National Aeronautics and Space Administration

Using Total Solar Eclipses as a Lens to Understand the Sun

Ronald M. Caplan,
Cooper Downs, and Jon A. Linker

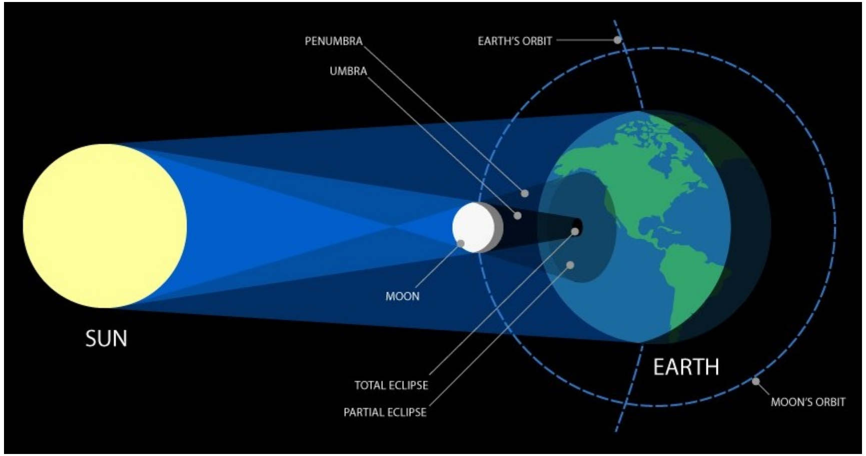
Predictive Science Inc.

predsci.com/eclipse

www.nasa.gov

What are total solar eclipses?

- A total solar eclipse occurs when the moon completely blocks the Sun in the sky
- This can occur because the moon's distance and size makes it nearly the same angular width as the Sun (sometimes a bit smaller or larger)

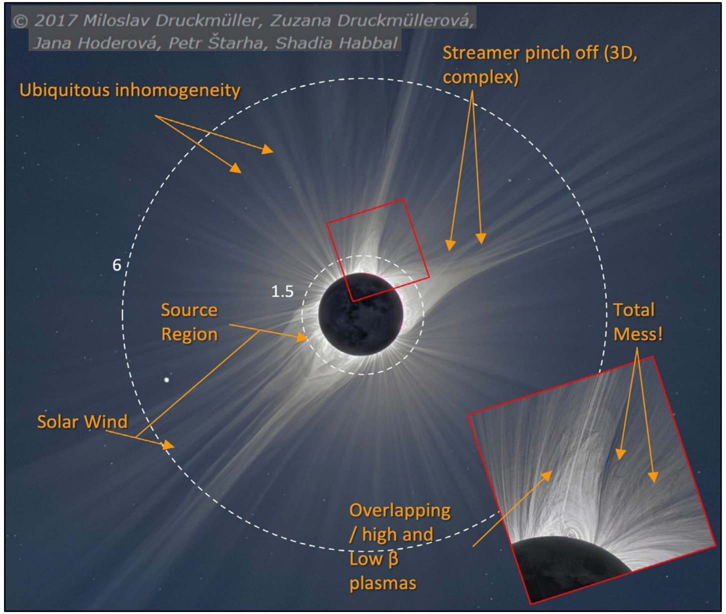


Eclipses are not just neat, they are useful too!

- Many advances and discoveries in physics were found by observing total solar eclipses including the discovery of new elements, and the testing of Einstein's theory of general relativity
- An eclipse provides an unbroken, high-resolution view of the dim solar atmosphere we usually cannot see
- This allows us not only to learn new things from the observations, but to also be able to test physical models of the Sun's atmosphere by comparing them to the observations

Here's What Scientists Have Learned From Total Solar Eclipses

By Nola Taylor Tillman published May 17, 2017
space.com/36785-solar-eclipse-science-throughout-history.html

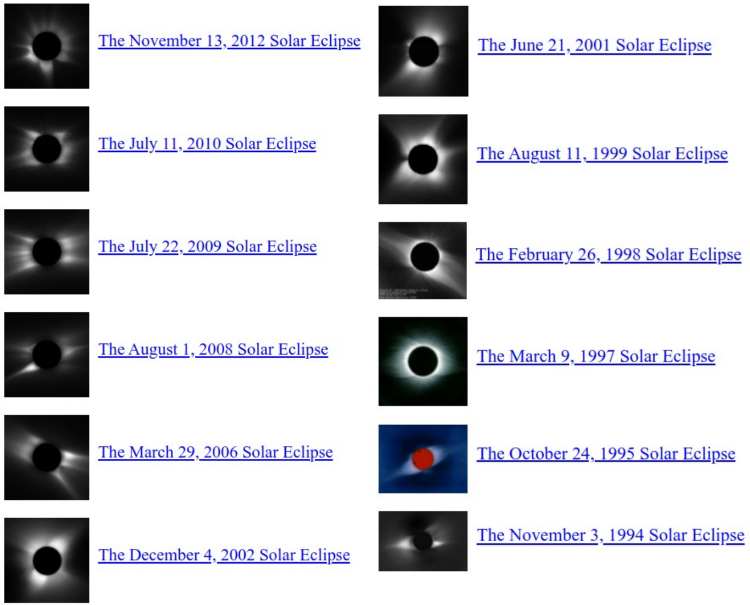


Predicting how an eclipse will look

- The team at Predictive Science Inc. has been posting solar eclipse predictions for decades
- The predictions are made using simulations of the Sun's atmosphere and posted ~2 weeks before the real event
- By comparing the predictions to the observed Sun during the eclipse, we can vet and refine our physics models
- The predictions also can provide context for observational planning

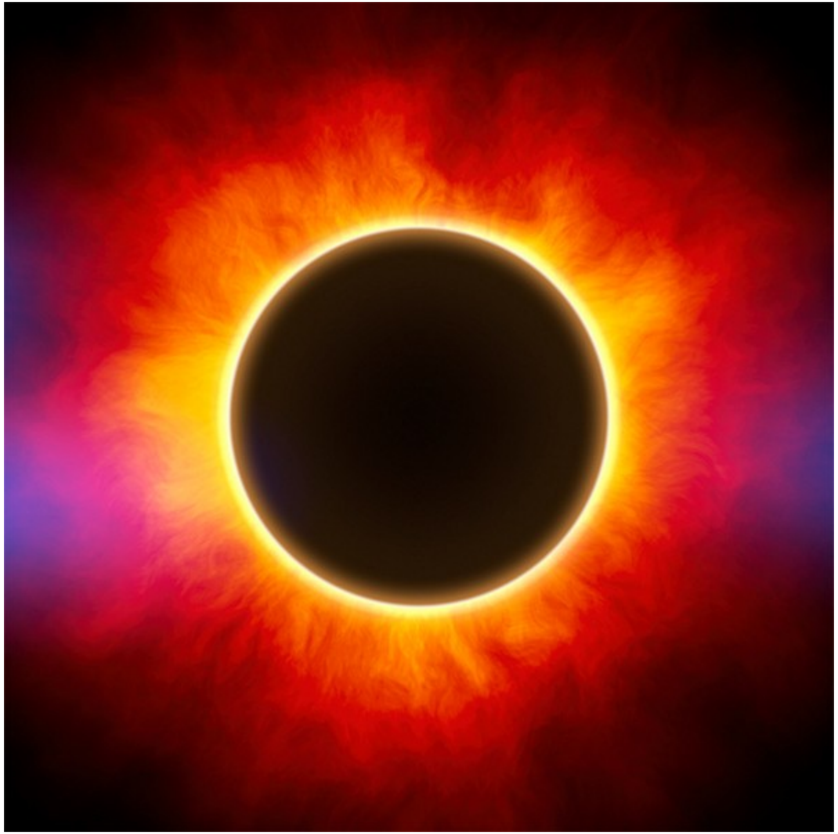
Predictive Science Inc.

predsci.com/eclipses



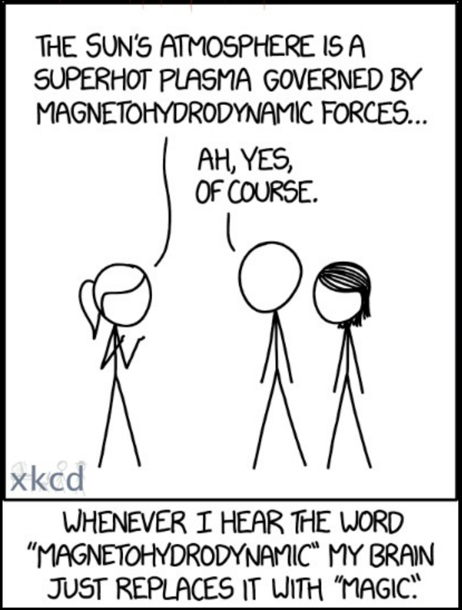
How do we simulate the Sun’s atmosphere?

- The lower atmosphere of the Sun is called the *corona* and it composed of extremely hot plasma embedded in strong dynamic magnetic fields
- Physics models of the corona can be made using a magnetohydrodynamic (MHD) description/model
- We use an MHD model called Magnetohydrodynamic Algorithm outside a Sphere (MAS)
- MAS calculates 3D plasma quantities (temperature, density, etc.) and magnetic fields of the corona
- These outputs can be used to model the light emission that one would see during an eclipse



MAS

MAGNETOHYDRODYNAMIC ALGORITHM OUTSIDE A SPHERE



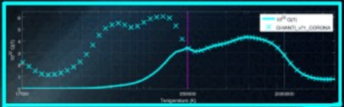
$$\frac{\partial \mathbf{A}}{\partial t} = \mathbf{v} \times (\nabla \times \mathbf{A}) - \frac{c^2 \eta}{4\pi} \nabla \times \nabla \times \mathbf{A}$$

RESISTIVITY

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

$$\frac{\partial T}{\partial t} = -\nabla \cdot (T\mathbf{v}) - (\gamma - 2)(T \nabla \cdot \mathbf{v}) + \frac{\gamma - 1}{2k} \frac{m_p}{\rho} \left[-\nabla \cdot (\mathbf{q}_1 + \mathbf{q}_2) - \frac{\rho^2}{m_p^2} Q(T) + H \right]$$

RADIATIVE COOLING



THERMAL CONDUCTION

$$\mathbf{q}_1 = -f(r)\, \beta_{\mathrm{Tcut}}(T)\, \kappa_0 T^{5/2}\, \hat{\mathbf{b}}\hat{\mathbf{b}} \cdot \nabla T$$

$$\mathbf{q}_2 = (1 - f(r)) \frac{k}{(\gamma - 1)} \frac{\rho}{m_p} T \mathbf{v}\, \hat{\mathbf{b}}\hat{\mathbf{b}}$$

CORONAL HEATING

$$H = H^* + \frac{\rho}{4\lambda_\perp} \left[|z_-|\, z_+^2 + |z_+|\, z_-^2 \right]$$

$$\lambda_\perp = \lambda_0 \sqrt{\frac{B_w}{|\mathbf{B}|}} \qquad |z_\pm(r = R_\odot)| = z_0$$

ALFVEN WAVES

$$\frac{\partial \epsilon_\pm}{\partial t} = -\nabla \cdot (\epsilon_\pm [\mathbf{v} \pm \mathbf{v}_\mathrm{A}]) - \frac{\epsilon_\pm}{2} \nabla \cdot \mathbf{v}$$

$$\frac{\partial \mathbf{v}}{\partial t} = -\mathbf{v} \cdot \nabla \mathbf{v} + \frac{1}{\rho} \left[\frac{1}{c} \mathbf{J} \times \mathbf{B} - \nabla p - \nabla \left(\frac{\epsilon_+ + \epsilon_-}{2} \right) + \rho \mathbf{g} \right] + \frac{1}{\rho} \nabla \cdot (\nu \rho \nabla \mathbf{v}) + \frac{1}{\rho} \nabla \cdot \left(S \rho \nabla \frac{\partial \mathbf{v}}{\partial t} \right)$$

VISCOSITY

SEMI-IMPLICIT OPERATOR

WAVE TURBULENCE

$$\frac{\partial z_\pm}{\partial t} = -(\mathbf{v} \pm \mathbf{v}_\mathrm{A}) \cdot \nabla z_\pm - \frac{z_\pm |z_\mp|}{2\lambda_\perp} + \frac{z_\pm}{4} (\mathbf{v} \mp \mathbf{v}_\mathrm{A}) \cdot \nabla (\ln \rho) + \frac{z_\mp}{2} (\mathbf{v} \mp \mathbf{v}_\mathrm{A}) \cdot \nabla (\ln |\mathbf{v}_\mathrm{A}|)$$

$\nabla \cdot \mathbf{B} = 0$ $\mathbf{B} = \nabla \times \mathbf{A}$ $\mathbf{J} = \frac{c}{4\pi} \nabla \times \mathbf{B}$

$p = 2kT\rho/m_p$ $\mathbf{g} = -g_0 R_\odot^2 \hat{\mathbf{r}}/r^2$ $\gamma = 5/3$

$\hat{\mathbf{b}} = \mathbf{B}/|\mathbf{B}|$ $\mathbf{v}_\mathrm{A} = \mathbf{B}/\sqrt{4\pi\rho}$ $B_w = 6.09\, G$ $v_c^2 = \gamma p/\rho$

$$\beta_{\mathrm{Tcut}}(T) = \begin{cases} (T/T_{cut})^{-5/2} & T < T_{cut} \\ 1, & T \geq T_{cut} \end{cases}$$

$T_{cut} = 3.5 \times 10^5\, K$ $f(r) = 1 - 0.5 \tanh[(r - 10 R_\odot)/R_\odot]$

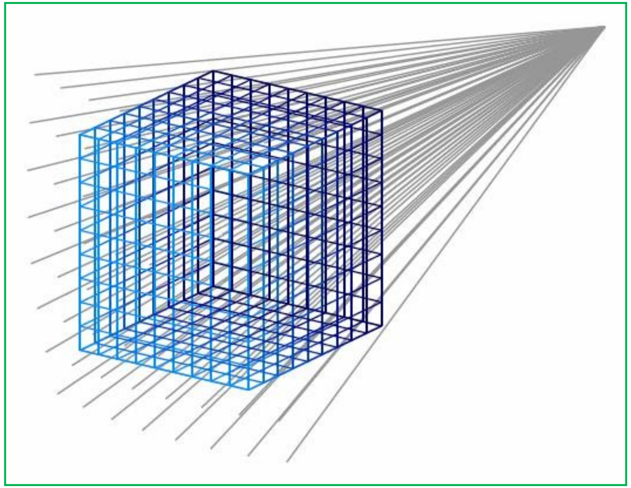
$S = (\Delta t^2 \tilde{k}^2)^{-1} (C_w^2/(1 - C_f)^2 - 1)$ $C_f = \Delta t\, \tilde{k} \cdot \mathbf{v}$ $C_w^2 = 0.25\, \Delta t^2 \tilde{k}^2 (v_c^2 + |\mathbf{v}_\mathrm{A}|^2)$ $\tilde{k}^2 = 4\left(\Delta r^{-2} + (r\Delta\theta)^{-2} + (r\Delta\phi \sin\theta)^{-2}\right)$

predsci.com/mas

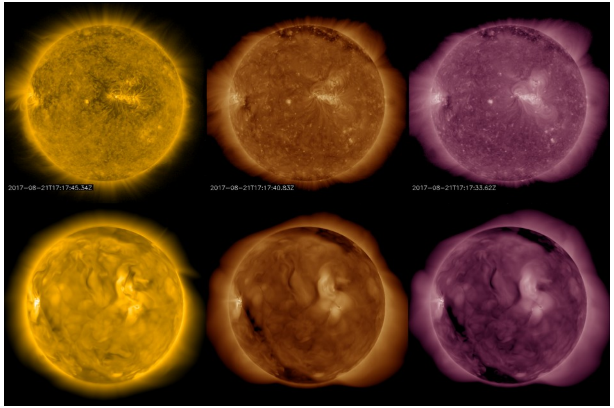
- Established MHD code with over 20 years of development
- Used extensively in solar physics research
- Written in Fortran (~70,000 lines of code)
- Parallelized to run on multiple multi-CPU and multi-GPU compute nodes

Forward modeling

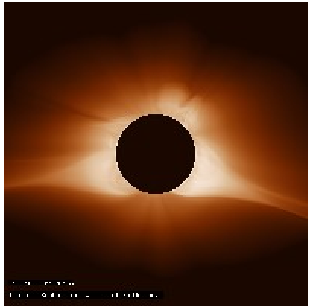
- MAS outputs plasma quantities (temperature, density, etc.) and magnetic fields for the entire 3D corona
- These can be combined with a model of light emission to obtain the light emitted over a range of wavelengths at every point in the corona
- By ray-tracing through the 3D emission, we can generate images that can be directly compared with detectors on satellites and ourselves (eyes)



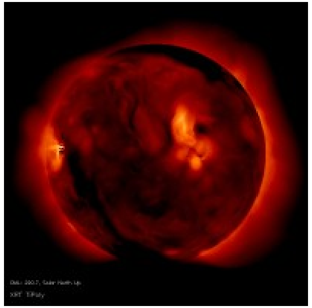
MAS



Extreme Ultra Violet (EUV)



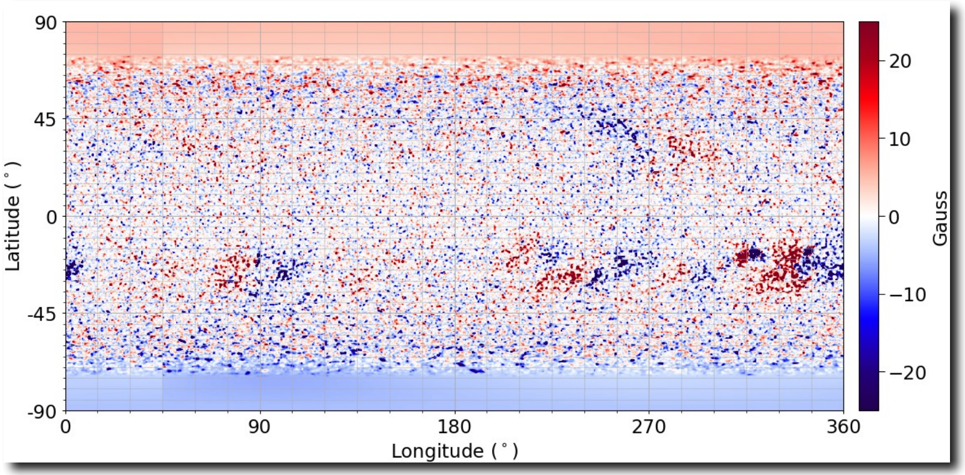
Visible



X-ray

The problem with solar observations

- MAS requires the radial component of the Sun's surface magnetic field as a boundary condition
- This can be observed by multiple instruments, but only routinely from the Sun-Earth line of sight.
- In order to make a boundary condition over the whole solar surface, old data from the Sun-Earth line can be used
- This old data makes predicting the eclipse corona difficult, especially during solar maximum when things are changing very rapidly on the Sun



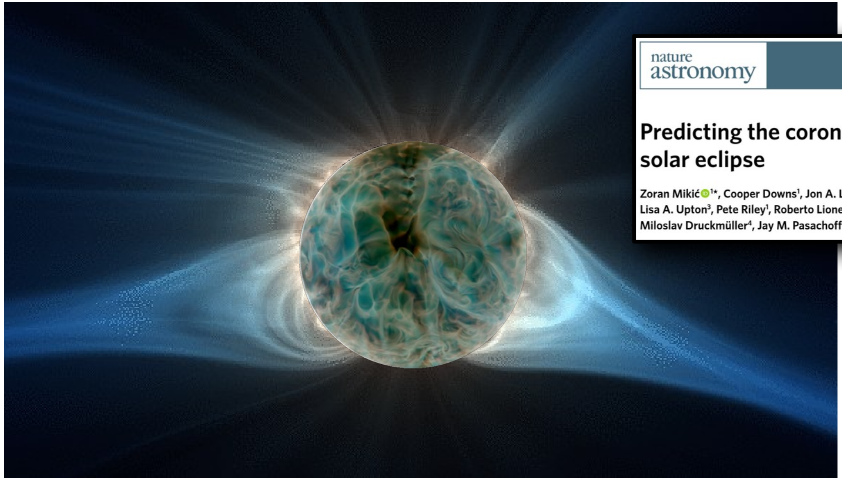
High performance computing

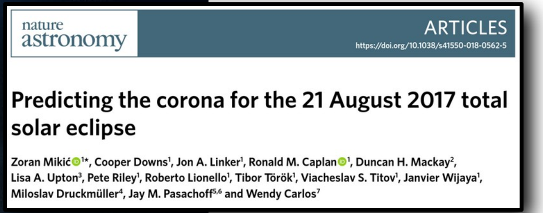
- To run the MAS code for the eclipse simulations, we require a large HPC system
- NASA's NAS HECC provides clusters across multiple CPU models, allowing us to process the simulations efficiently
- To find a steady solution to the corona, we use a resolution of ~60 million cells and need to run the simulation for 70 hours of physical time
- These simulations run in real time, taking ~70 hours using hundreds of CPU nodes

Recent eclipses: 2017

predsci.com/eclipse2017

- Several new model features including higher resolution, new heating model, energization of filament channels (stay tuned…)
- New visualization of 3D “squashing factor” that shows magnetic structure, and was used to help interpret hard-to-understand observations of the eclipse





nature astronomy

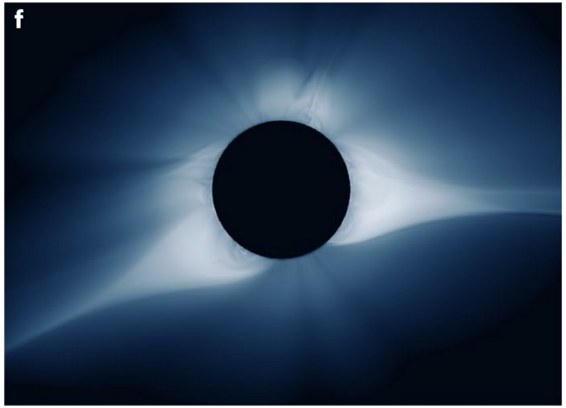
ARTICLES

https://doi.org/10.1038/s41550-018-0562-5

Predicting the corona for the 21 August 2017 total solar eclipse

Zoran Mikić[1]*, Cooper Downs[1], Jon A. Linker[1], Ronald M. Caplan[1], Duncan H. Mackay[2], Lisa A. Upton[3], Pete Riley[1], Roberto Lionello[1], Tibor Török[1], Viacheslav S. Titov[1], Janvier Wijaya[1], Miloslav Druckmüller[4], Jay M. Pasachoff[5,6] and Wendy Carlos[7]

Prediction



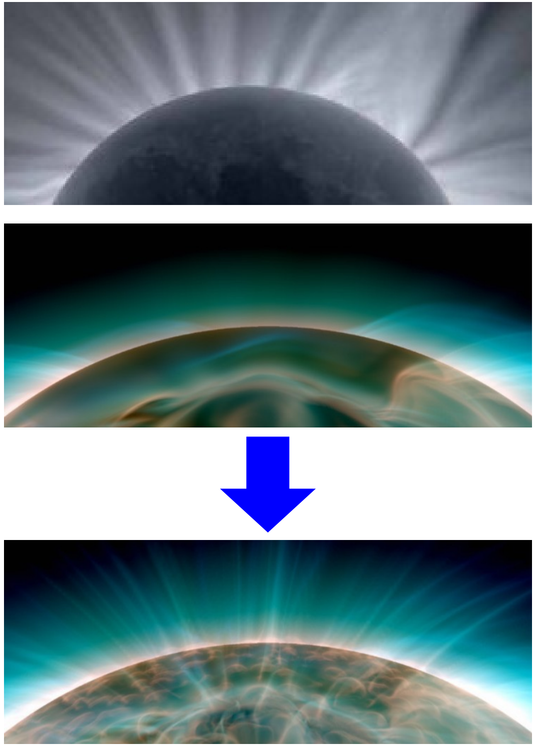
Observation

Recent eclipses: 2019

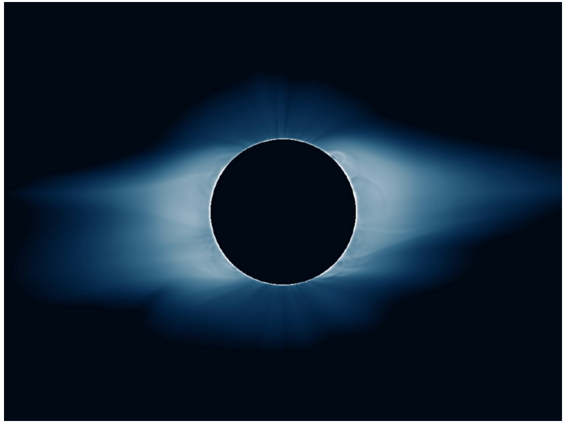
predsci.com/eclipse2019

- Here, the heating model was further refined by comparing to observations before the eclipse
- We also modified the input data to generate a more realistic polar magnetic field yielding polar features consistent with observations
- Other aspects of the prediction were comprehensibly compared with expedition measurements

[Boe et. al. (2021,2022,2023)]



Prediction

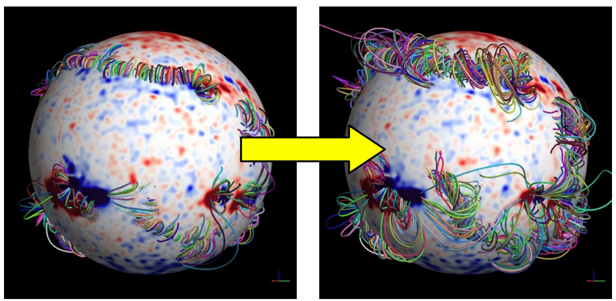


Observation

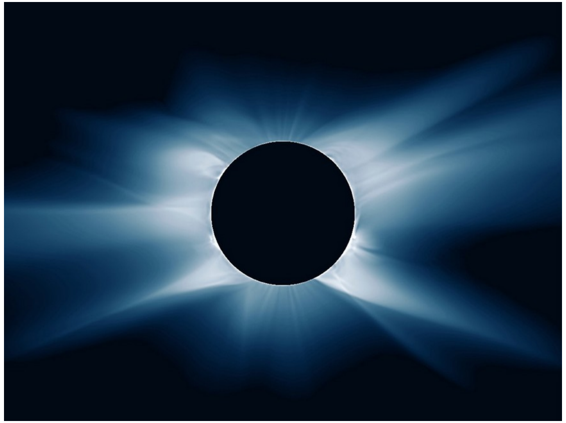
Recent eclipses: 2020

predsci.com/eclipse2020

- In this case, we tried using a new “two-temperature” model, but found that, while it improved the solution far from the Sun, it made it worse close in
- Great example of how vetting the model against observations helps to determine which/where model additions/modifications are valuable, and when/where it is better to leave them out
- We again energized filament channels and one of them erupted into an “accidental” solar storm, resembling a real one that occurred near the time of the eclipse



Prediction

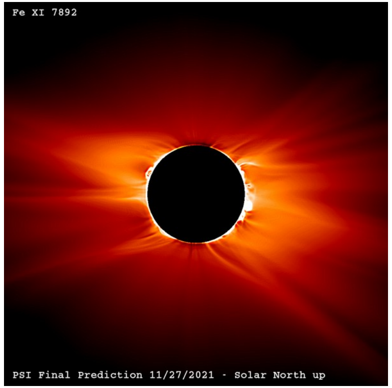


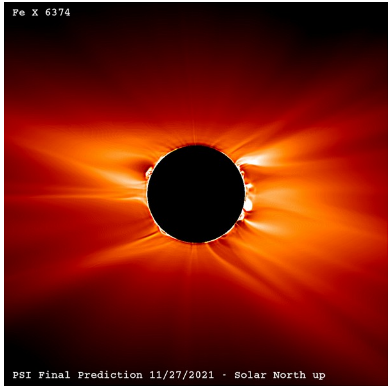
Observation

Recent eclipses: 2021

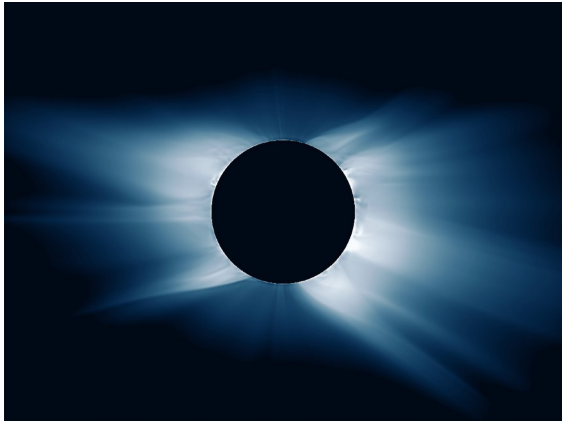
predsci.com/eclipse2021

- Here, we have added new forward-modeled observables including photoexcited spectral lines at visible and infrared wavelengths
- These lines are emitted by hot minor ions (e.g. iron). They are sensitive to density, temperature, and solar radiation, and are useful in probing the properties of the corona





Prediction

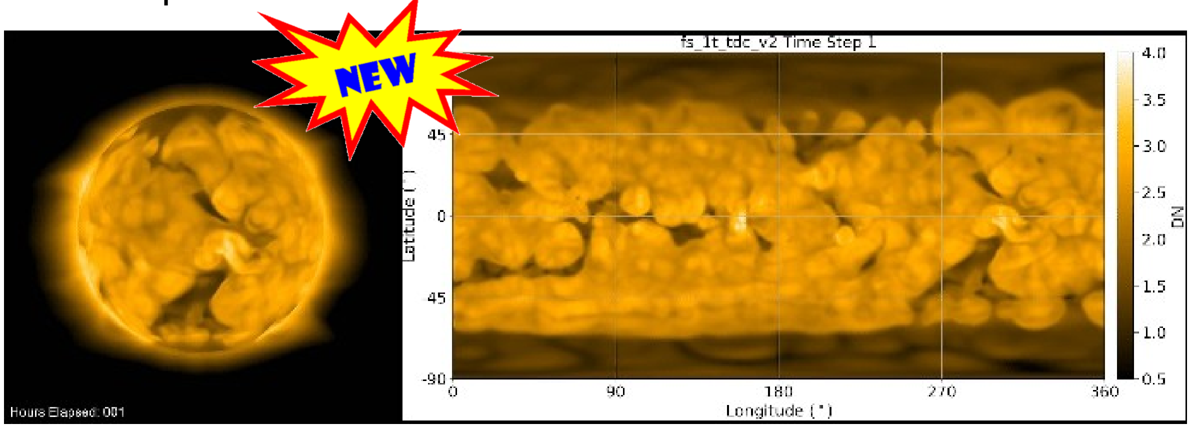


Observation

Coming soon! Eclipse 2024

predsci.com/eclipse

- On April 8th 2024 there will be a total solar eclipse across North America
- Two major advancements of our MAS model this time around:
- First, we will use observations from the PHI instrument aboard Solar Orbiter to reduce the amount of "old data" in our surface boundary conditions
- Second, instead of running the simulation with a single surface boundary map (with 10-day old data), we will run the model continuously, updating the boundary as new data becomes available. This will improve the prediction as the eclipse time approaches. It will also automatically energize filament channels, and reduce the total computational costs of the runs.



Coming soon! Eclipse 2024

NEW

April 8, 2024, Solar Eclipse

On April 8, 2024, a total solar eclipse will cross North America, passing over Mexico, United States, and Canada.

Predictive Science Inc.

predsci.com /eclipse