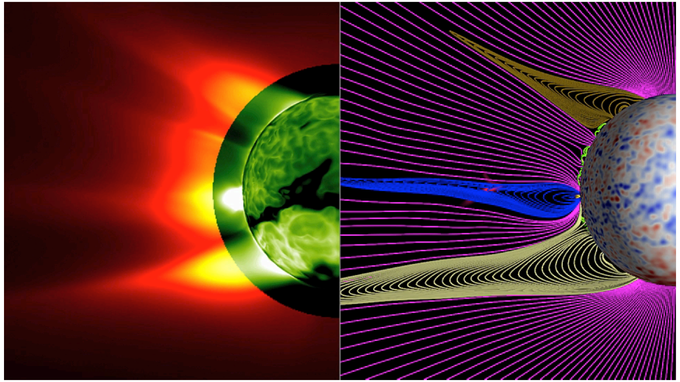
Mok et al. 2016

Example III: Thermal-Magnetic Signatures of Solar Eruptions

- Magnetic & Thermal changes are highly coupled when an eruption occurs (CMEs, Flares, EUV Waves, RXN flow, etc.).
- When we see transient structures in emission, we'd really like to know how the underlying magnetic field is evolving.
- Measuring the energized "pre-eruption" field directly would provide key constraints on CME models (i.e. pre-existing flux-rope vs. shear converted into rope during eruption).
- Traditionally my colleagues at PSI have used boundary flows + flux cancellation to create eruptive flux systems.
- We are currently experimenting with inserting stable flux-ropes into the model, which gives more flexibility.
- Get close to instability, relax, then erupt through boundary flows.



3D MHD model of Bastille day 2000 CME


3D MHD Model of the 2009, Feb 13 Event

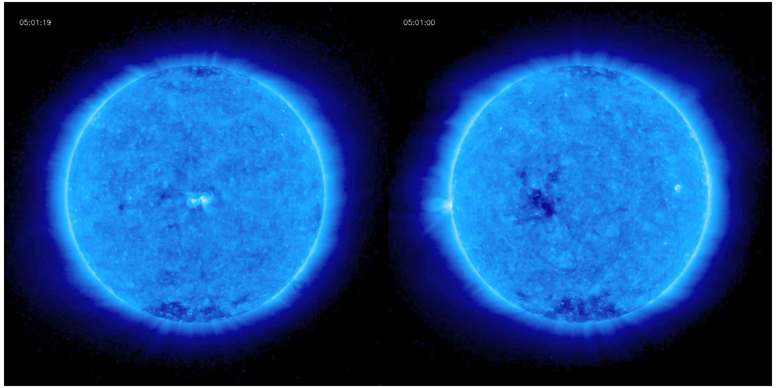
Modeling the Feb 13, 2009 “Simple” CME

Observations: A slow CME originating from a ‘simple’ bipolar AR surrounded by quiet-sun.

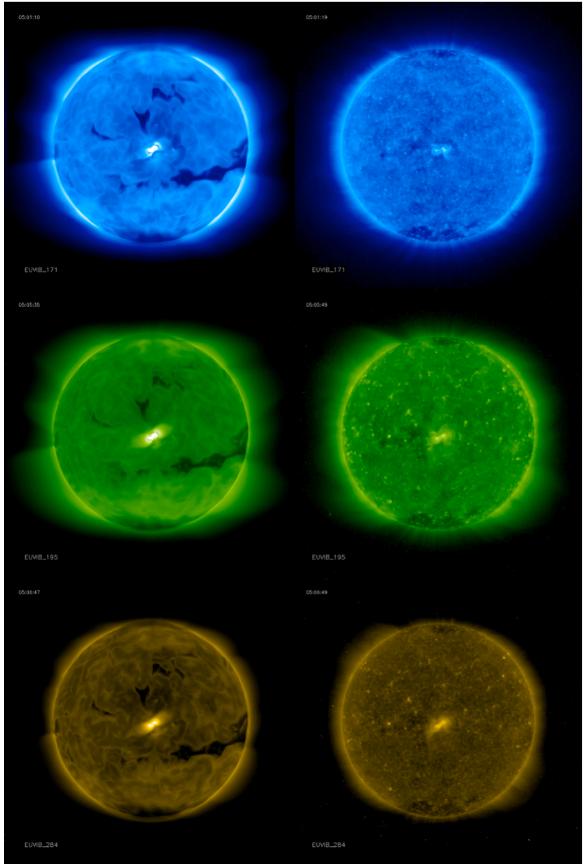
- Pristine EUV wave observed.
- Clear twin dimming signatures.

Model: 3D MAS, a thermodynamic MHD model

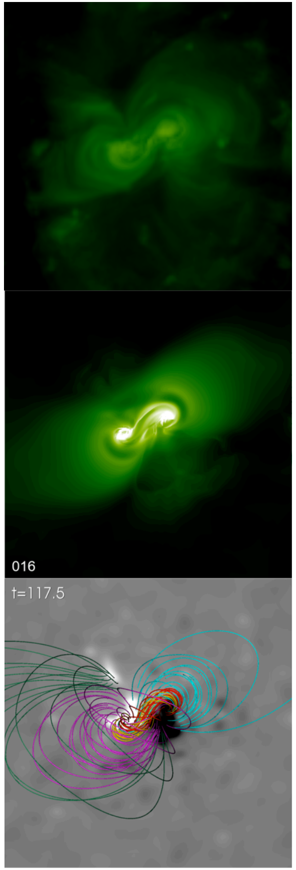
- Eruptive configuration built using the TDm flux rope (Titov et al. 2014).
- Stable configuration is driven quasi-statically until eruption.



STB/EUVI 171 STA/EUVI 171



Full-Sun Comparison (EUVI-B)



AR Zoom + Energized Field

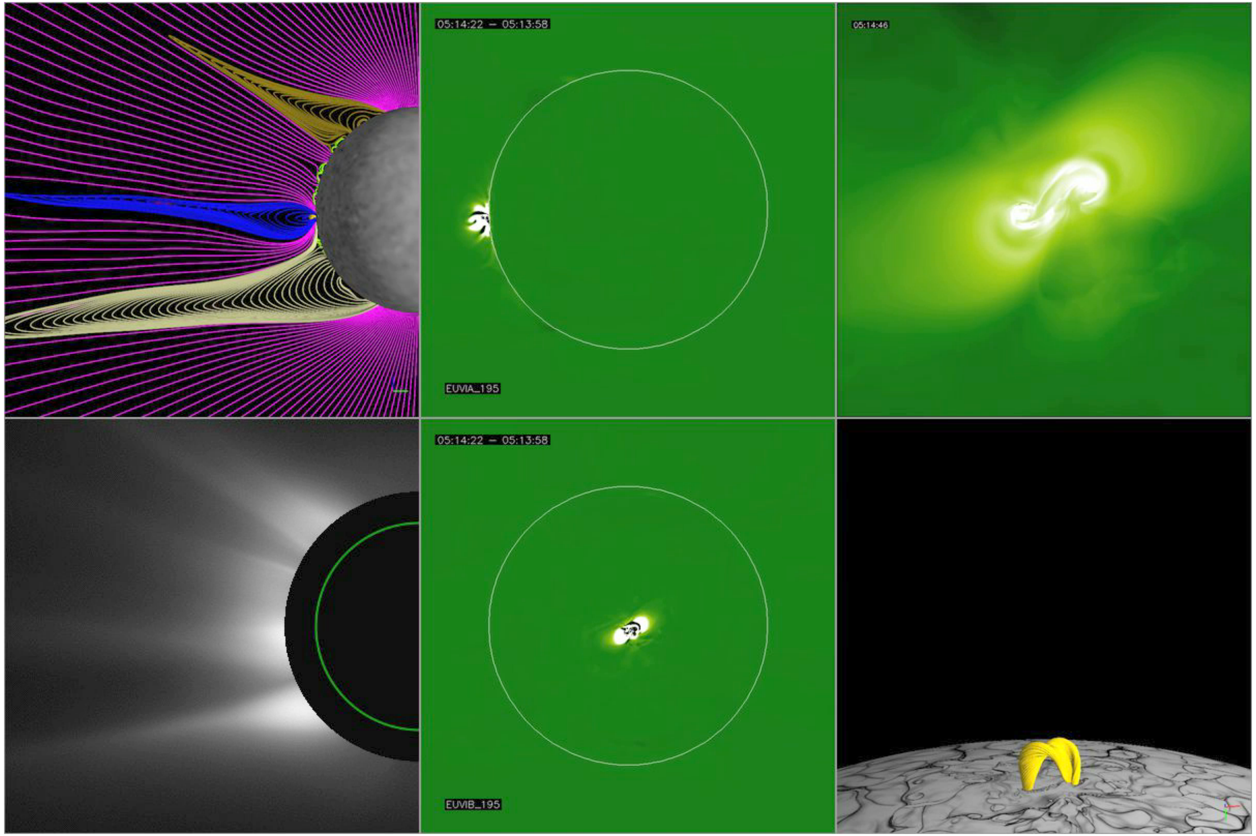
Modeling the Feb 13, 2009 “Simple” CME

Connect erupting FR (gold) to white light polaried brightness signatures.

EUV front clearly decouples from the flux-rope → Spherical MHD wave

We can connect magnetic evolution and time-dependent connectivity to the EUV dimming signatures.

Forward modeling helps connect the underlying magnetic field evolution to remote sensing observables.



CME Evolution | EUV waves | Coronal Dimming

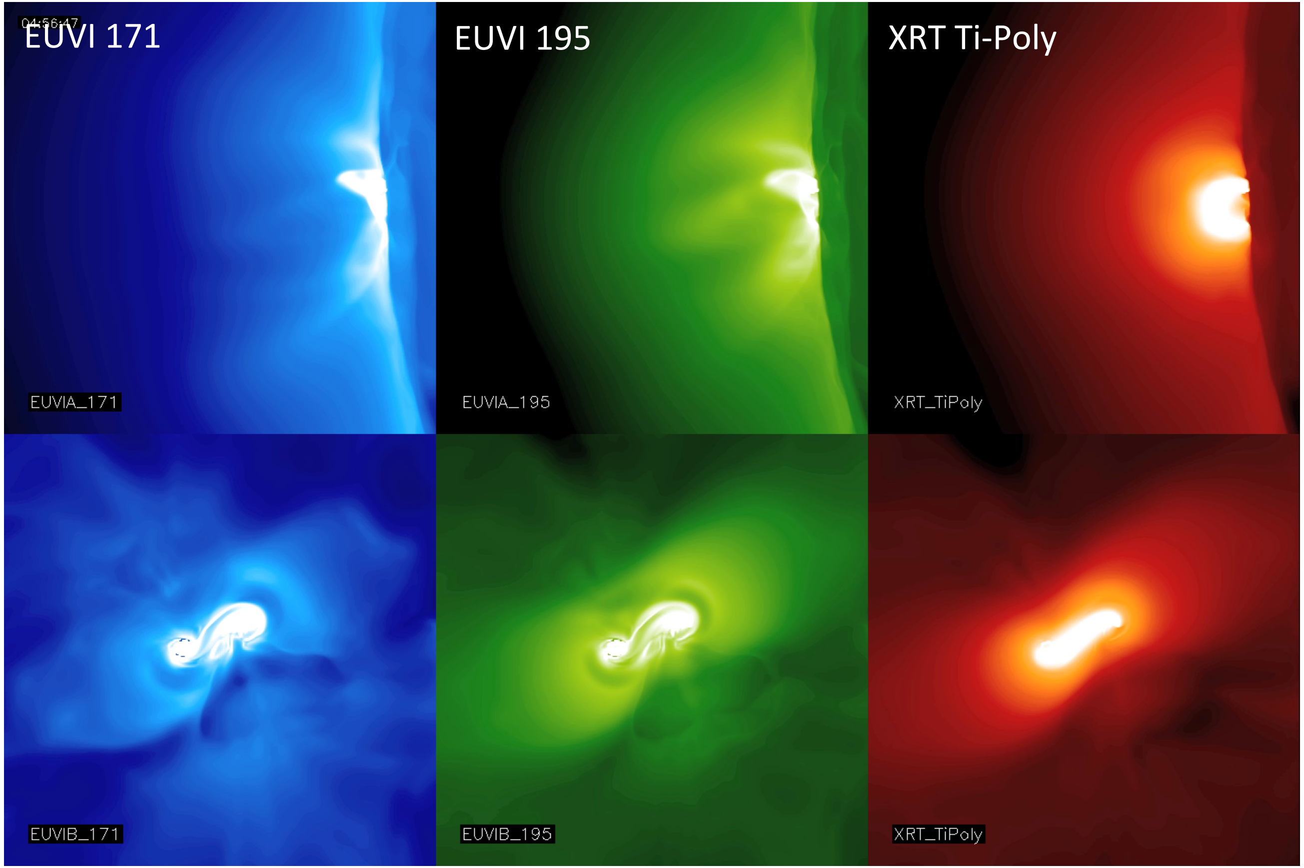
Evolution of Observables in the AR

See LOS oriented Energized structure rise and then erupt.

High contrast between energized core and surrounding region → temperature sensitivity + magnetic field diagnostics.

Low coronal dimming off-limb forms a nice v-shaped evacuated region bounded by bright structures. This is essentially the boundary between the CME footprint and surrounding arcade.

This might look interesting in polarized IR lines!



Potential Signatures in the LOS Magnetic Field?

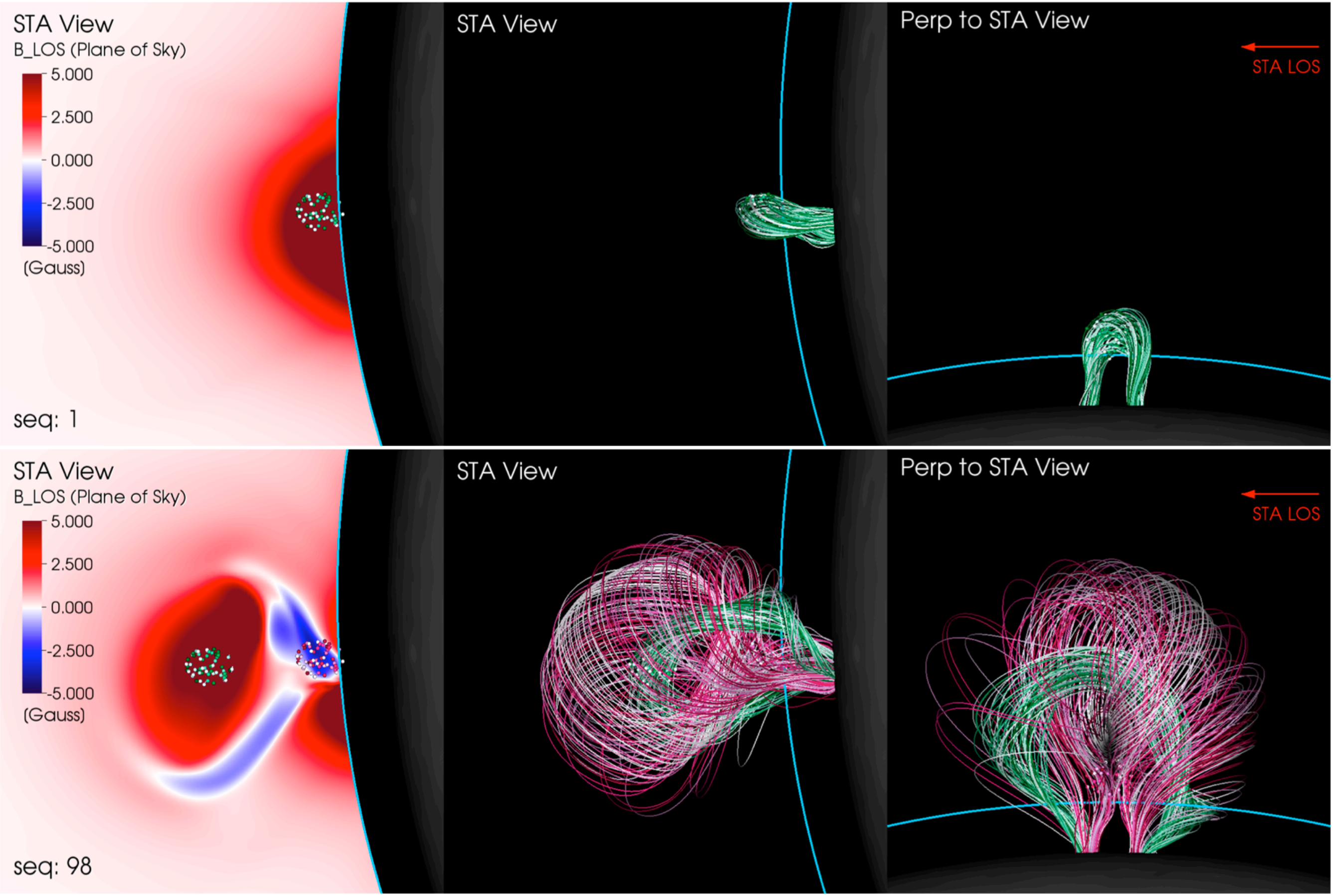
Didn't get a chance to calculate LOS integrated Fe XIII emission.

But, still look at LOS B field evolution during the course of the event.

See changes in sign due to rope expansion/evolution/ reconnection.

Reconnected flux systems inside rope cause sign to change in places.

Polarized IR information might inform us to how flux-ropes form/evolve during CMEs!



Some Closing Thoughts

- The Solar Atmosphere is inherently complex and 3D.
  - LOS effects need to at least be considered, particularly when studying specific events or complex geometric structures with density and temperature contrasts.

- Models and Observations can go hand in hand!
  - We can use them to interpret/understand the complexity / limitations of data.
  - We can use them to test inversion methods.

- There many benefits by modeling from the 3D thermal-magnetic state of the corona:
  - Retain complexity in the 3D field.
  - Hydrodynamics is self consistent with field geometry.
  - LOS effects are naturally accounted for: e.g. limb brightening, off limb integration, AR rotation.
  - Such modeling could be used to vet or test assumptions made when interpreting observations.

- However 3D Modeling is time consuming, optically thin corona is only one part of the puzzle.
  - Even if the such modeling was perfect (its not), forward modeling has uncertainties: atomic physics, unknown lines, unknown rates, non-equilibrium, kappa dist?

- Polarization measurements are rich in information content, and we have a range of simulations/tools at our disposal.
  - DKIST observables should provide new constraint on our models (heating/magnetic fields).

END

Coronal Simulations from the Web

Our website: http://www.predsci.com/hmi

Thermodynamic runs from CR2096 to present are freely available for download

2 heating models to choose from (Density stratification and amount of opened up field differ slightly)

I can provide the IDL routine to read and interpolate the simulation to a standard datacube.

Even better, its compatible with FORWARD!