Comparative Study of the Solar Wind: Modeling Charge State Distributions in the Heliosphere

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Today's Discussion

- A Brief Corona, Pseudo-Streamer, and Solar Wind Overview
- Motive for Investigation
- History of Previous Solar Storms
- Method:
  - Magnetohydrodynamics Around a Sphere (MAS) Model
  - Ulysses/SWICS Instrument
  - Non-equilibrium Ionization (NEI) simulation
- Results
- Conclusions (Unfortunately no Nobel Prize. We didn't solve it!)
- Future Work

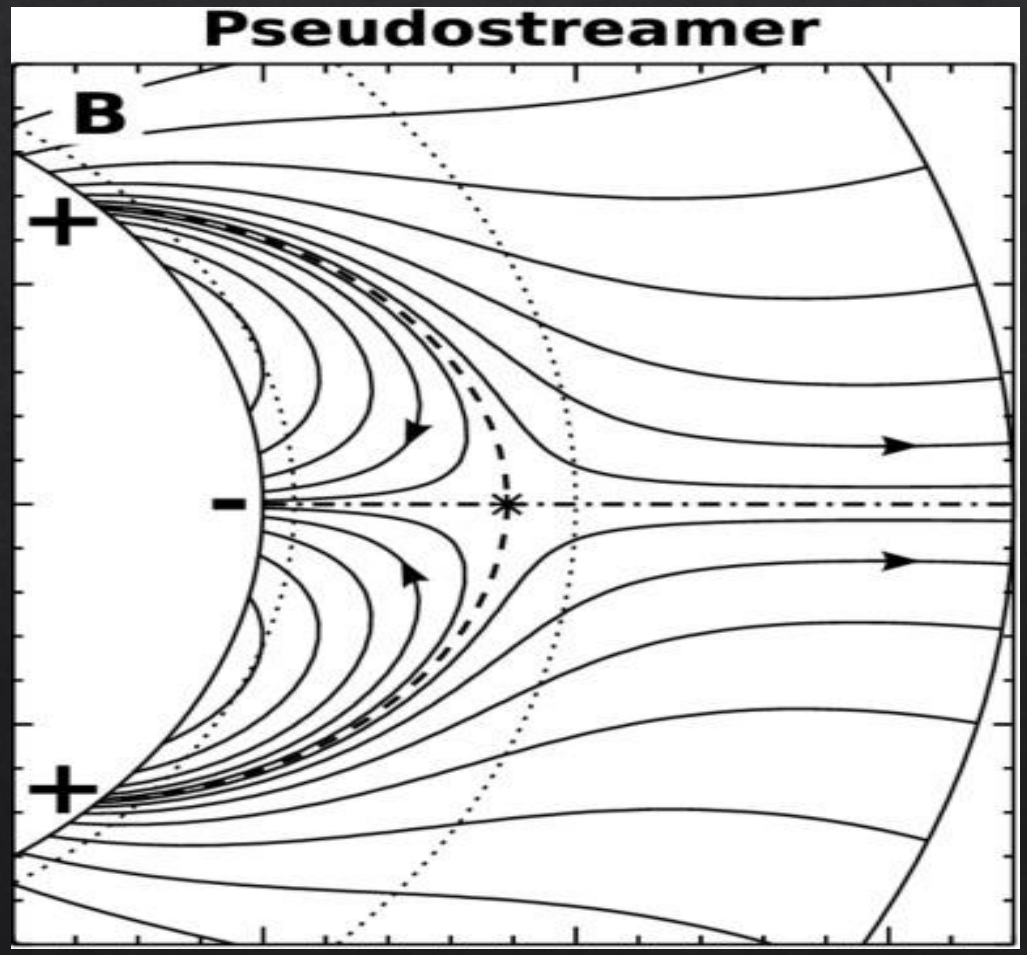
The Sun's Corona

- Corona: The outermost part of the Sun's atmosphere, hundreds times hotter than the surface
- Can only be seen via coronagraph or total solar eclipse
- Key Characteristics:
  - Low density
  - In collisional ionization equilibrium (most of the time)
  - Carries high-energy particles (a few million degrees)
- Why is it so hot?
  - WE. JUST. DON'T. KNOW.

The Sun's Corona (Eclipse)

Streamers

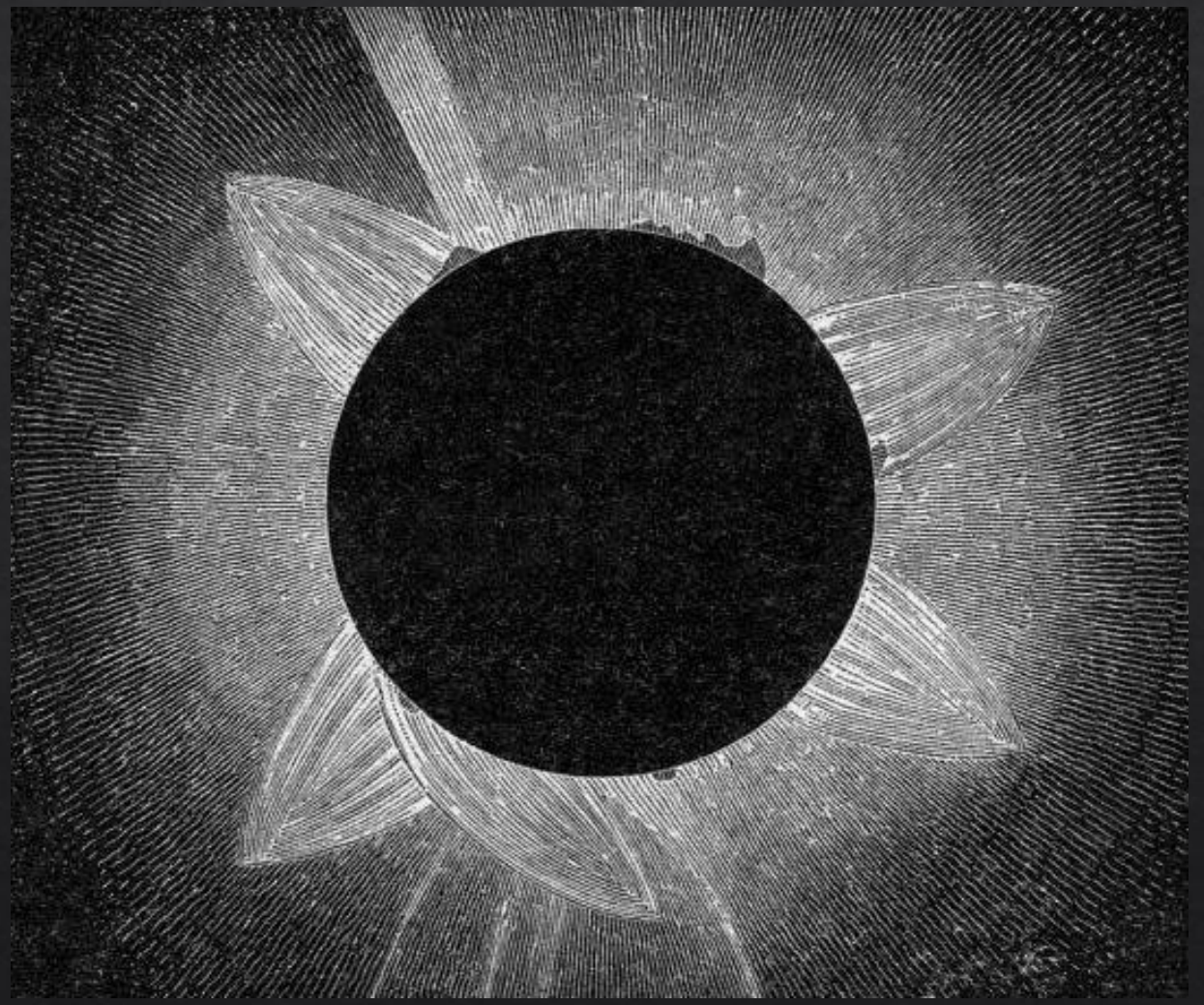
- Pseudo-streamer: Loop-like structure in the corona of the Sun (and other stars)
- Occur over twin loop arcades and separate coronal holes of the same polarity.
- Extend high into the corona and appear similar to helmet streamers in white light
- Generally a steady, stable flow and can have outflow speeds of a few hundred kilometers per second



Field Traces

Figure Credit: Rachmeler et al. (2014)

Streamers

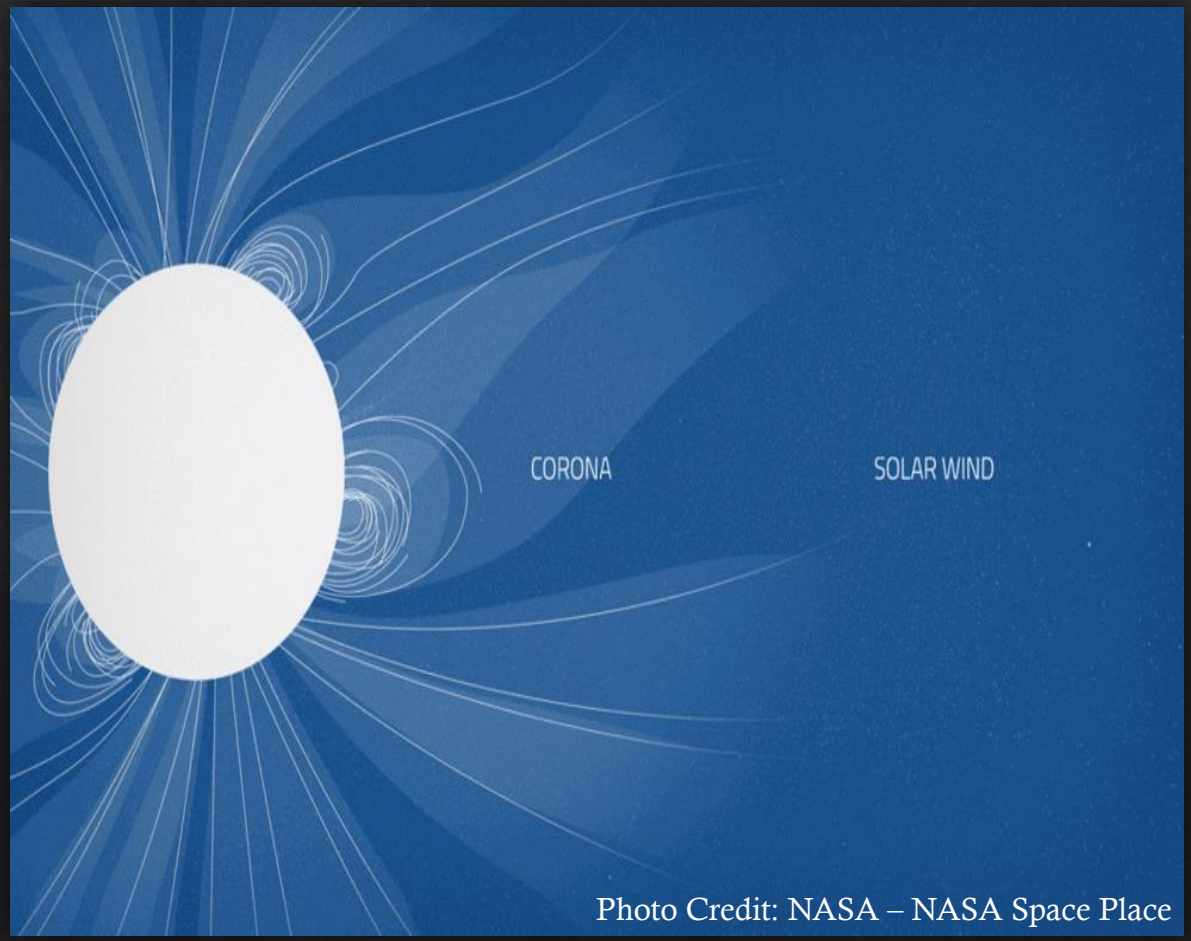


Helmet Streamers during Sept 7, 1859 Eclipse

Figure Credit: Emmanual Liais

The Solar Wind

- Solar Wind: Stream of charged particles released by the Sun's upper atmosphere (corona)
- Two Main Components:
  - Fast Wind (> 450 km/s)
  - Slow Wind (< 450 km/s)
- Applications
  - Stellar Winds
  - Plasma Physics
  - Interaction w/ Earth

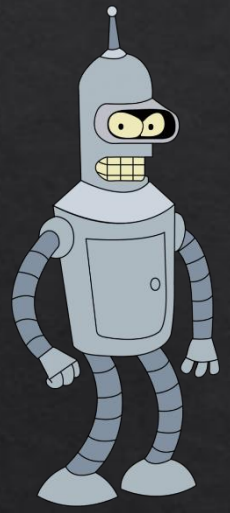


Corona and Solar Wind Particles

History of Solar Storms

“Carrington-Class” Coronal Mass Ejection (2012)

Motive for Investigation (Aristotelian)



Ethos

- Who are we, the credible scientists, to deny the public more knowledge about our nearest plasma laboratory?

Logos

- Test validity of:
  - MAS Model
  - NEI simulation
- Nuanced thermodynamics of solar wind
- Shine more light on magnetic field dynamics of the solar corona

Pathos

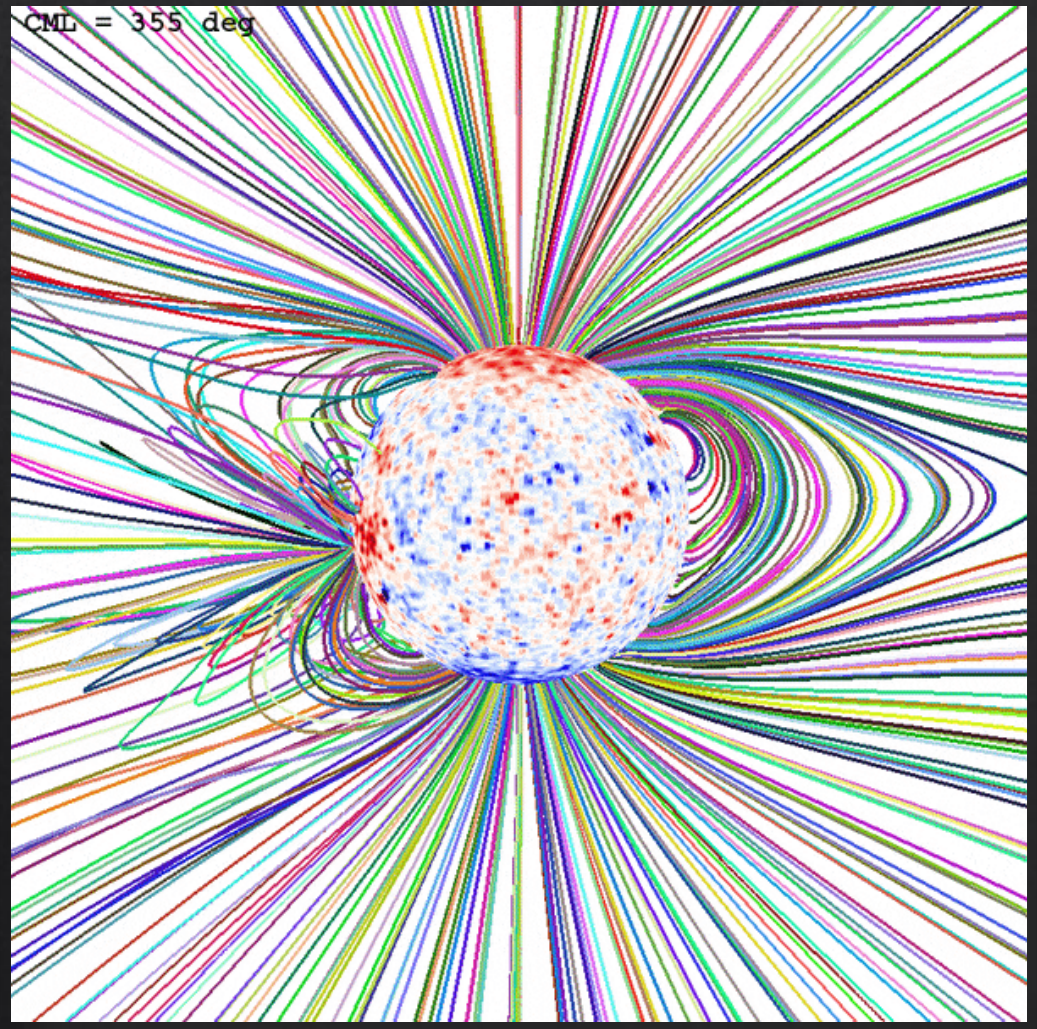
- Be able to predict:
  - ~~Armageddon~~ Space Weather
  - When it would be a good time to take significant other out to see the Aurora

Flashing Colors Warning

- WARNING: The video in the next slide may potentially trigger seizures for people with photosensitive epilepsy. Viewer discretion is advised.

MAS Model

- A well-developed MHD model of the solar corona, extends out to 20 solar radii
- Depends on magnetogram data (old) and solves resistive MHD equations
- Contains valuable information about plasma traveling through the coronal streams

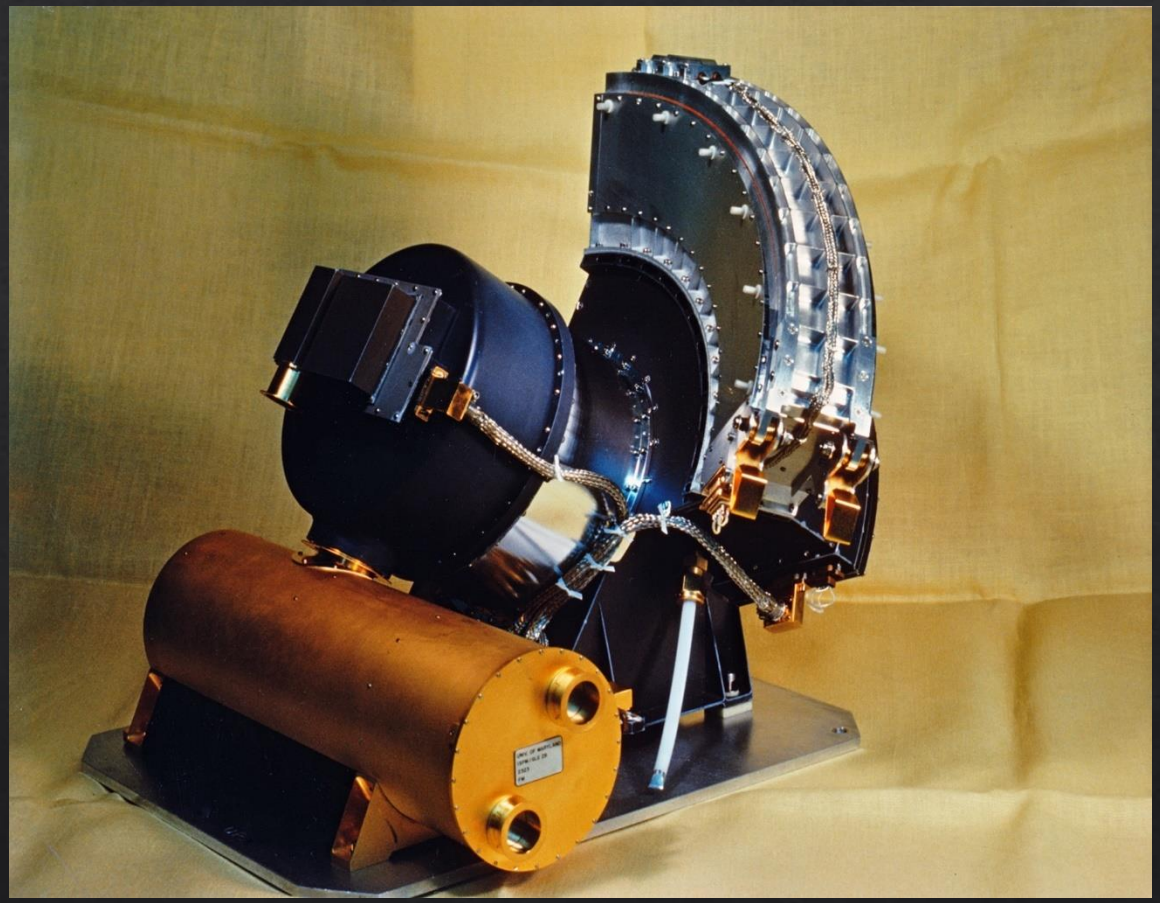


Whole Sun Month (CR) 1913 Rotation

Photo Credit: Shen et al. (2017)

Ulysses/SWICS

- Solar Wind Ion Composition Spectrometer (SWICS)
- Determine the elemental and ionic-charge composition, temperature, and mean speeds of all major solar-wind ions
- Wind speeds range from 145 km/s (protons) to 1352 km/s (Fe +8) throughout mission
- About a 3.5 hour cadence in between measurements



SWICS Instrument

Photo Credit: University of Maryland

Tracing Back to the MHD Model

- Whole Sun Month Interval (CR) 1913 (1996 August 22 to September 18)
- Plasma takes ≈ 11 days to reach Ulysses from 20 solar radii boundary
- Shift Ulysses observation dates 11 days ahead of the (CR) 1913 rotation

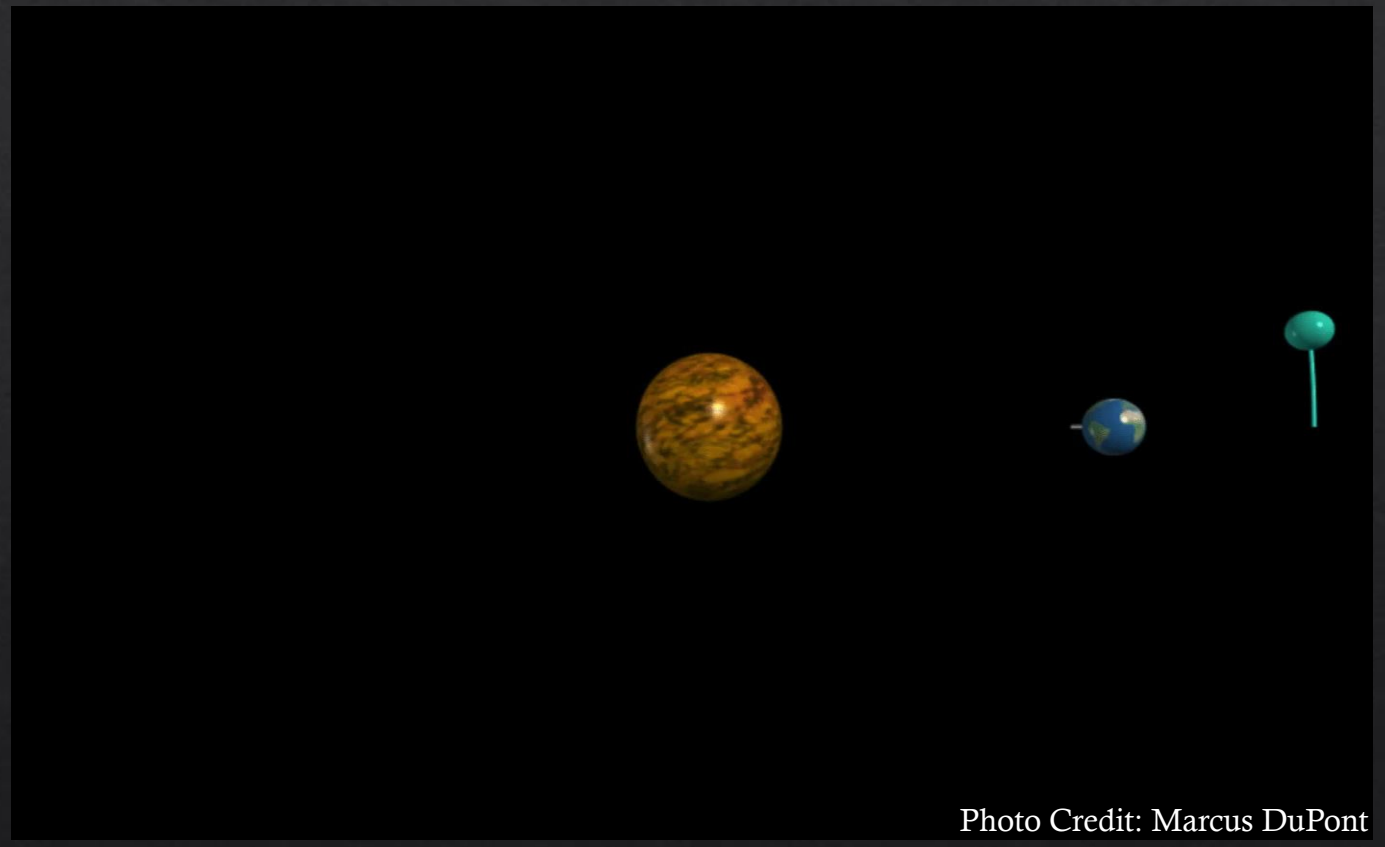
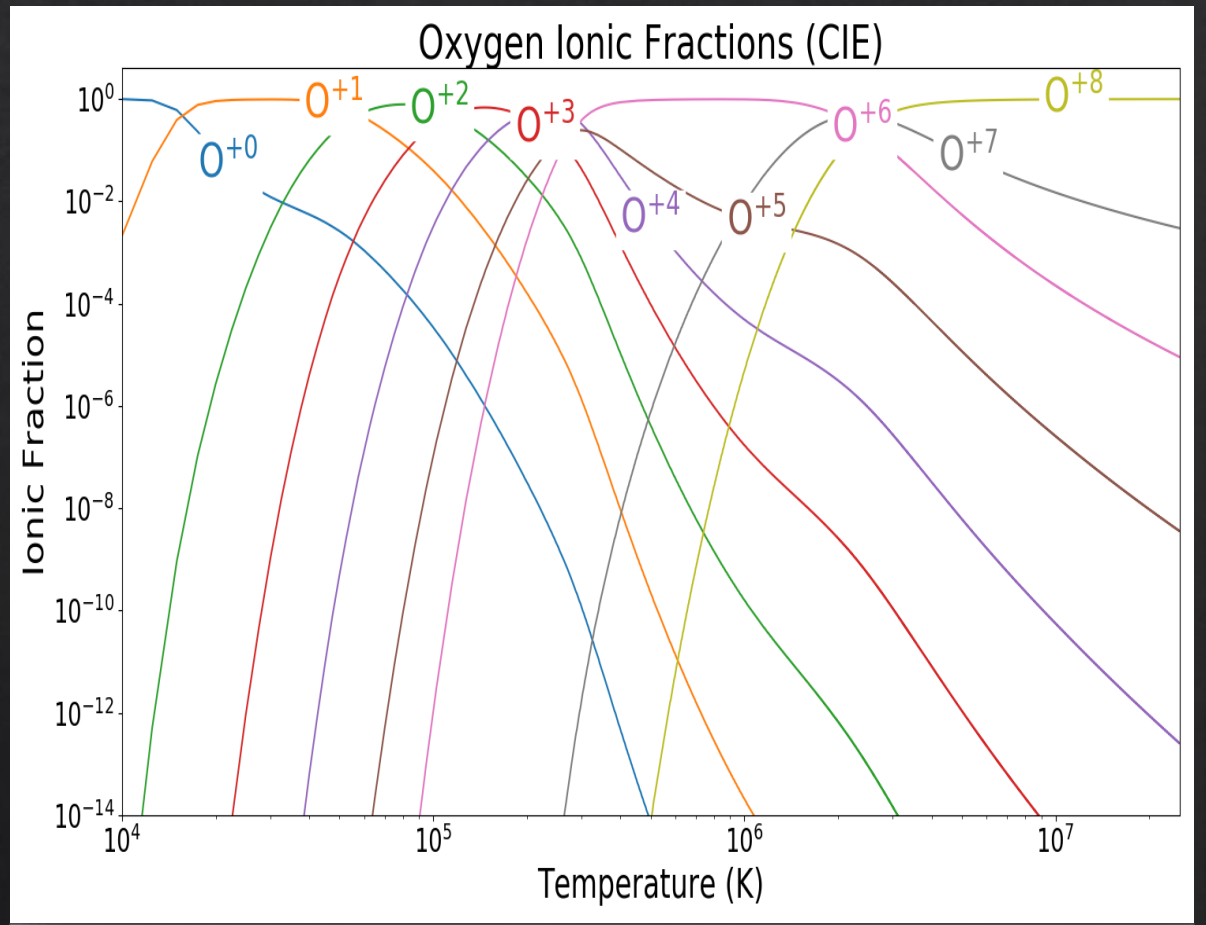


Photo Credit: Marcus DuPont

Ulysses Spacecraft Trajectory

Non-Equilibrium Ionization Model

- Models plasma as it moves away from the Sun
- Time, temperature, abundance, and plasma density inputs
- We assume a Maxwellian electron (thermodynamic equilibrium) distribution throughout



Oxygen Charge State Evolution in Equilibrium

Non-Equilibrium Ionization Model

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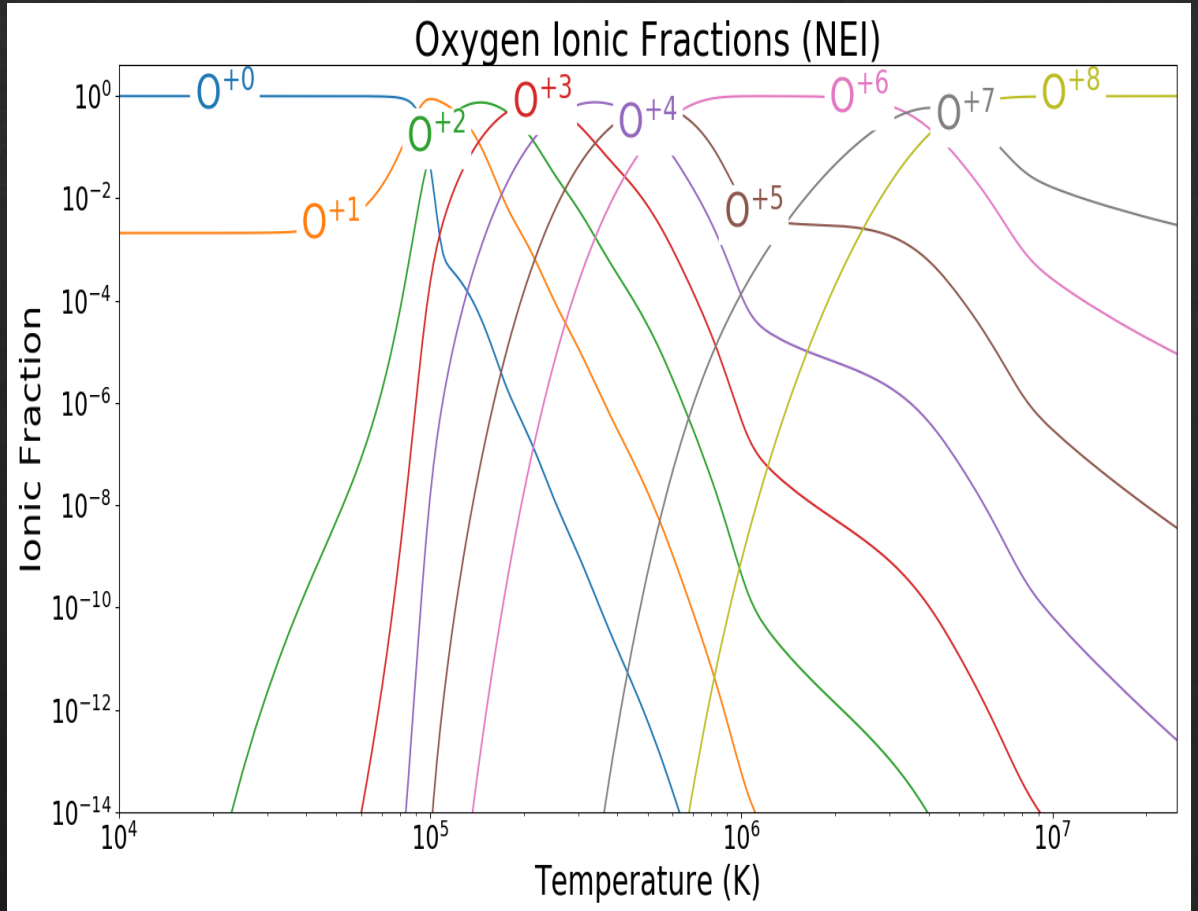
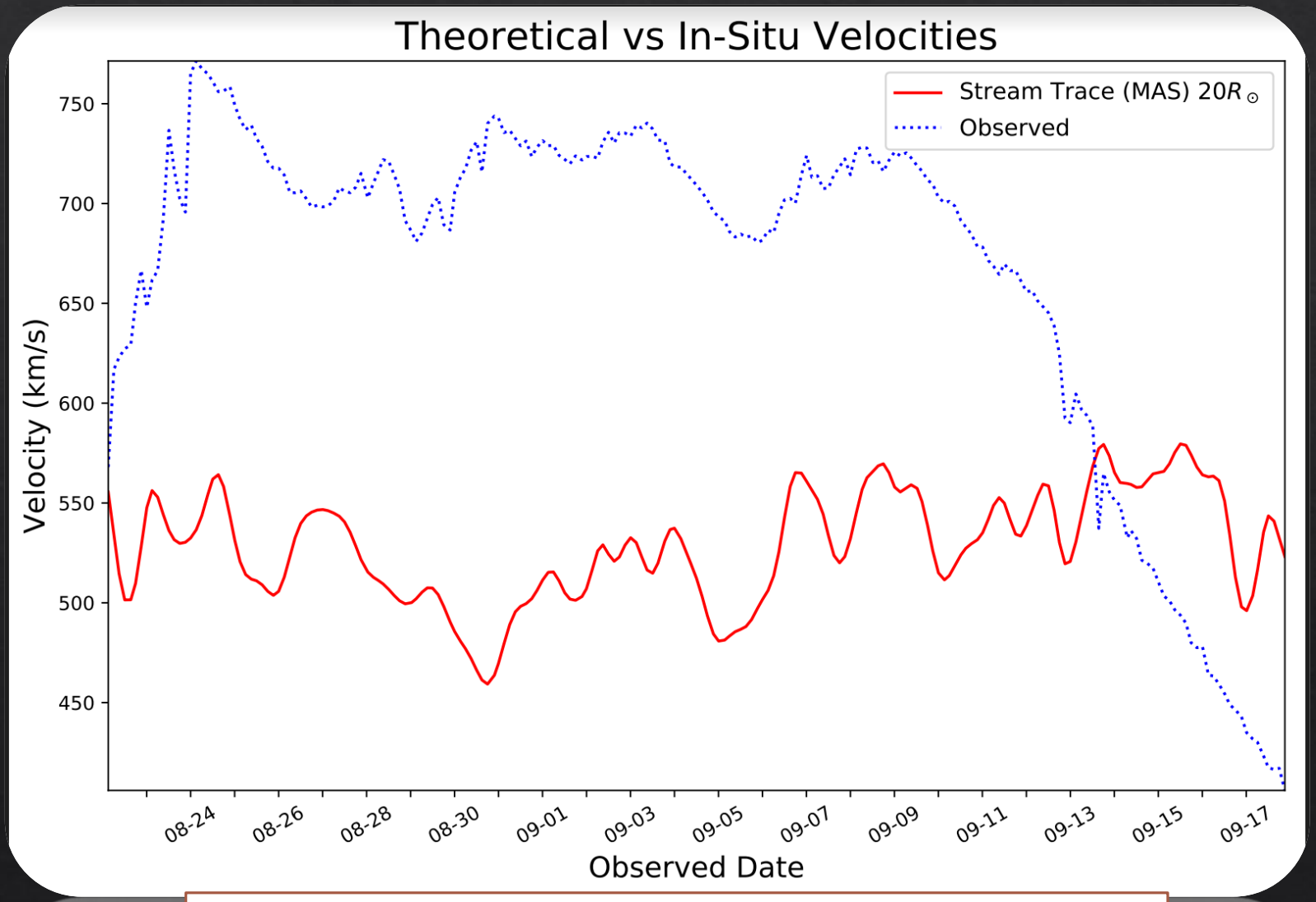


Oxygen Charge State Evolution in Non-Equilibrium

Findings (1)

a) – Differences are significant b/w both

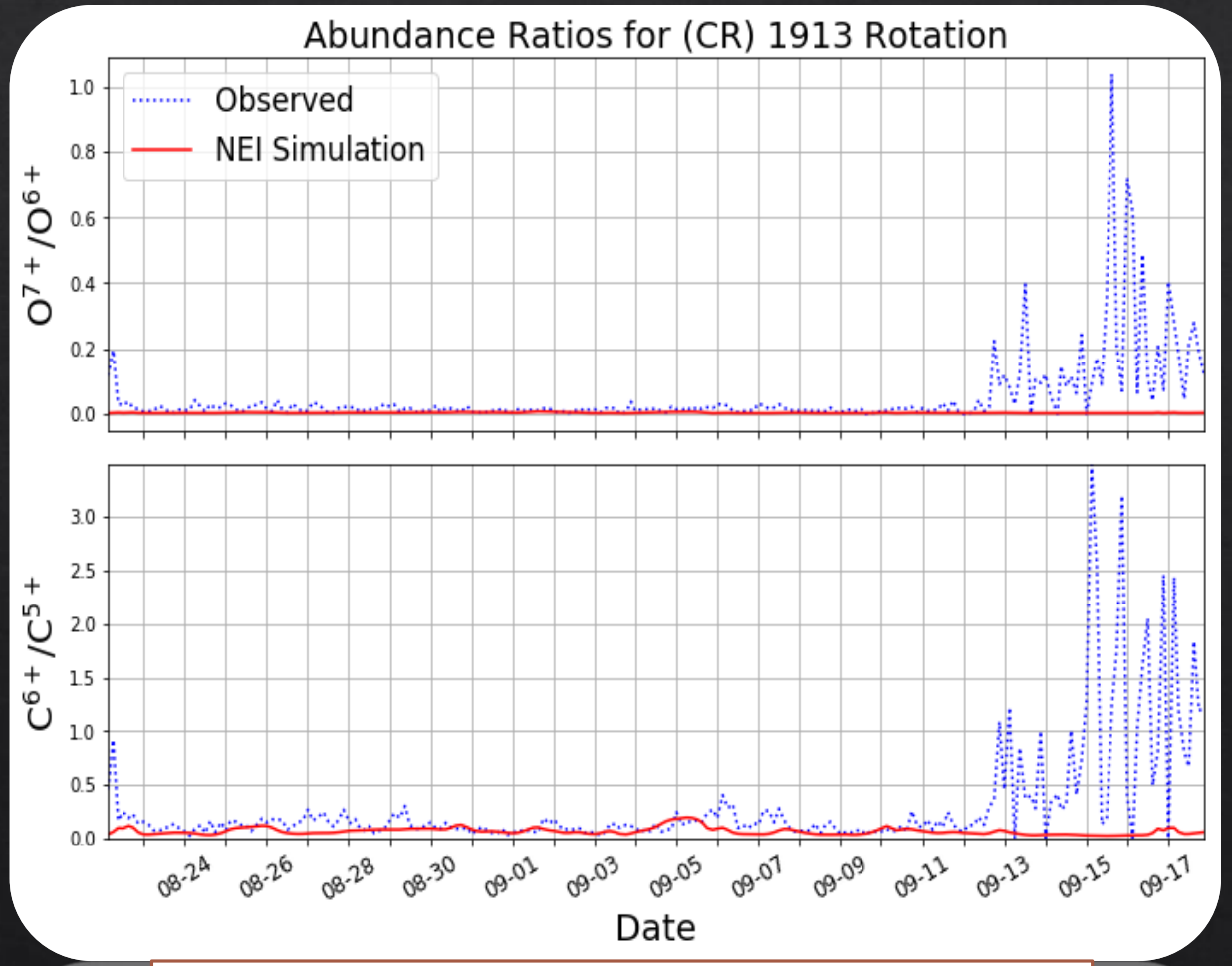
b) – Both in fast wind stream while the MAS model is less fast



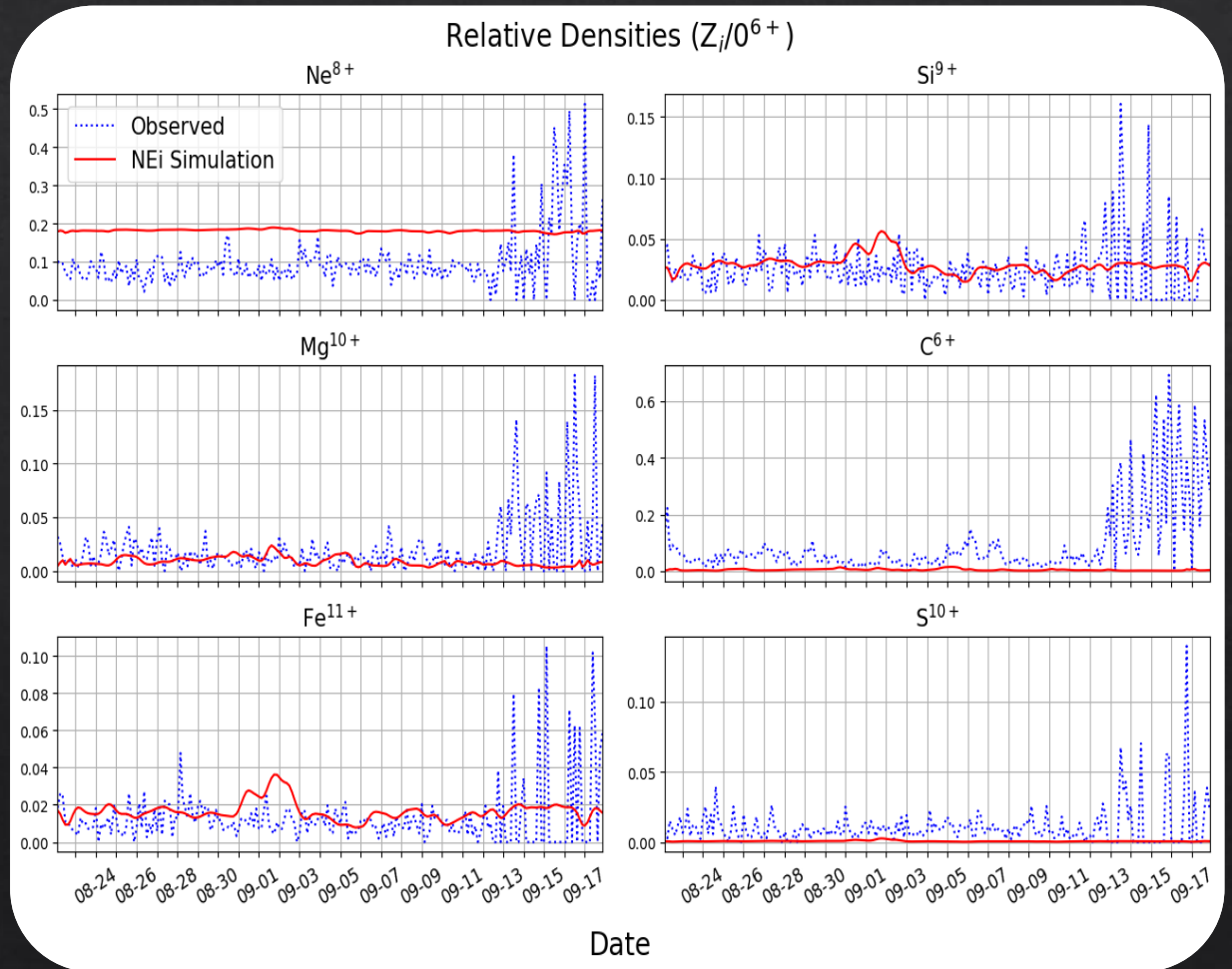
Velocity Comparison (Observed vs at MAS Boundary)

Findings (2)

a) – Modeled charge states within reasonable agreement in some areas
b) – There is an area of increased ionization not predicted by the MAS model

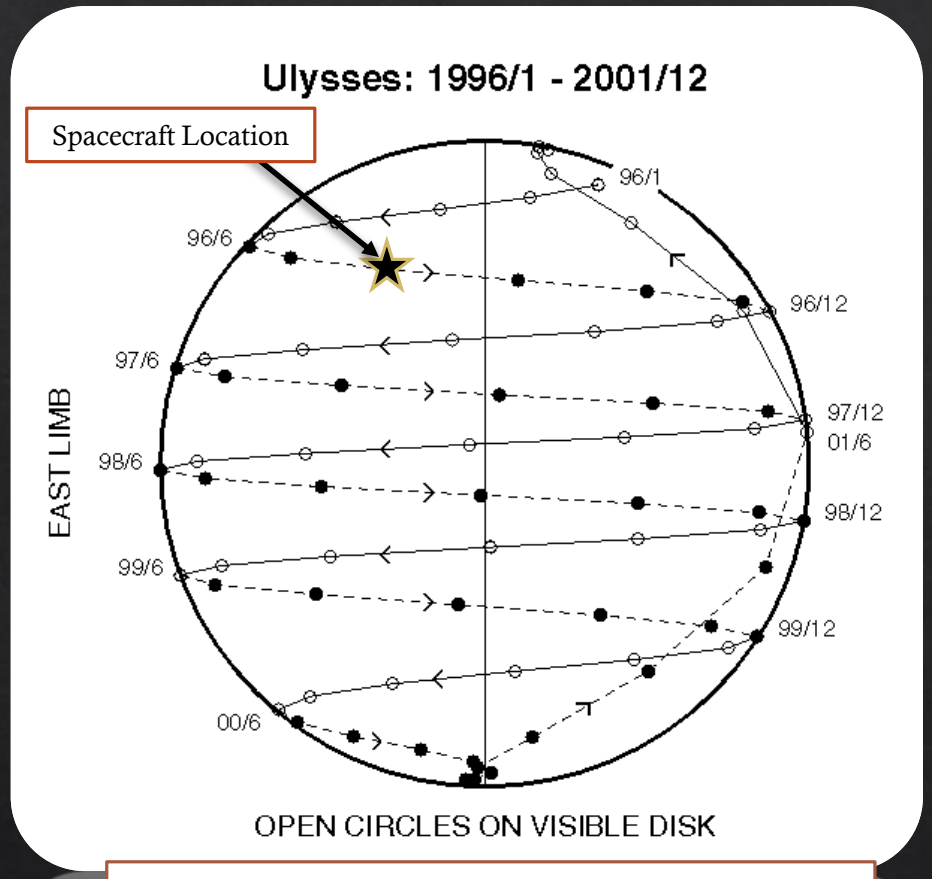


Abundance Ratios (Observed vs Simulated)

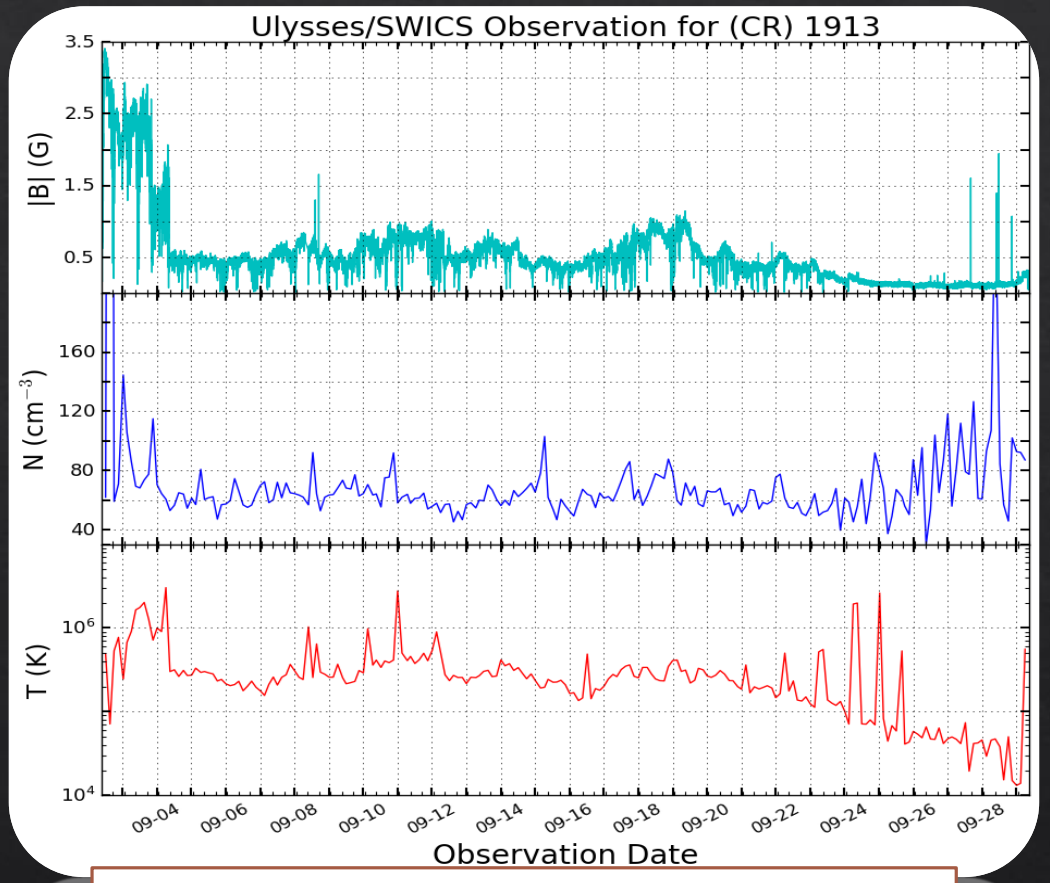


Density Ratios (Observed vs Simulated)

Was There An Event?



Ulysses Projection on solar disk relative to Earth viewing angle

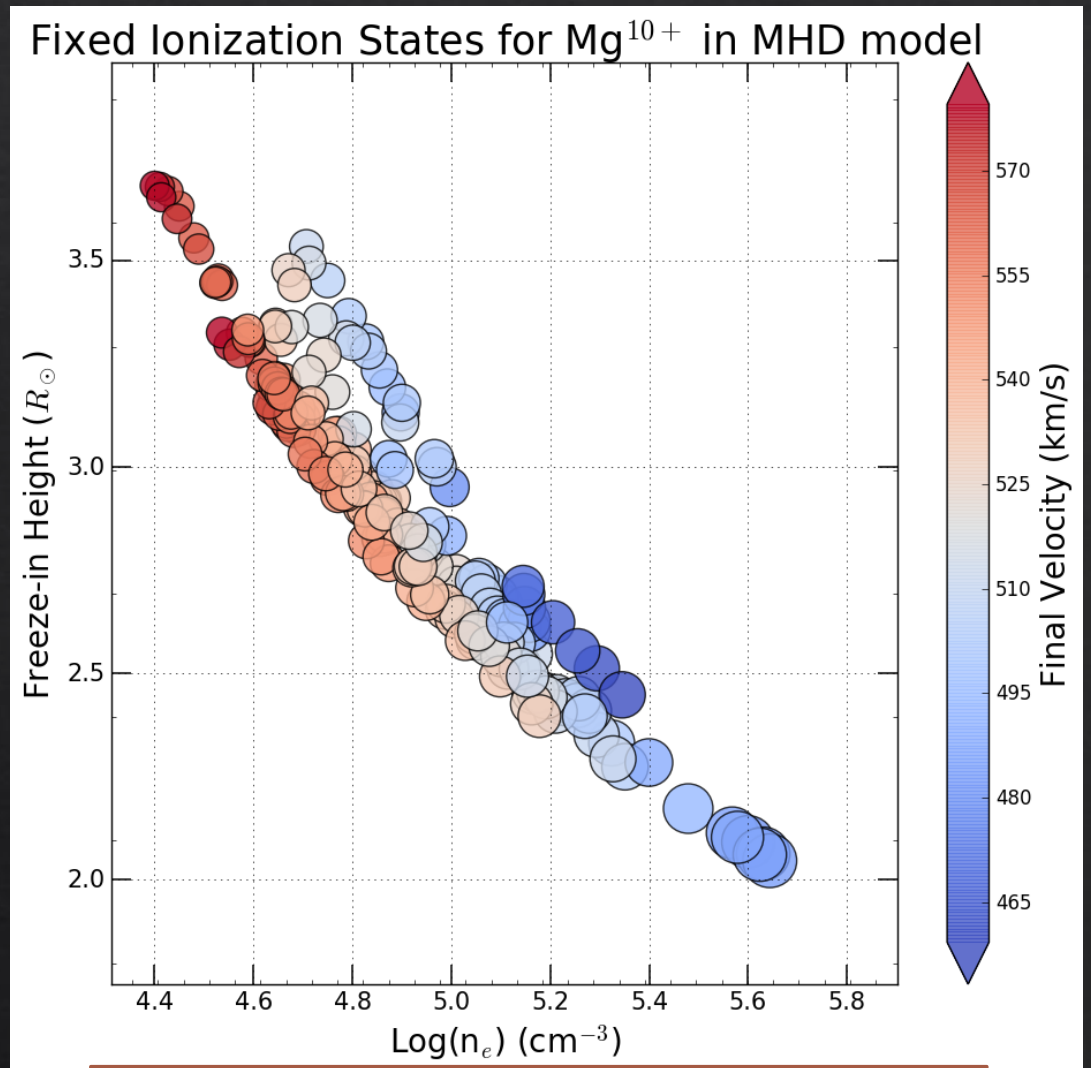


Observed magnitude of **B** field, alpha^{+} density, and alpha temperature

We search in the magnetometer data since Ulysses was on the far side of the Sun during the (CR) 1913 rotation and any CME or eruption would have been occulted by available coronographs

$^{+}$Alpha Particle: ^{4}He Nuclei

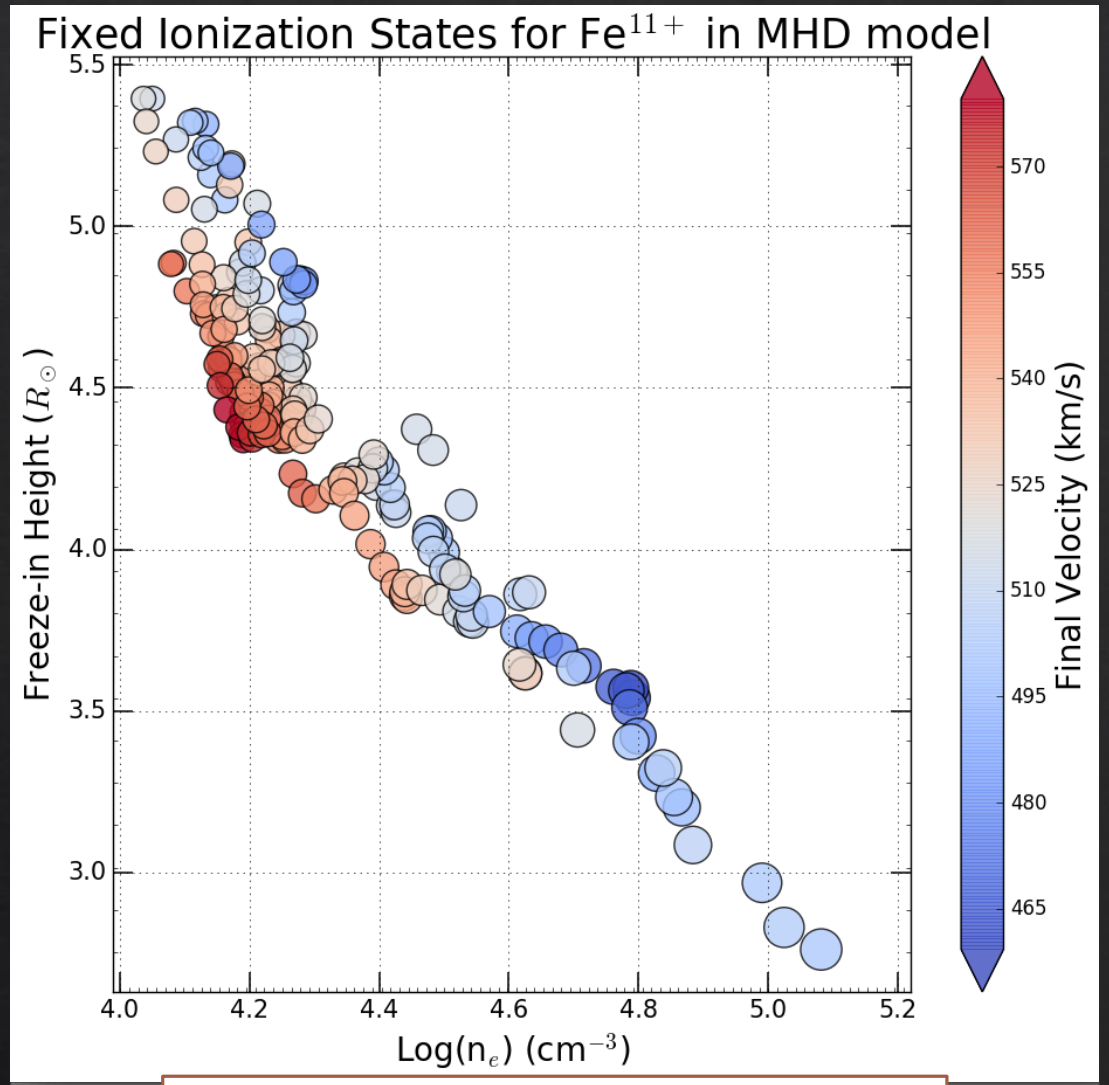
Findings (3)



Freeze-in height & density of Mg^{+10} w/ final velocities of each streamer

- Tracking the "freeze-in" distance of each solar wind ion
- Compare with in-situ abundances
- Solar wind propagation, which assumptions match more towards observation

Findings (3)



Freeze-in height & density of Fe^{+11} w/ final velocities of each streamer

- Tracking the "freeze-in" distance of each solar wind ion
- Compare with in-situ abundances
- Solar wind propagation, which assumptions match more towards observation

In Summary

- Time-dependent ionization in model of corona
  - In-situ coordinates
  - MHD model
  - NEI population
- Velocity discrepancies between MAS model and observation
- NEI simulation very sensitive to discrepancies (electron density and temperature)
- We analyzed variations of freeze-in heights with velocity and density

Future Work

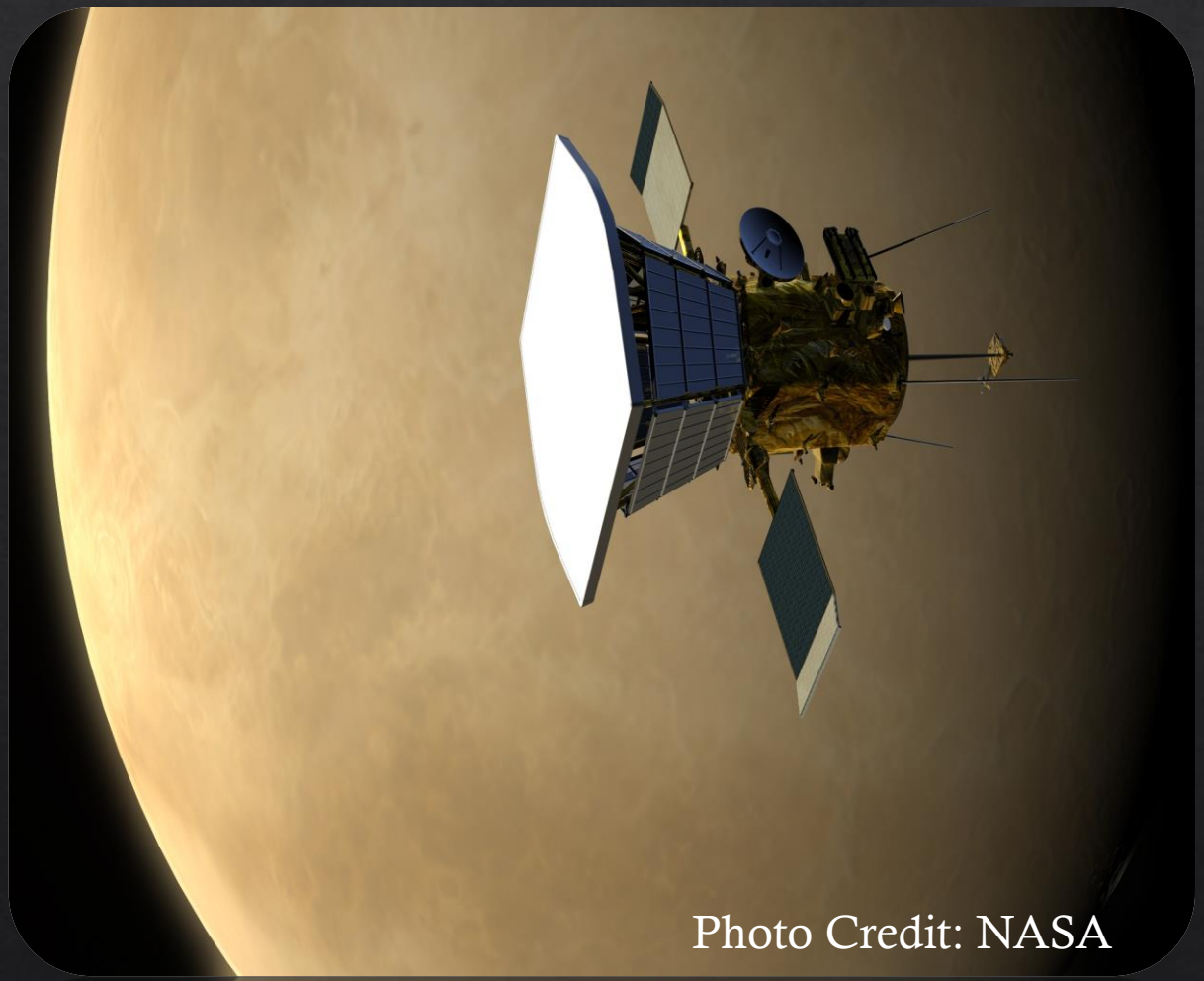


Photo Credit: NASA

Solar Probe Plus

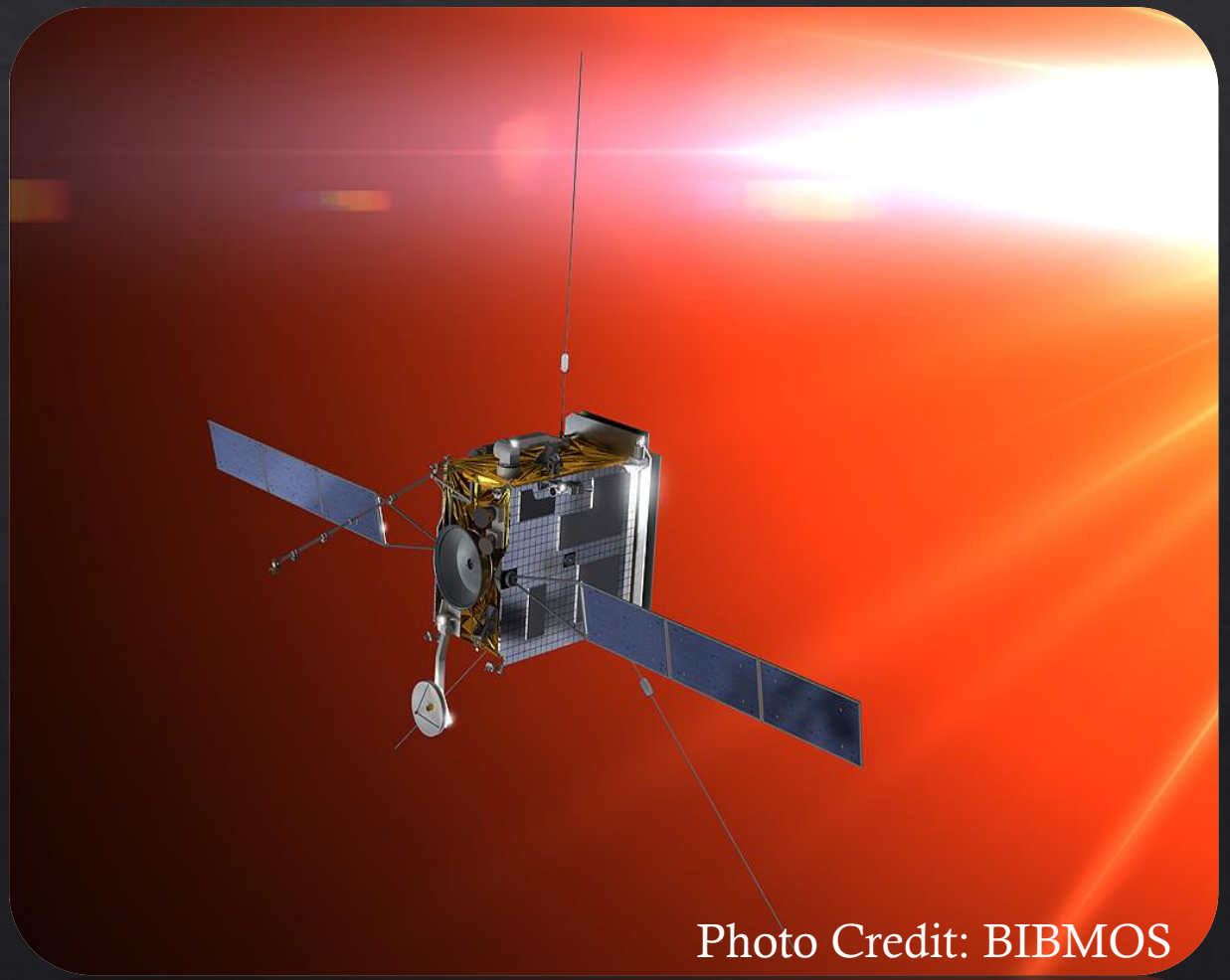


Photo Credit: BIBMOS

Solar Orbiter

Acknowledgements

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References

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