Nonequilibrium Ionization Analysis of a Coronal Shock Driven by a CME

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Terminology

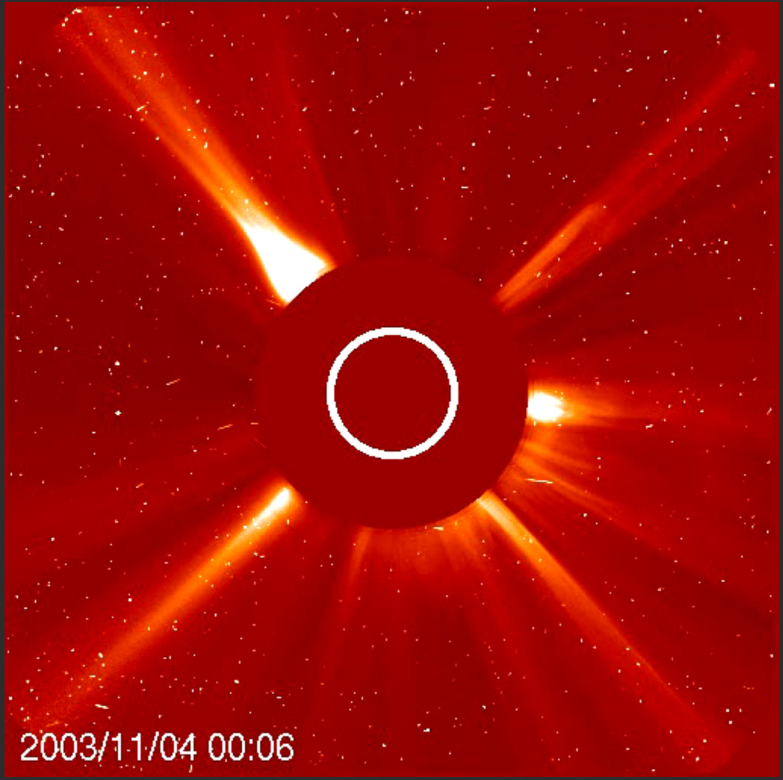
Coronal Mass Ejections (CME)

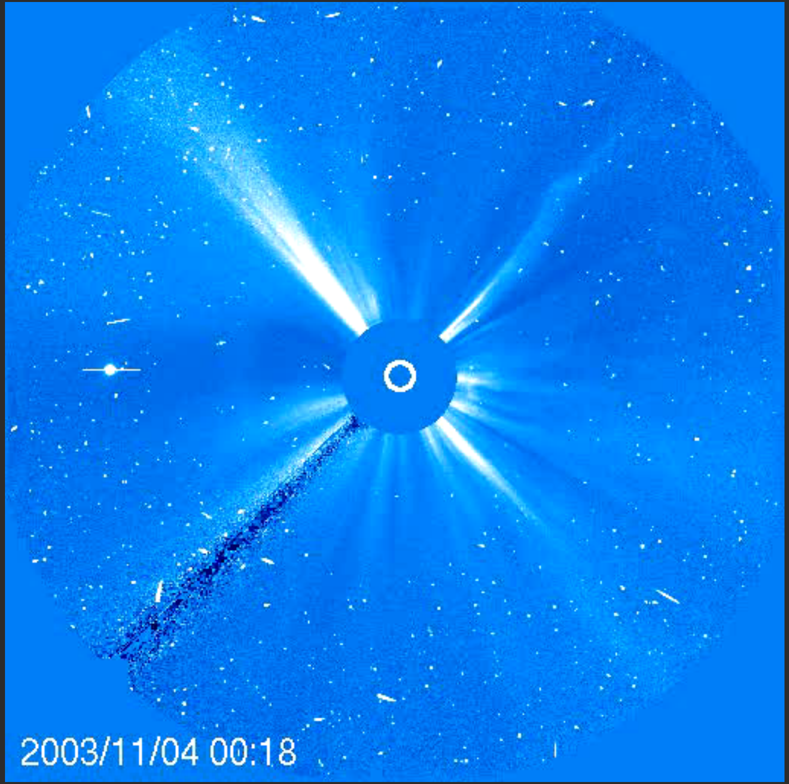
- Large discharge of plasma from the Sun's corona
- Speeds of 250 - 3000 km/s
- Fastest can reach earth in ~15 hrs
- Often preceded by solar flares
- ~ 3 CME's every day during solar maximum

Coronal Shocks

- Magnetohydrodynamic waves
- Characterized by abrupt, nearly discontinuous, changes in density and temperature
- Accelerate particles in solar wind creating Solar Energetic Particles that can be harmful satellites

Obligatory CME Video

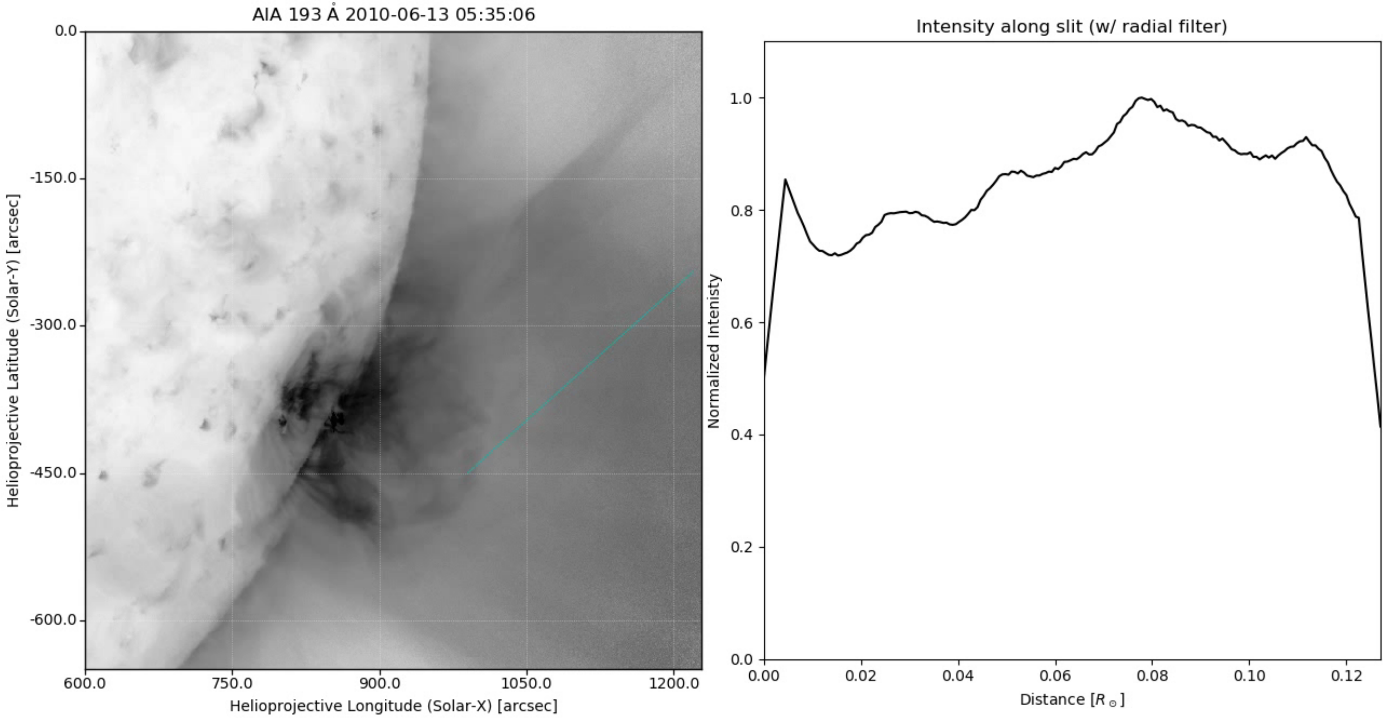


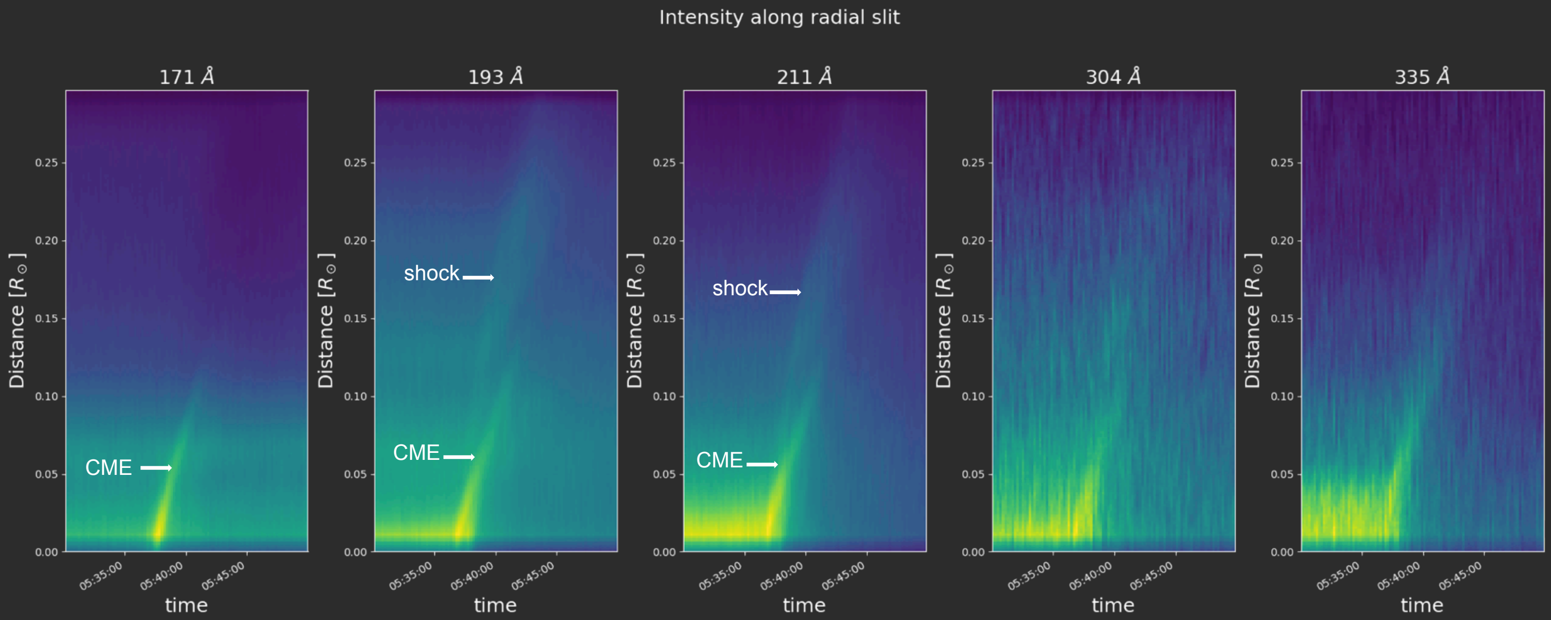


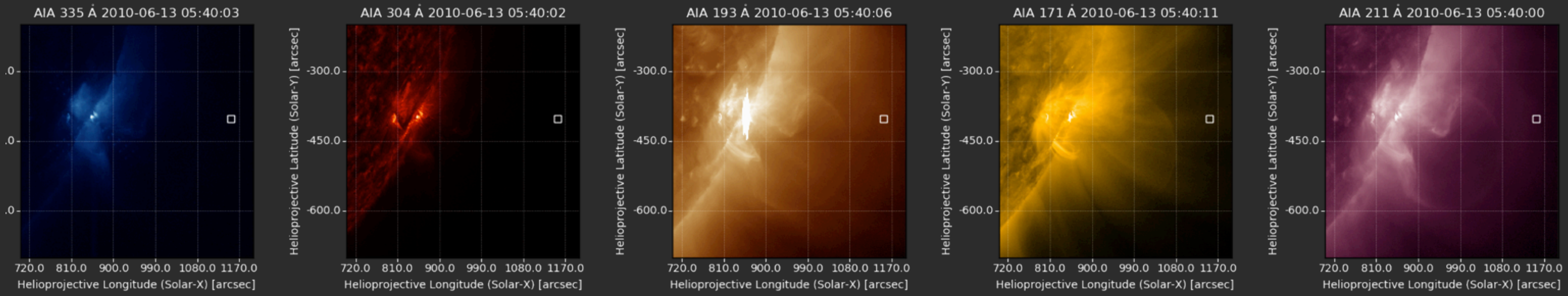
Source: https://lasco-www.nrl.navy.mil/daily_mpg/2003_11/

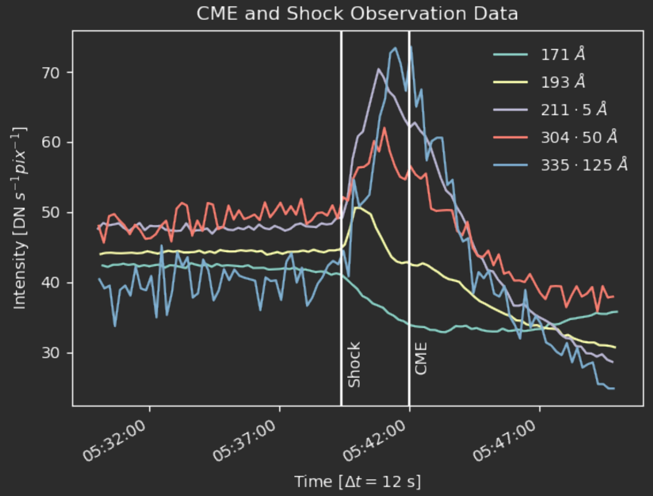
June 13, 2010 Observations -- Ma et al. 2011

- CME observed using AIA in 171, 193, 211, 335Å channels
- Shock clearly visble in 193, 211Å
- Associated Type II radio burst observed consistent with CME
- Density compression ratio ~1.56
- Post-shock temperature ~2.8 MK
- Shock layer thickness ~2 x 10^4 km
- Shock speed varied slightly from ~600 km/s


AIA 193 Å 2010-06-13 05:35:06
Helioprojective Latitude (Solar-Y) [arcsec]
Helioprojective Longitude (Solar-X) [arcsec]
0.0
-150.0
-300.0
-450.0
-600.0
600.0
750.0
900.0
1050.0
1200.0
Intensity along slit (w/ radial filter)
Normalized Intenisty
Distance [$R_\odot$]
0.0
0.2
0.4
0.6
0.8
1.0
0.00
0.02
0.04
0.06
0.08
0.10
0.12


Intensity along radial slit
171 Å
193 Å
211 Å
304 Å
335 Å
Distance [$R_\odot$]
0.00
0.05
0.10
0.15
0.20
0.25
05:35:00
05:40:00
05:45:00
time
CME
shock





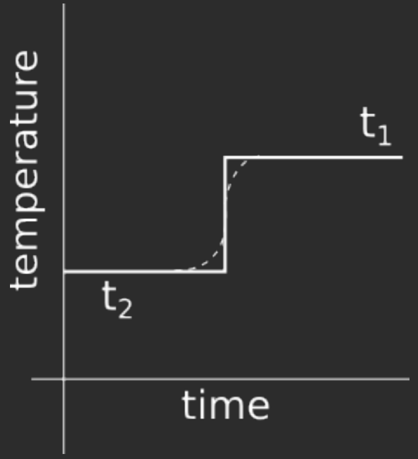
- Shock corresponds to sudden deviation from background
- CME passes through window during the peak in 335 Å
- Notice the lag between peaks in 193, 211, 335Å channels → indicative of ionization timescales

Nonequilibrium Ionization

- **Equilibrium Ionization:** temperature changes smoothly and slowly
- **Nonequilibrium Ionization:** rapid changes in temperature / electron density that are shorter than ionization and recombination time scales
  - Ionic fractions obtained by solving **time-dependent** ionization equations (right)
    - n_e - electron number density
    - C_i , R_i - i^{th} ion ionization and recombination coefficients
    - f_i - i^{th} ion fraction
  - Ionization equations can be encoded into a matrix form and solved for time dependence using Eigenvalue methods
- Model the shock as discontinuous **step function** in temperature.

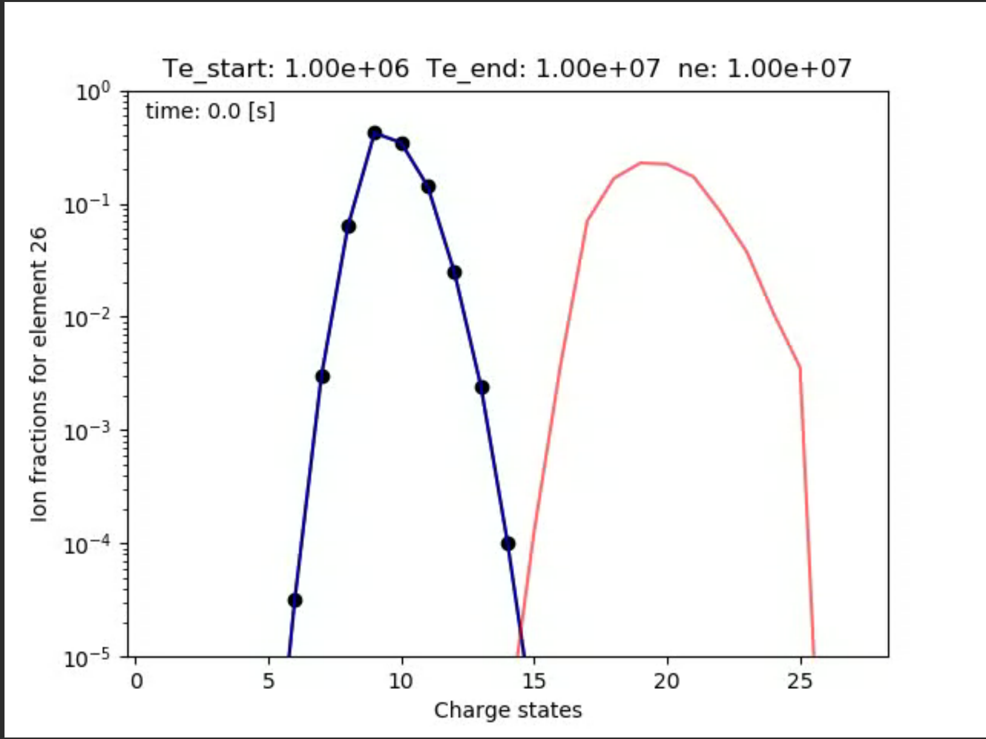
$$\frac{df_i}{dt} = 0$$

$$\frac{df_i}{dt} = n_e[C_{i-1}f_{i-1} - (C_i + R_i) + R_{i+1}f_{i+1}]$$



Example simulation output

- Simulations track ion fraction for each ion of a desired element
- Plasma never reaches equilibrium fractions (red) despite waiting for thousands of seconds
- The CME shock is on order of tens of minutes necessitating nonequilibrium simulation (grey)



Creating a Synthetic AIA Observation

Constituents

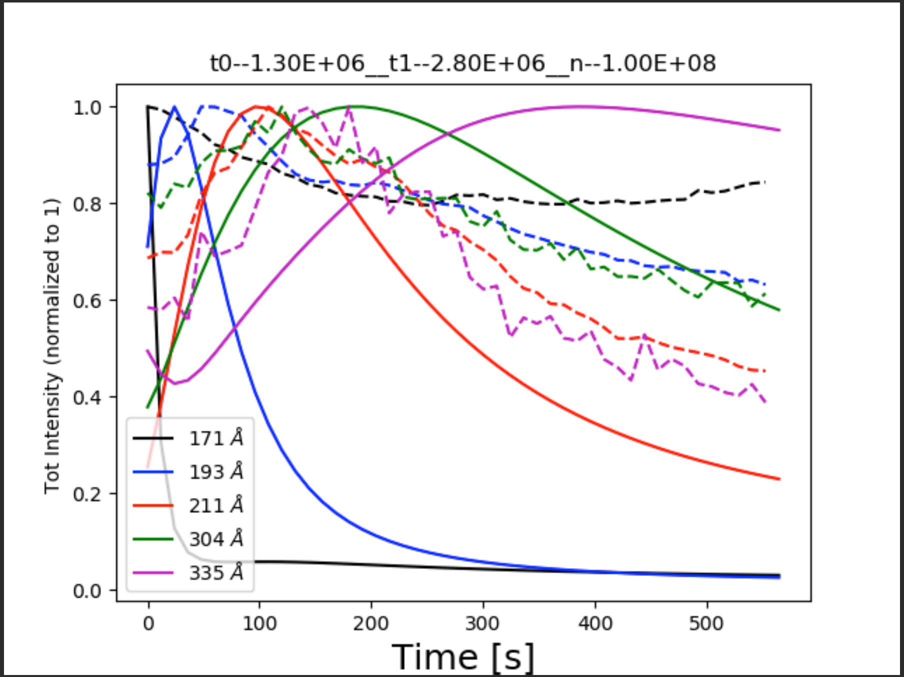
- **Ionic Fractions:** Generated by NEI simulation code
- **Emissivity:** Contribution function taken from Chianti for each (element, ion, density, temperature)
- **AIA Wavelength Response:** Taken from the via SSWIDL according to Boerner et al. 2014
- **Coronal Abundance:** Values relative to hydrogen taken from Feldman et al. 1992 (hosted in Chianti)

Calculation

1. For each element, loop through all relevant ions
2. For each ion, loop through each AIA channel
3. Multiply emissivity by response function
4. Sum counts across all wavelengths in channel
5. Adjust by ion fraction and elemental abundance
6. Add to that channel’s total for that time step

Synthetic Response Example

- The ionization timescale goes inversely with the density for optically thin plasma
  - allows us to adjust the position of the peaks
- Initial value can be tweaked by changing t_0
  - Can constrain this value using the background intensity before the shock
- Despite exploring many parameter ranges, we couldn't get a satisfactory fit



Geometry of the Shock: Adjusting simulation Output

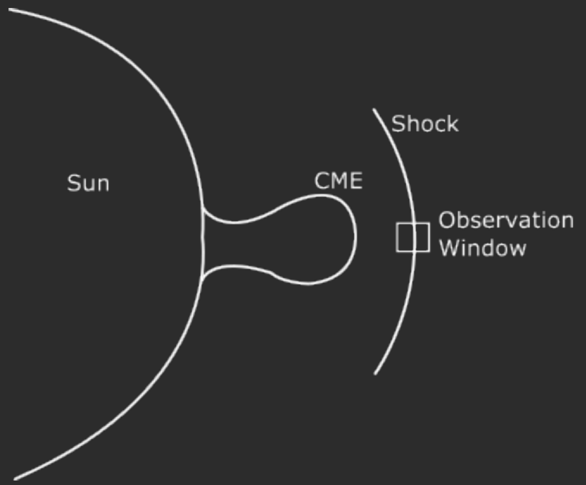
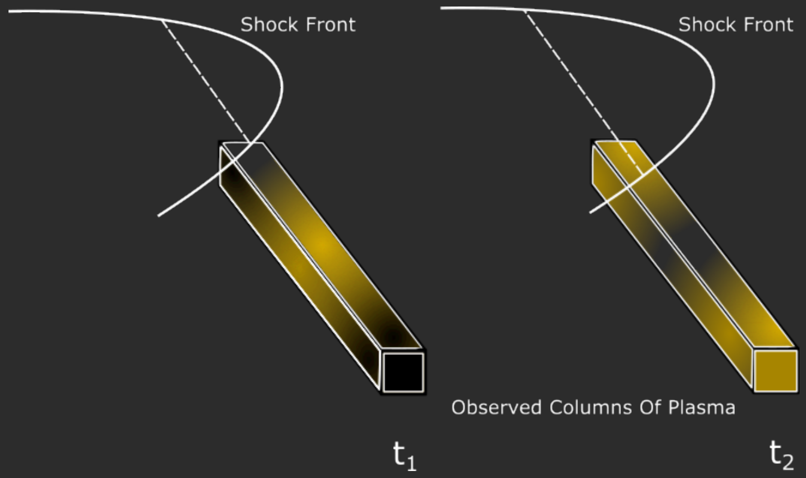


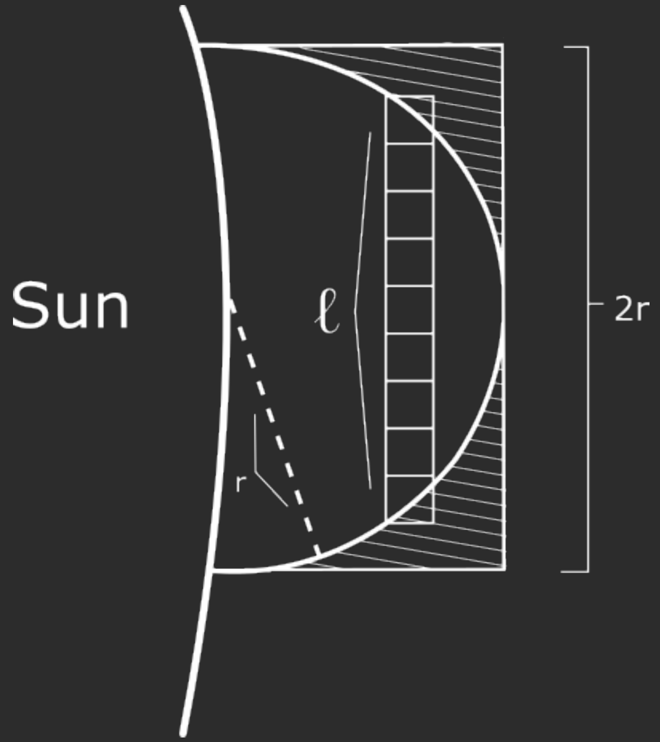
Diagram of AIA observation image



Observed Column of plasma at two different times

Adjusting Simulation Output

- Fit circle to observation window at t=0
- Increase radius according to Ma et al velocity each time step
- Calculate ℓ from window's position and circle geometry
- Use ℓ to determine how much background to include as well as number of cells to stack for the plasma's depth
- Determine distance from each cell to the shock and subsequently the time since shock has passed



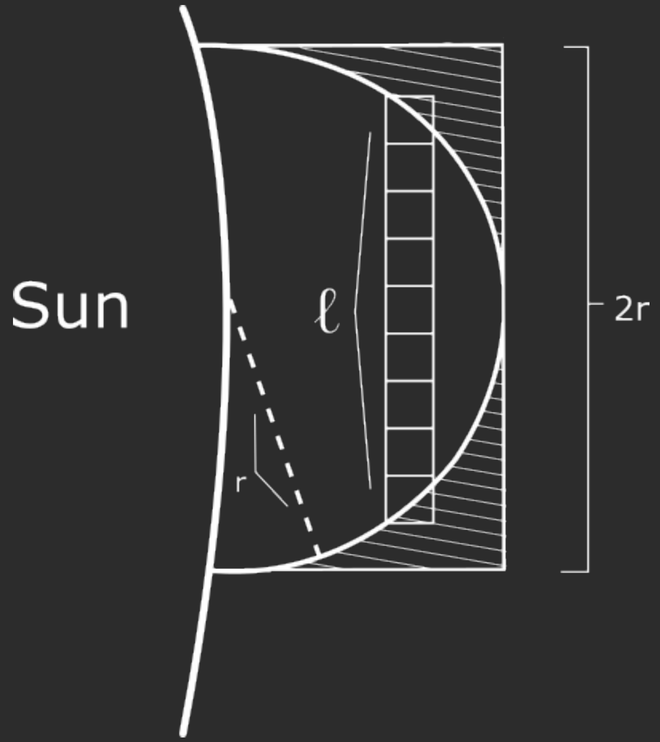
continued...

- Using time index, grab appropriate emissivity value from simulation output
- Sum all of the emissivities for each channel in each window

Free parameters: t_0, t_1, n, Δx

$$I_{\text{observation}} = I_{\text{background}} + I_{\text{source}}$$

$$I_{\text{observation}} = I_0\left(1 - \frac{\ell}{2r}\right) + \sum_{i}^{N} X^2 n_0^2 \Delta x \varepsilon_i(d_i) c$$



Future Work

- Once the model fits the original window, construct more along the shock front
- Map out the electron temperatures and densities along shock
- Combine this new information with shock speed and other reported values
- Couple this information with MHD jump conditions (continuity equations i.e. mass flux, E & B fields, etc…) to further explore shock conditions

Acknowledgements

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Feedback: My peers

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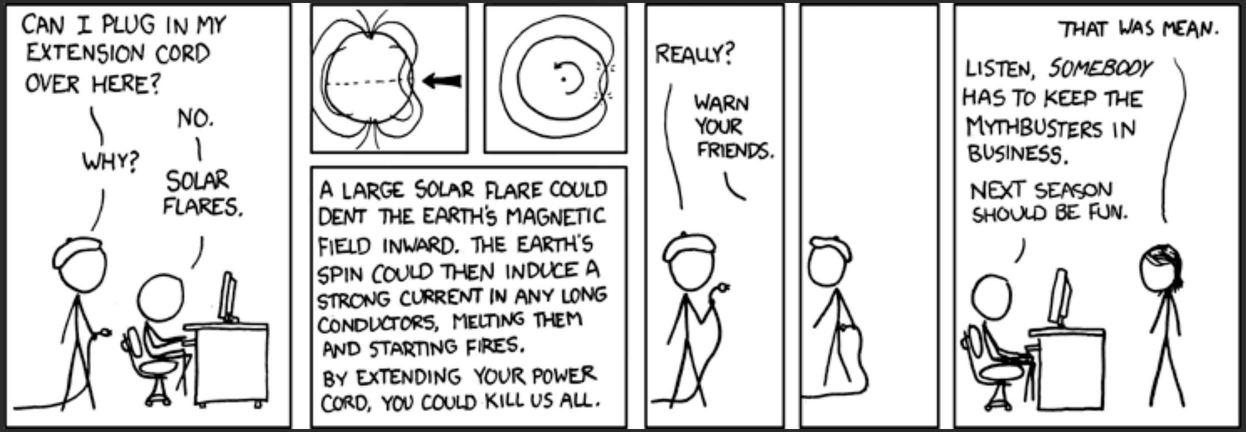
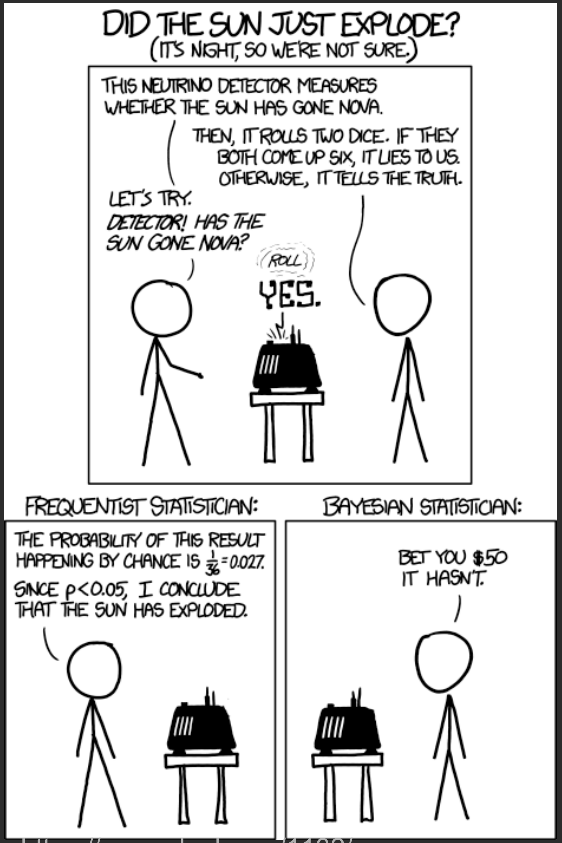
Thanks for listening!



https://www.xkcd.com/509/



https://www.xkcd.com/1132/