Solar Wind In the Outer Heliosphere

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BS in Physics: Clemson University, Clemson SC
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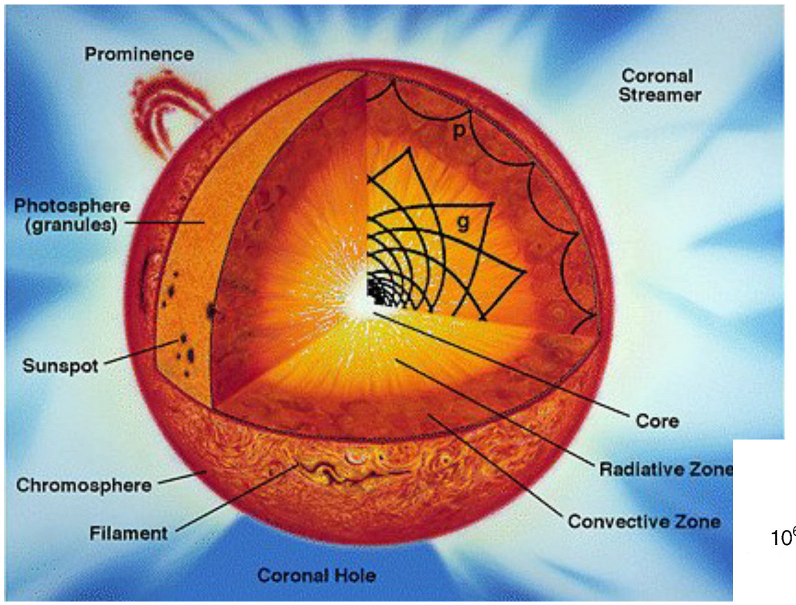
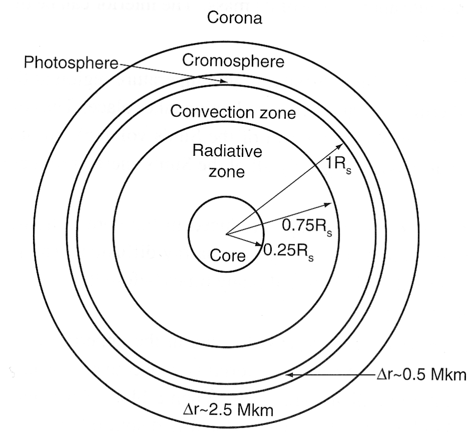
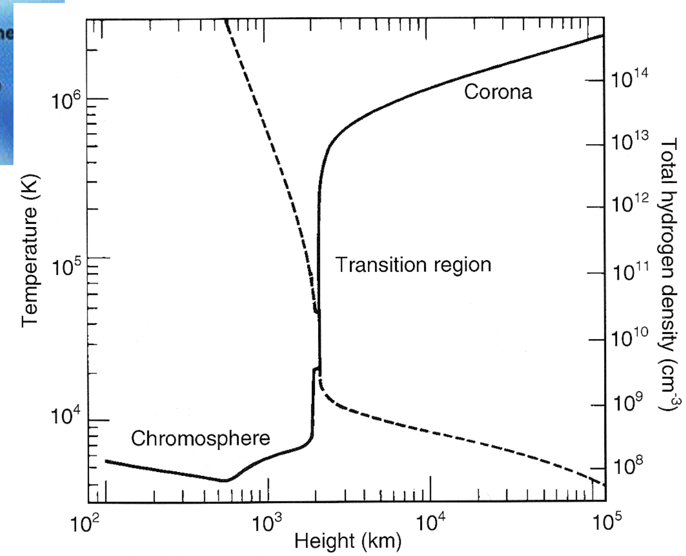
Sun and Corona

The Sun

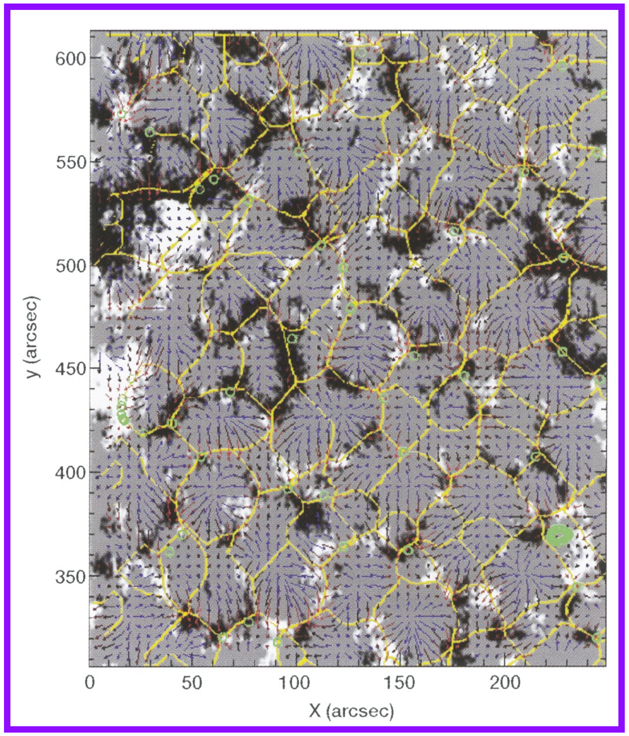




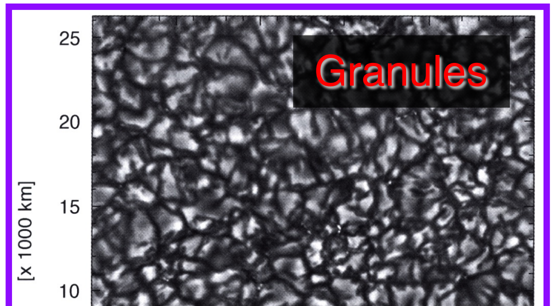
Hydrogen	92.1%
Helium	7.8%
Oxygen	0.061%
Carbon	0.030%
Nitrogen	0.0084%



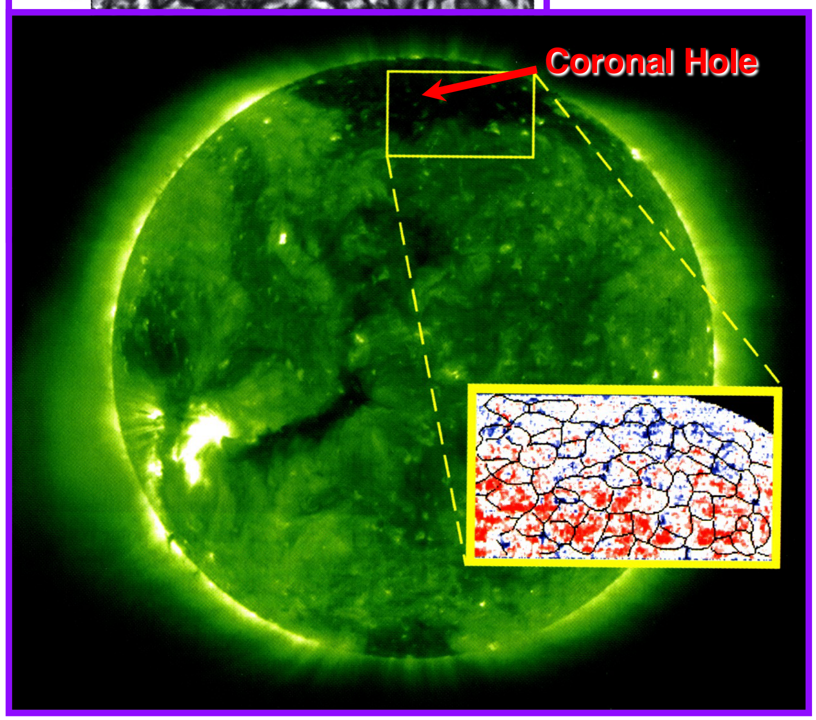
Granulation, and Outflow



Superganules convection cells;
chromospheric network



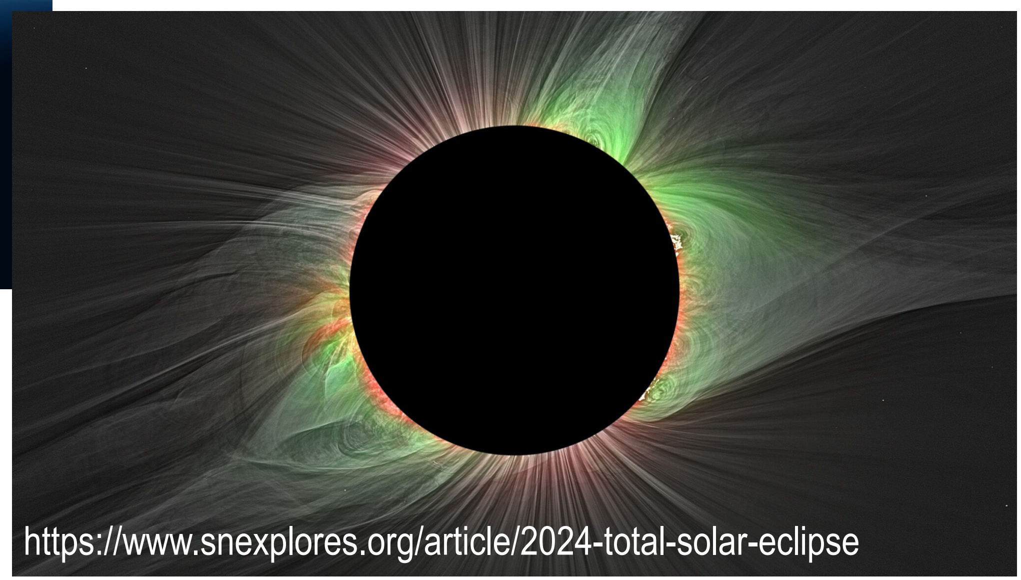
White rising
Dark falling



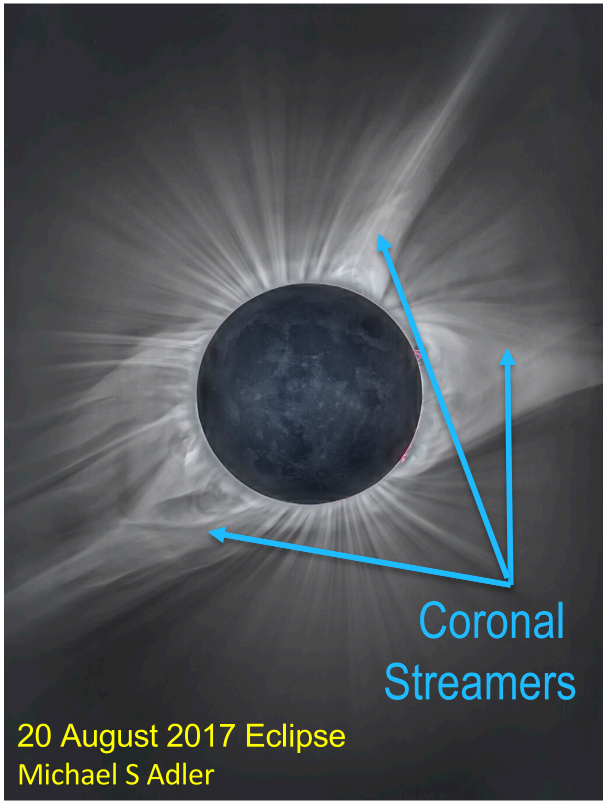
Strongest outflows (blue) at edges of chromospheric network.

Hassler et al., 1999

Corona the Solar Atmosphere



Solar Wind Source Regions: Coronal Streamers



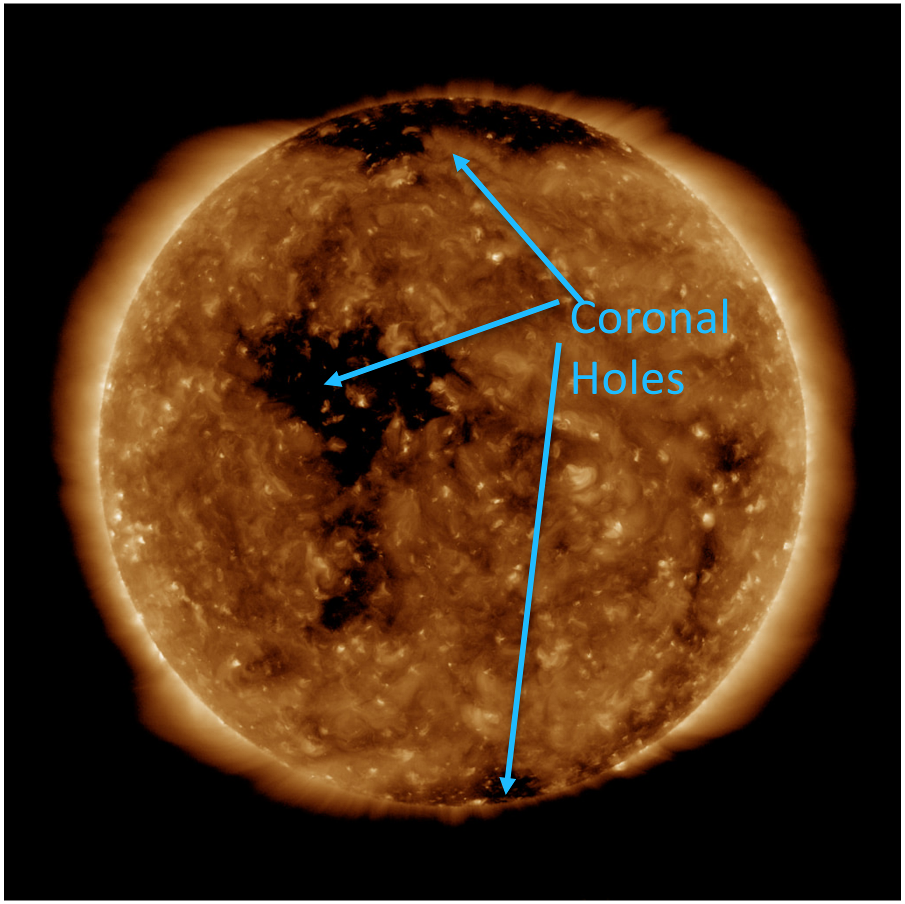
- Coronal streamers are bright regions in coronagraph and eclipse images.
- The slow wind (< 450 km/s) is more variable, cooler, more dense, and may have multiple sources such as the streamers and or edges of coronal holes.

Citizen Continental-America Telescopic Eclipse (CATE)
https://eclipse.boulder.swri.edu

Solar Wind at 1 au

Property at 1 AU	Slow wind	Fast wind
Speed (v)	~400 km/s	~750 km/s
Number density (n)	~10 cm^{-3}	~3 cm^{-3}
Flux (nv)	~3×10^{8} cm^{-2} s^{-1}	~2×10^{8} cm^{-2} s^{-1}
Magnetic field (Br)	~3 nT	~3 nT
Proton temperature (Tp)	~4×10^{4} K	~2×10^{5} K
Electron temperature(Te)	~1.3×10^{5} K (>Tp)	~1×10^{5} K (<Tp)
Composition (He/H)	~1 – 30%	~5%

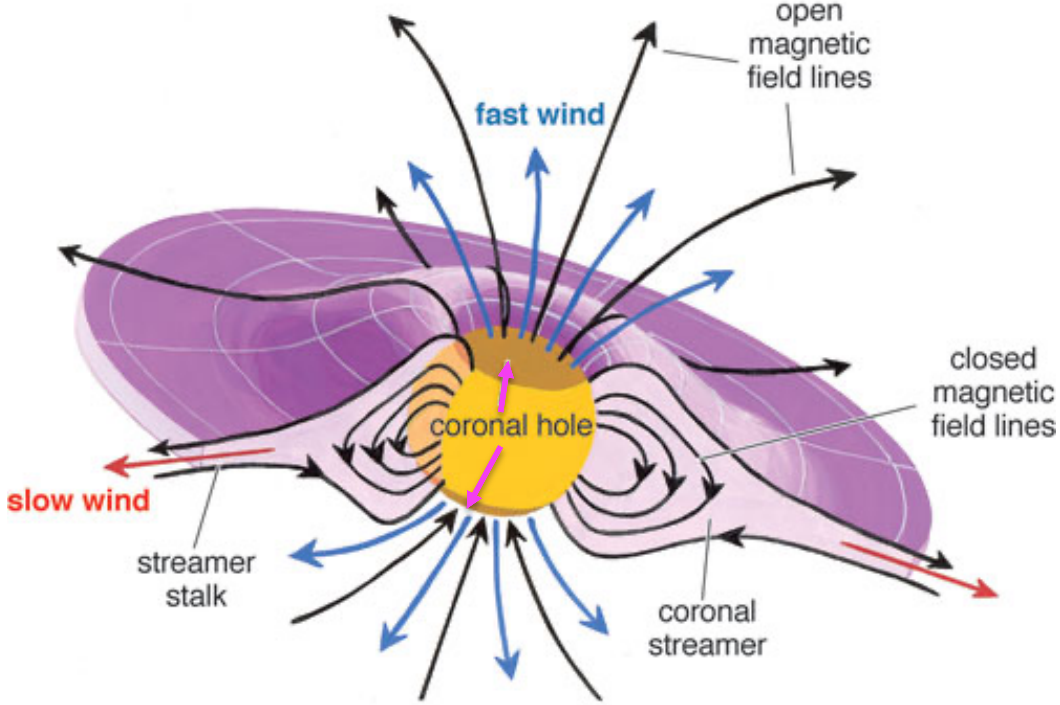
Solar Wind Source Regions: Coronal Holes



SDO/AIA/193Å EUV Filter

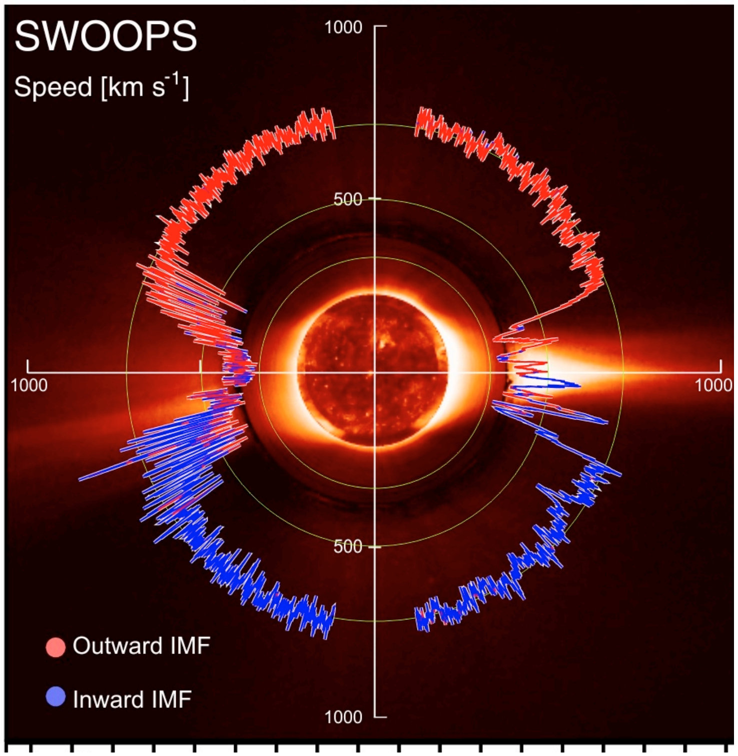
- Coronal holes are dark regions in EUV images of the Sun.
- Emit fast solar wind
- Fast solar wind is hotter and lower in density.
- Holes have open magnetic field lines.

Magnetic Field Lines



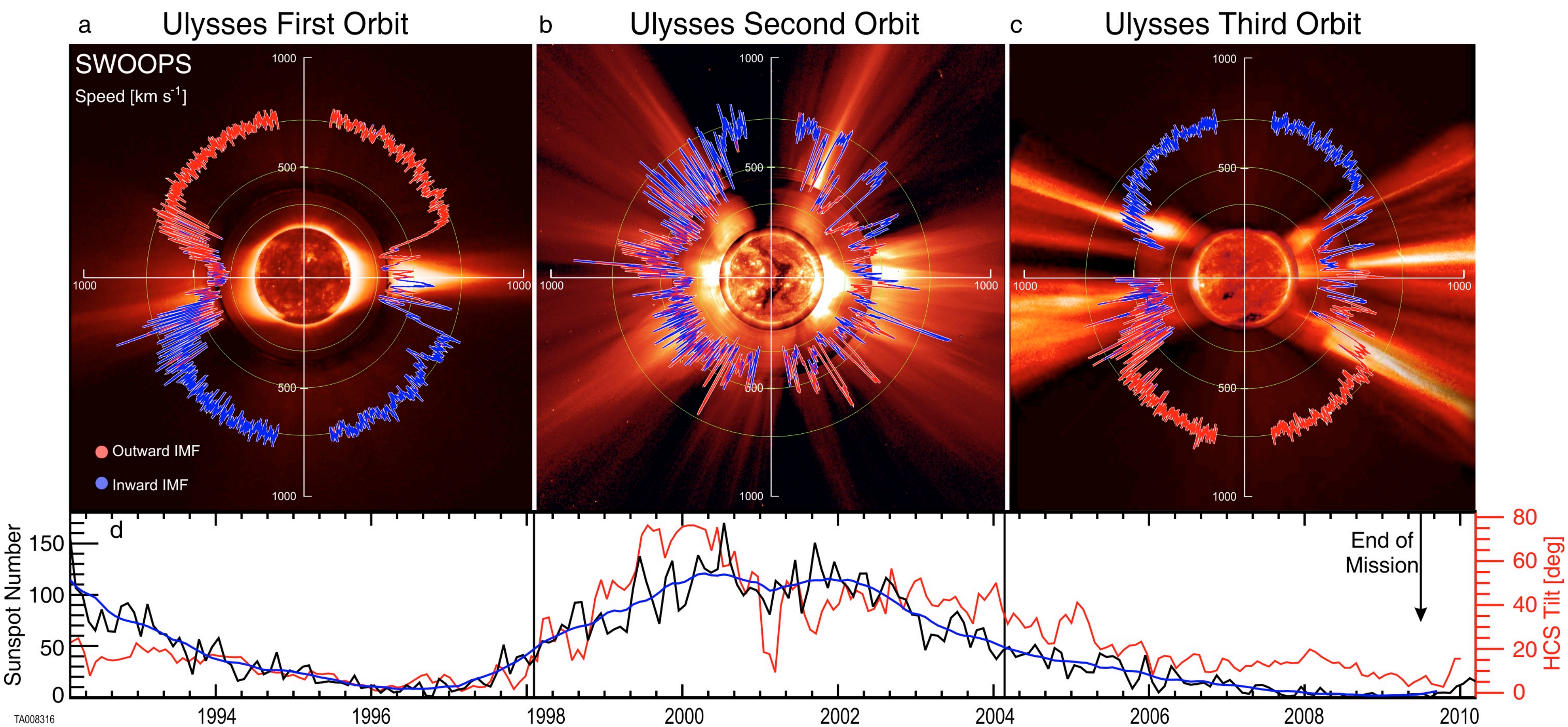
Tom Dunne

a Ulysses First Orbit



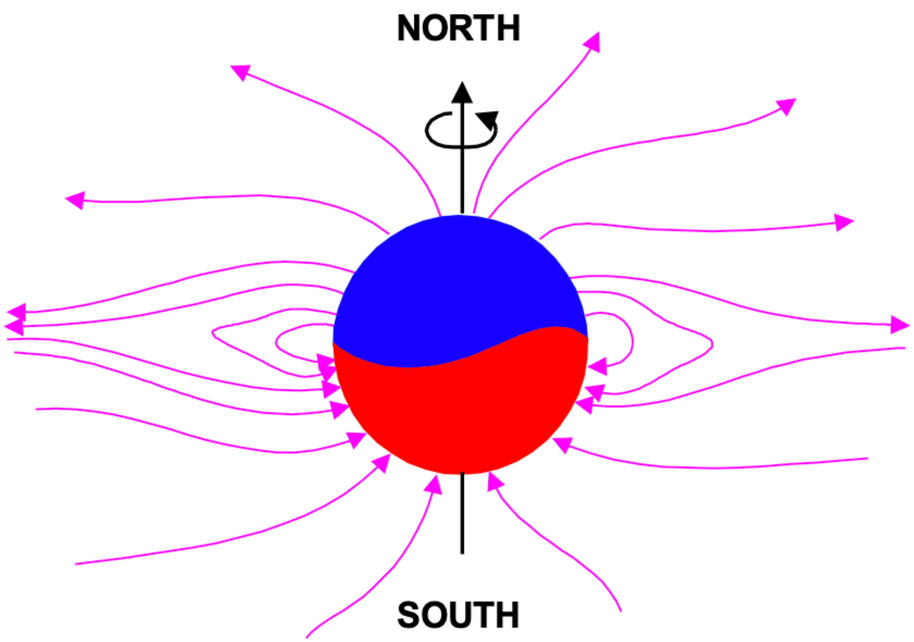
McComas et al. 2008

Solar Wind Speed and Coronal Structures: More Complex at Solar Maximum

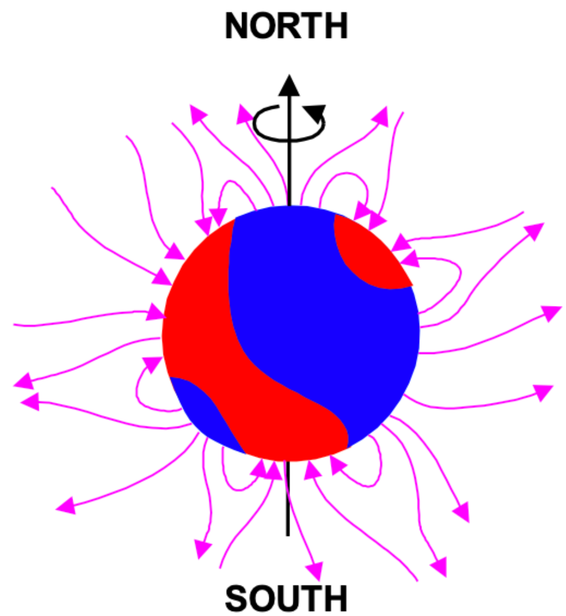


McComas et al. 2008

Magnetic Field Lines: Solar Minimum vs Solar Maximum

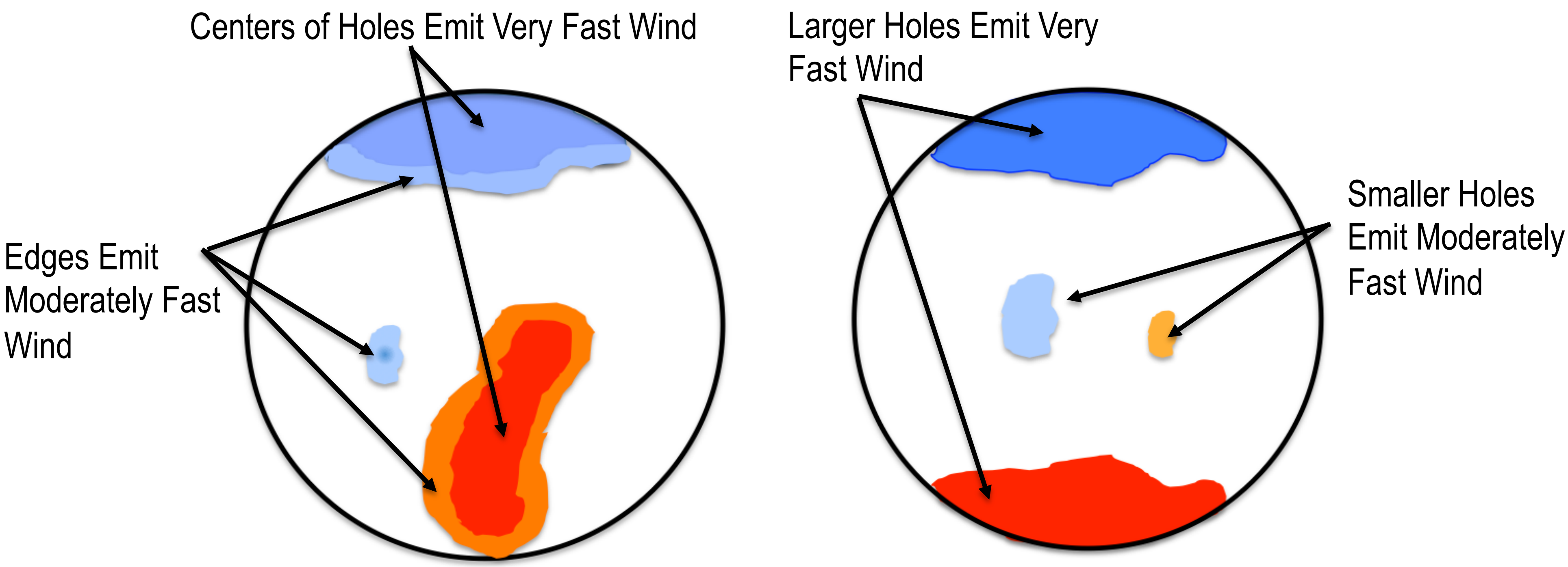


CORONAL MAGNETIC FIELD LINES AT SOLAR MINIMUM ACTIVITY



CORONAL MAGNETIC FIELD LINES AT SOLAR MAXIMUM ACTIVITY

Coronal Holes and The Fast Wind



- Moderately fast wind (450-650 km/s) from small low latitude coronal holes and/or from the edges of larger coronal holes.
- Open magnetic field lines bend more at the edges of coronal holes.
- The centers of large polar coronal holes (and their low latitude extensions)emit very fast solar wind with speeds from 650 to 860 km/s.

Wang-Sheeley-Arge Empirical Speed Forecast Formula

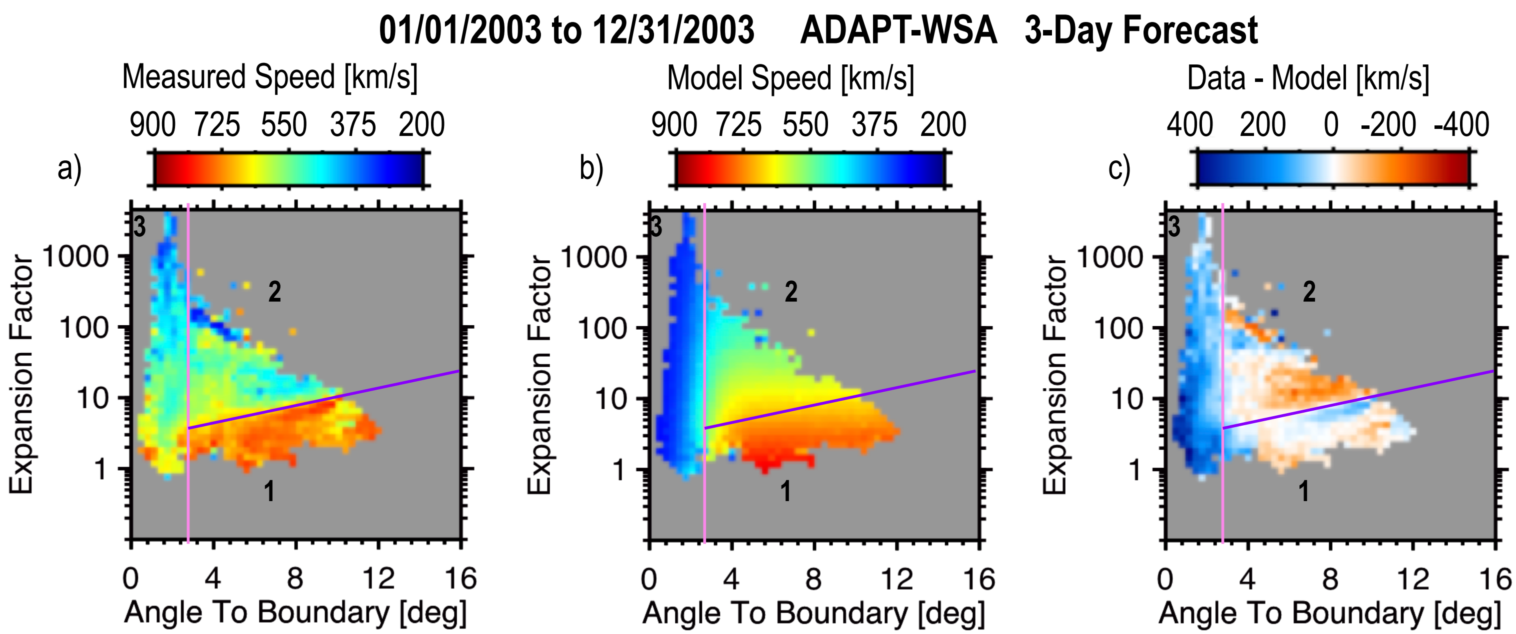
$$v_{\mathrm{wsa}}(f_{\mathrm{p}}, d; v_0, v_1, \beta, \gamma, w, \delta) = v_0 + \frac{v_1 - v_0}{(1 + f_{\mathrm{p}})^{\alpha}} \cdot \left\{ \beta - \gamma \cdot \exp[-(d / w)^{\delta}] \right\}^3$$

(Reiss et al., 2019)

Dependent Variables:

- *fp* -expansion factor; how much the field lines bend
- d – separation angle to the open-closed field line boundary (~angle to edge of the coronal hole)
- Other quantities are constants/fit parameters

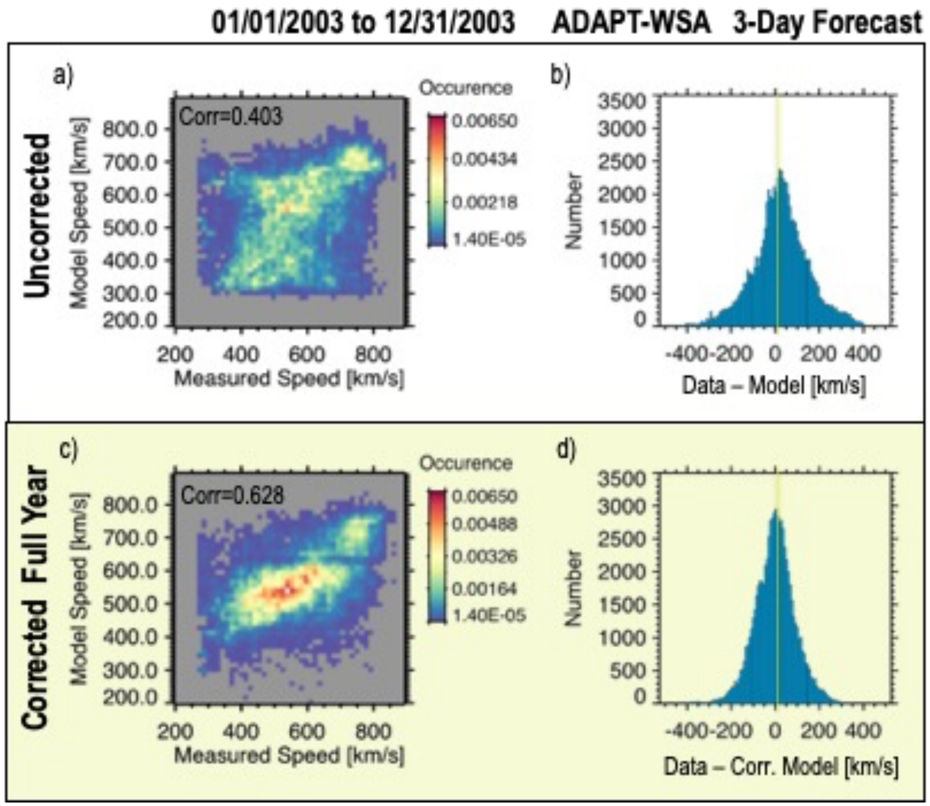
Speed and Residual Error Dependence on Expansion Factor and Angle to the Boundary



Elliott et al. 2022

- <u>Left:</u> Data sorted by expansion factor (fp) and angle to the coronal hole boundary (d).
- <u>Middle:</u> ADAPT-WSA 3-Day forecast vs. fp and d (visual representation of WSA formula).
- <u>Right:</u> Residual speed errors vs. fp and d.

Overview of Residual Errors With and Without Corrections



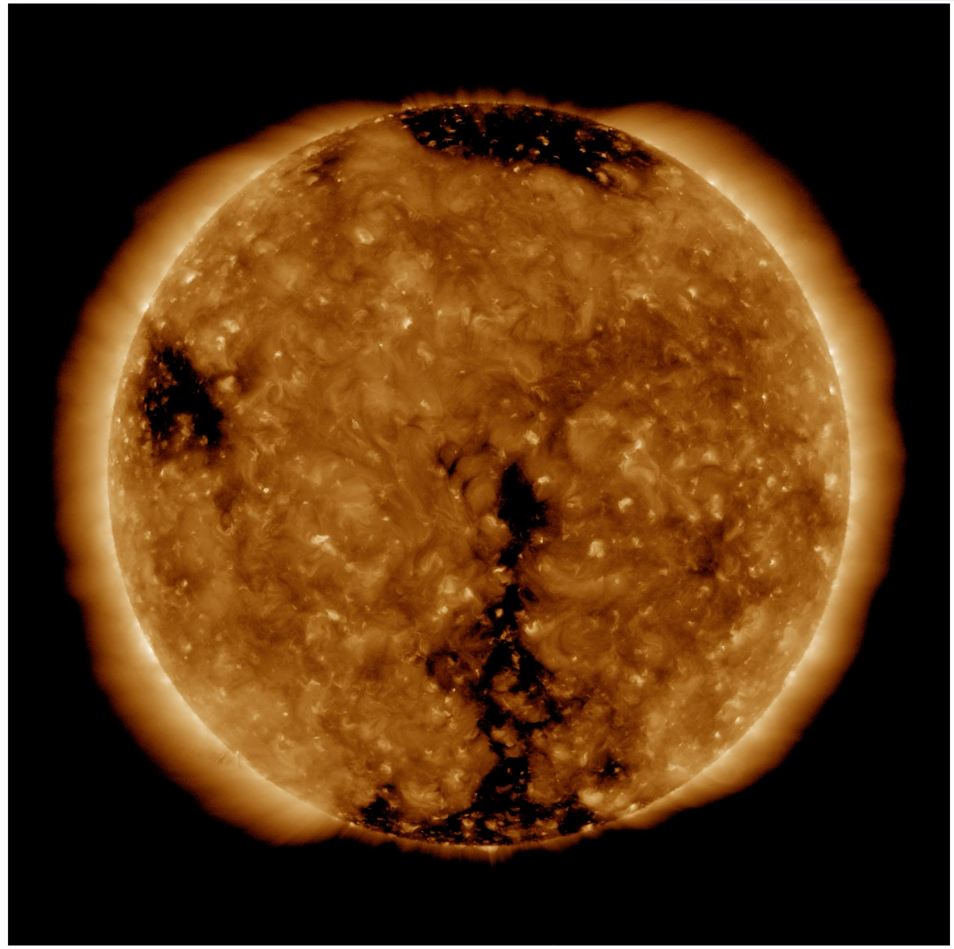
Elliott et al. 2022

- Overall comparison between ADAPT-WSA (top) and corrected ADAPT WSA speeds (bottom) vs. the measured speed, and residual error histograms.

Solar Rotation

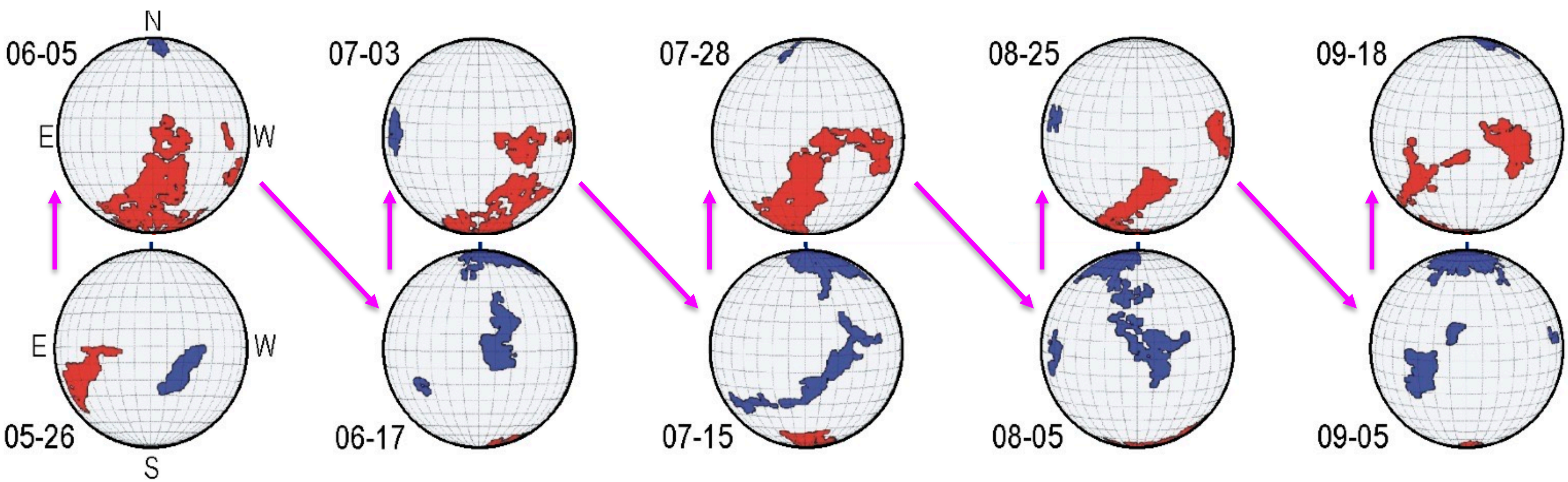
- One solar rotation takes 25.38 days.

- In measurements taken at Earth, or the Earth system, or L1 a period of 27 days will be observed since Earth moves around the Sun as the Sun rotates.



SDO/AIA/193Å EUV Filter

Solar Features Evolve and Change As the Sun Rotates



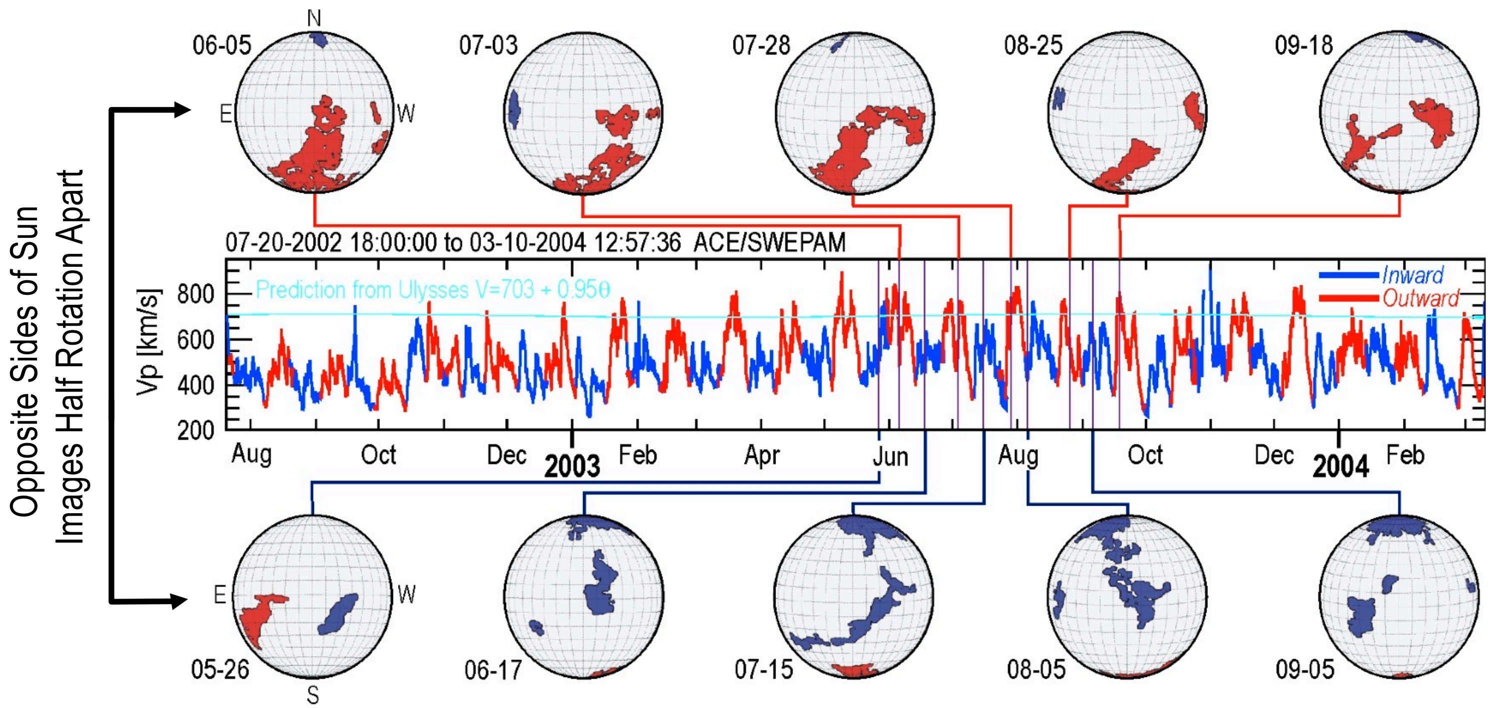
Adapted from Elliott et al., 2012

Sun and Corona: Summary and Conclusions

1. The corona is very hot.
2. The fast wind is associated with coronal holes.
3. Two sources of slow wind are coronal streamers and edges of coronal holes
4. Large polar coronal holes emit very fast wind.
5. Smaller equatorial coronal holes emit moderately fast wind
6. The solar rotation rate is 25.38 days.

Solar Wind and Inner Heliosphere

Fast and Moderately Fast Wind From Coronal Holes

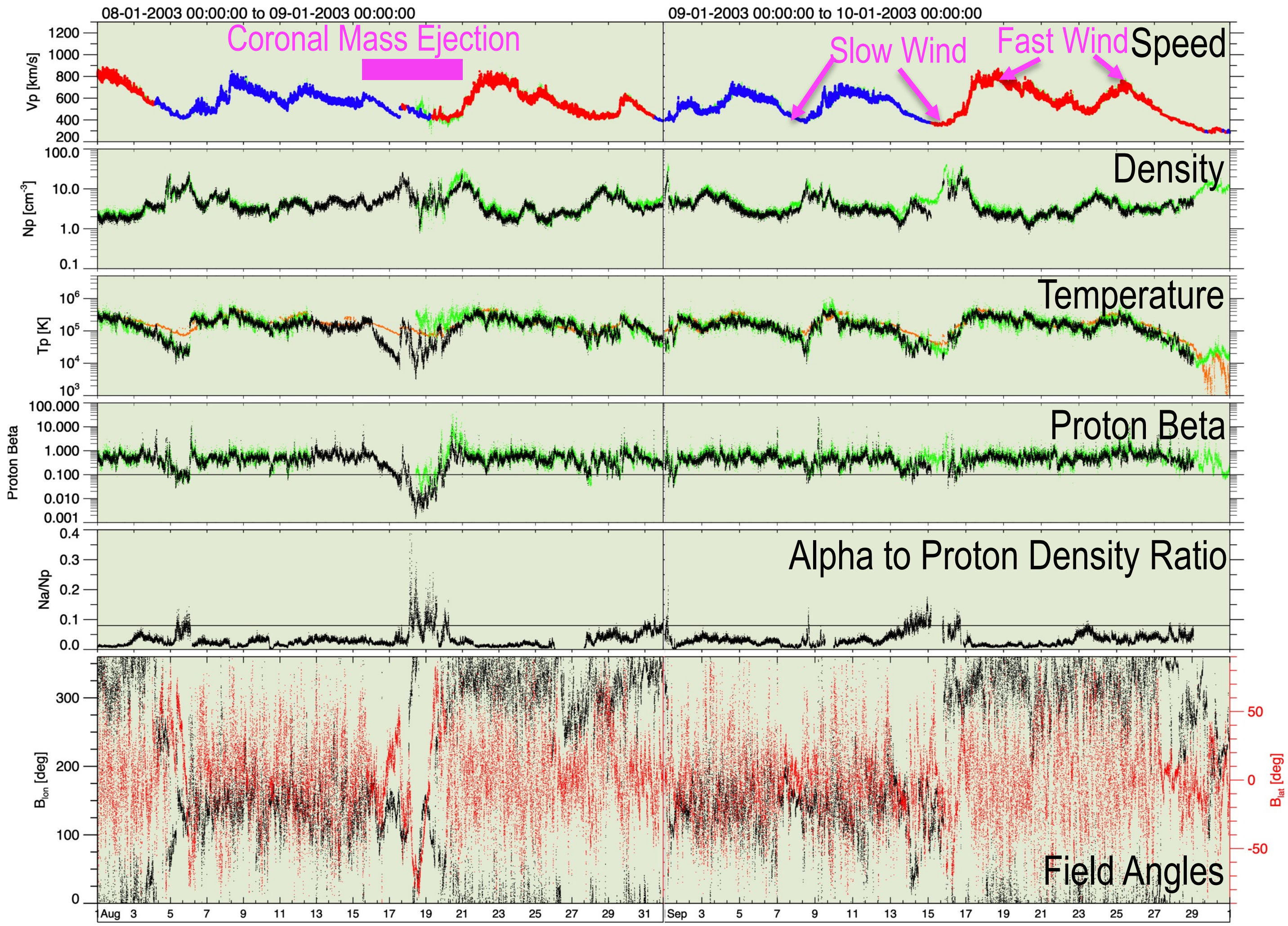


Large polar coronal hole extensions emitting very fast wind.

Small equatorial holes emitting moderately fast wind.

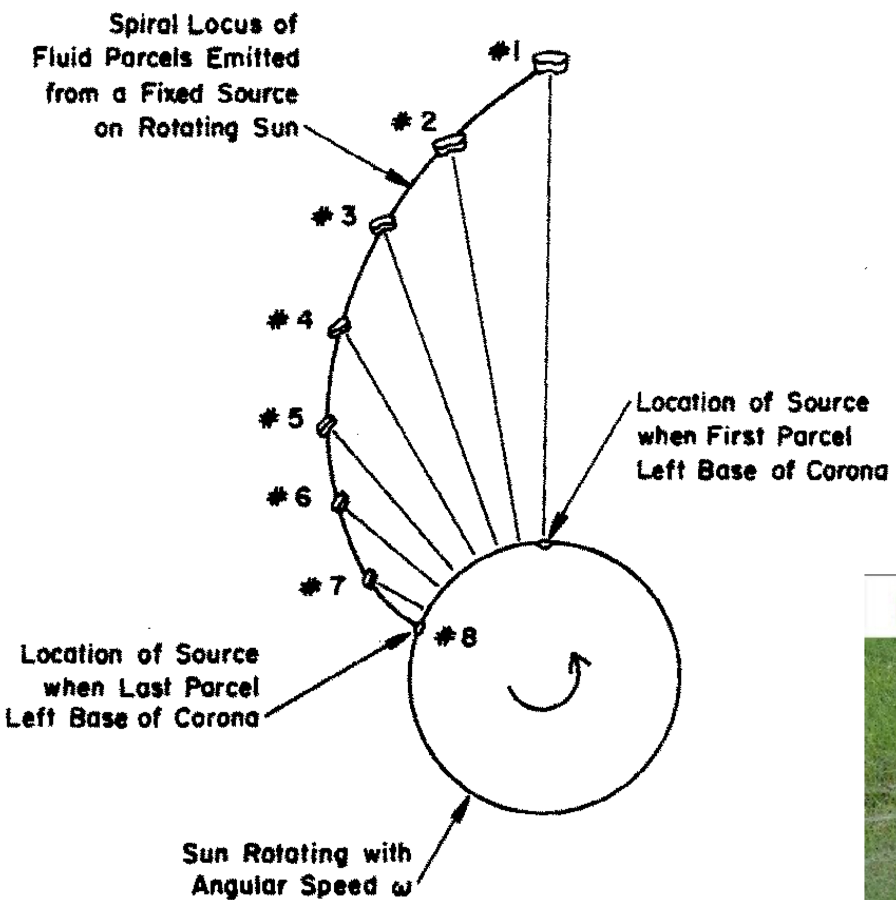
Elliott et al., 2012

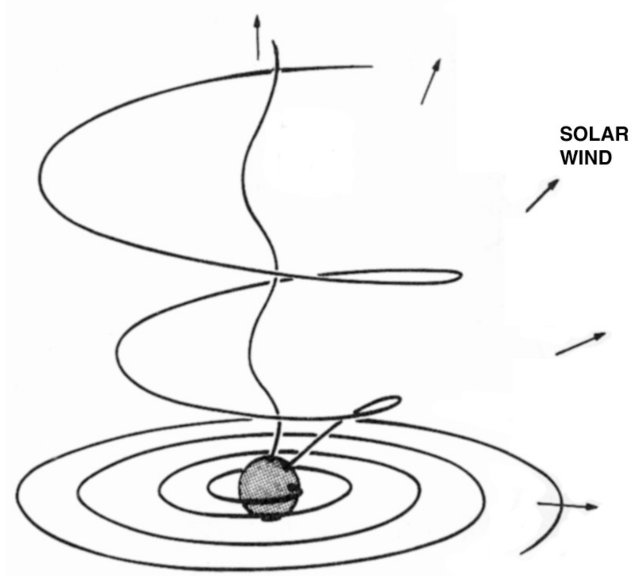
Time Series of Solar Wind Parameters



- Fast Wind is hotter and less dense than the slow wind.
- Alternating pattern of fast and slow wind owing to solar rotation.

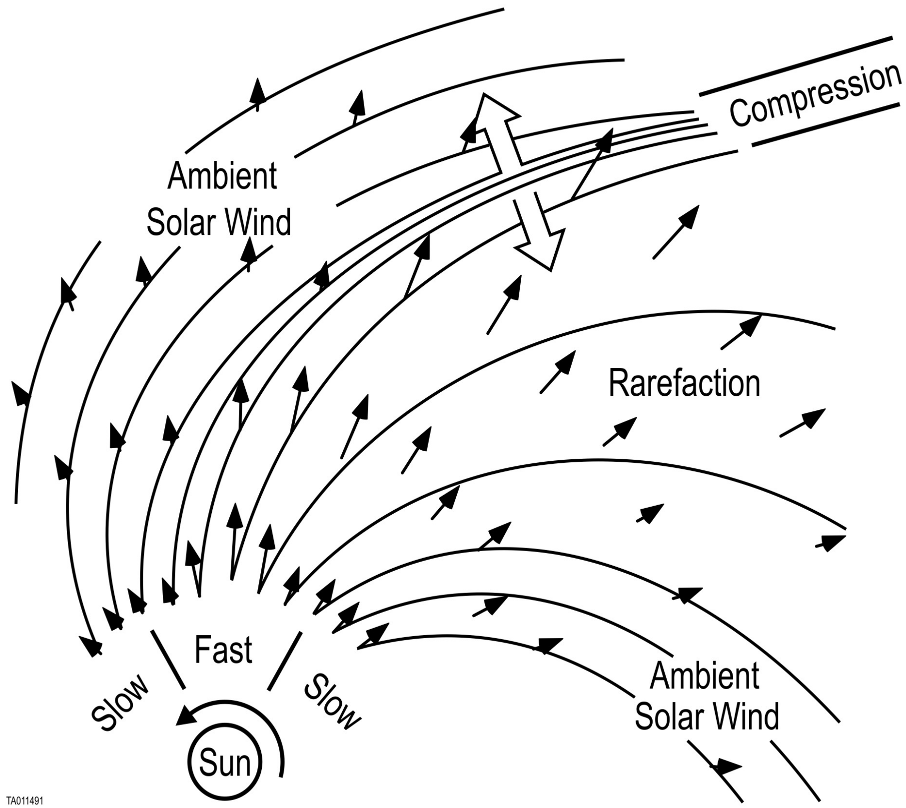
Parker Spiral & Interplanetary Magnetic Field





https://www.youtube.com/watch?v=g2c-qOq8Pac

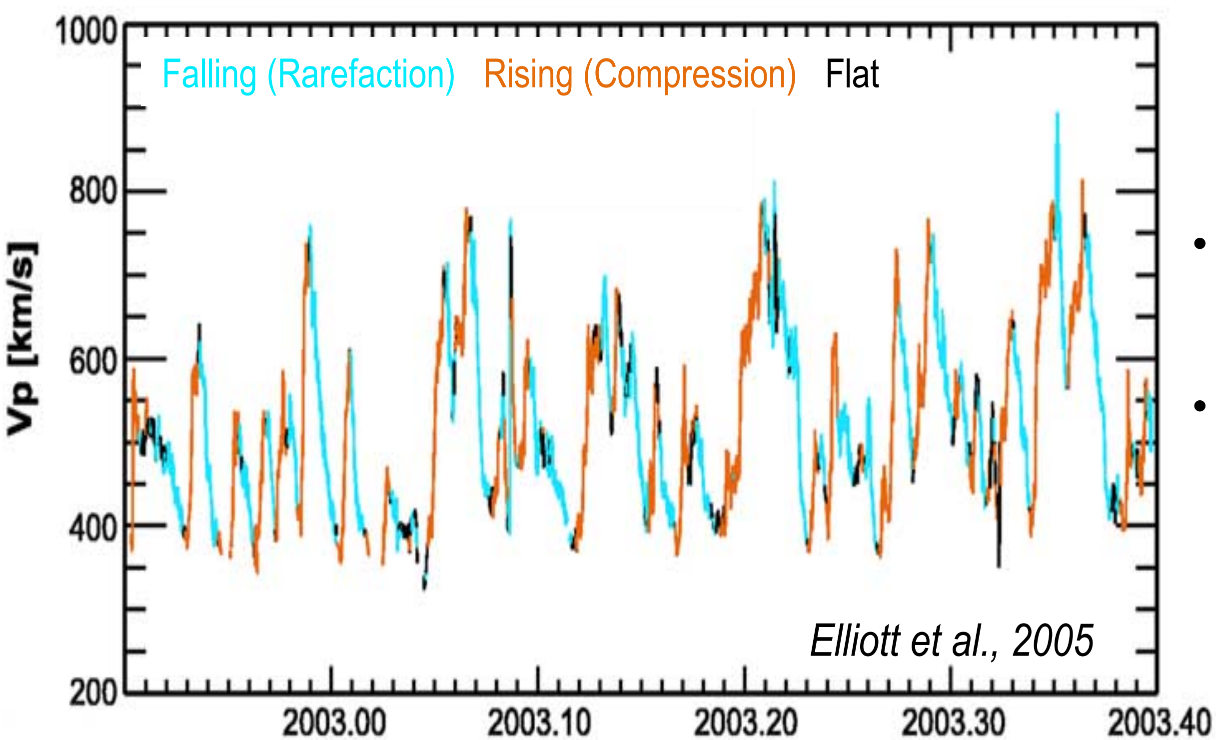
Dynamic Interactions Occur Between the Sun and Earth



Pizzo, 1978

- The solar wind primarily moves in the radial direction (black arrows).
- The solar wind carries with it the magnetic field giving rise to the Interplanetary Magnetic Field (IMF) shown as black lines.
- Since the Sun rotates a fast wind region can rotate to the same longitude where previously slow wind was emitted.
- The fast wind as it moves away from the Sun can catch up to the slow wind emitted earlier and create a compression region.
- Compression regions are hotter, more dense and have enhanced field strength.

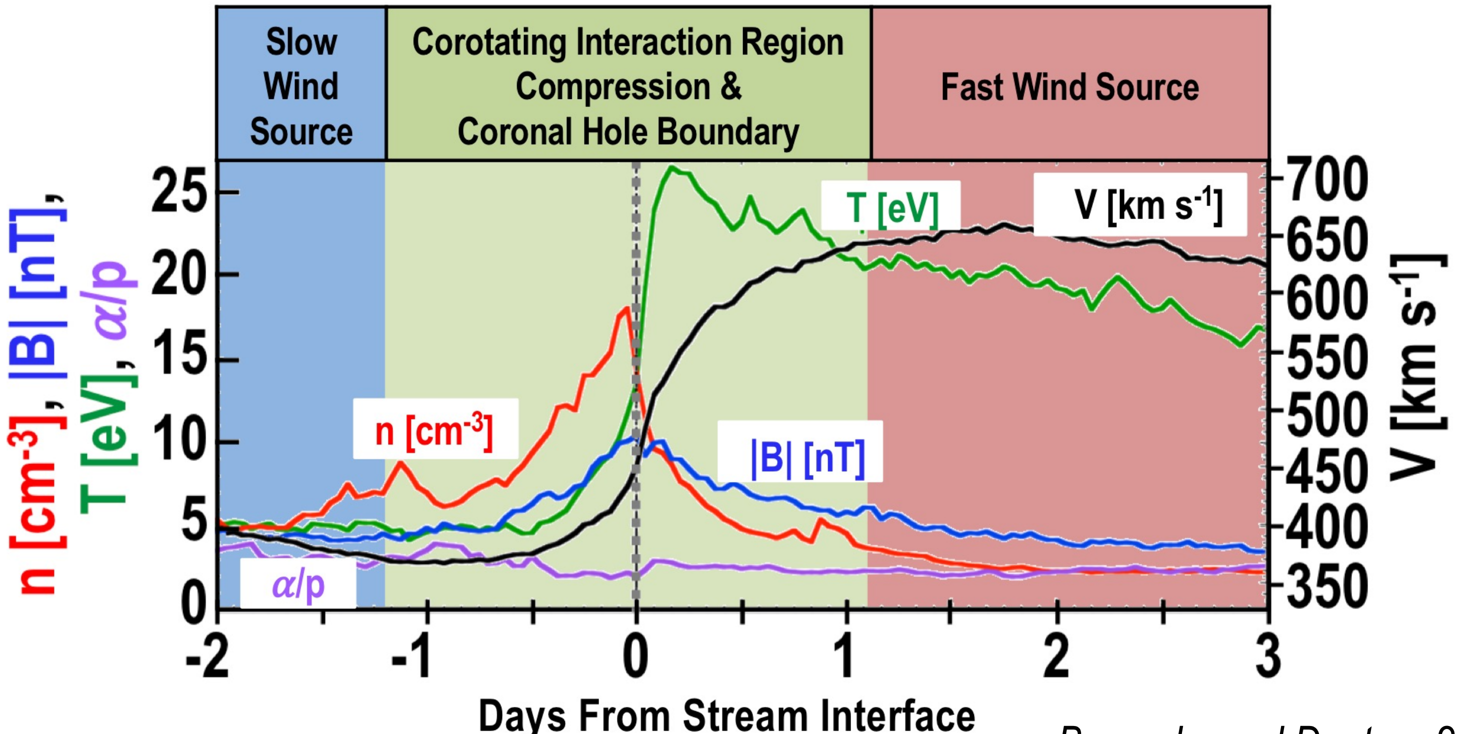
Using the Steepness Speed Time Profile To Reveal Dynamic Interactions



- Determine steepness from examining <dV/dt> in 2-day windows
- Slide the window for every time step (1 hour)

We can use the steepness (dV/dt) of the rise and fall of the solar wind speed profile to identify compressions (rising) and rarefactions (falling).

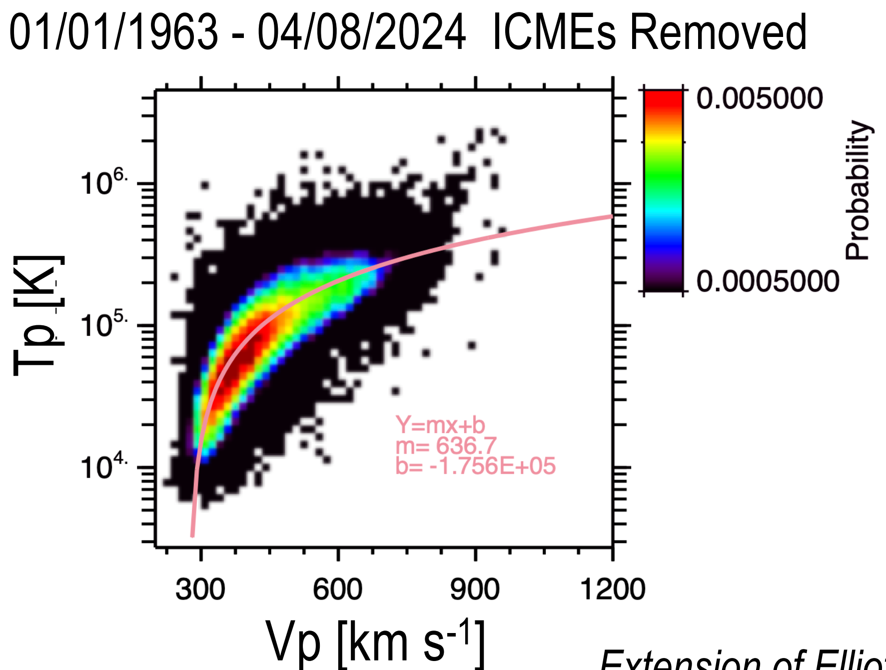
Dynamic Interactions and Source Properties

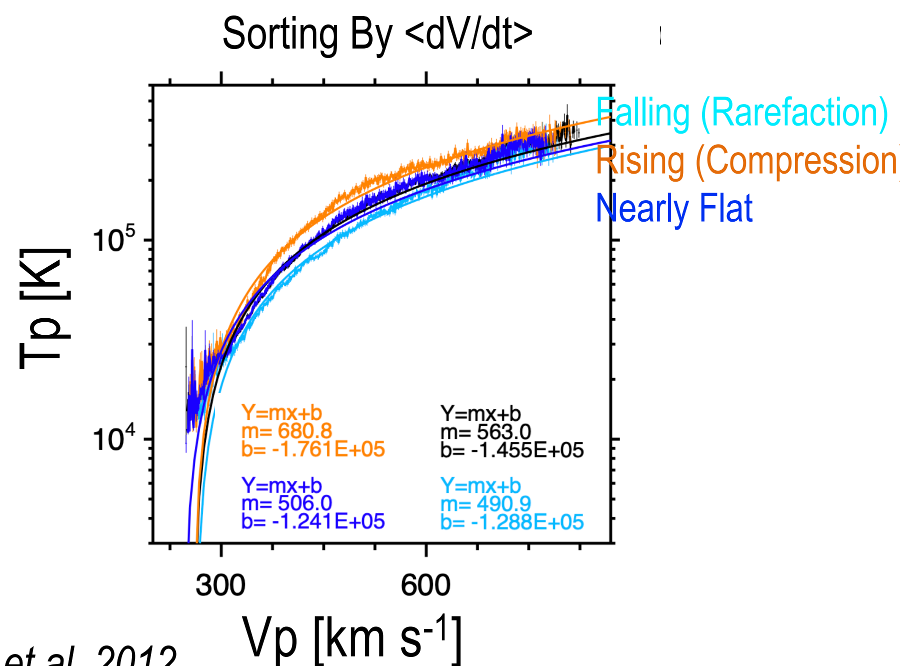


Borovsky and Denton, 2010

Superposed epoch analysis of 27 CIRs illustrates contributions of source properties and dynamic interactions, which produce correlations amongst solar wind and IMF parameters.

Temperature-Speed Relationship



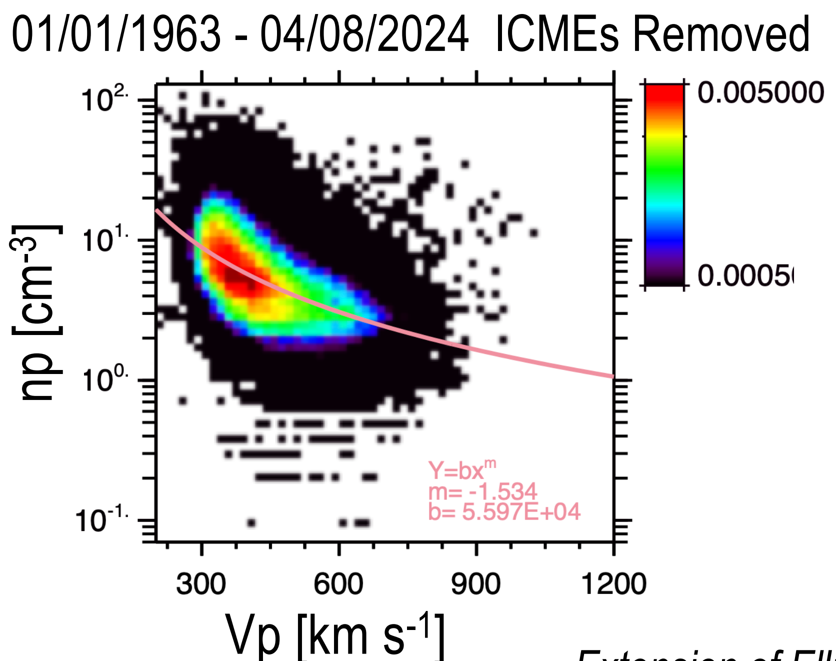


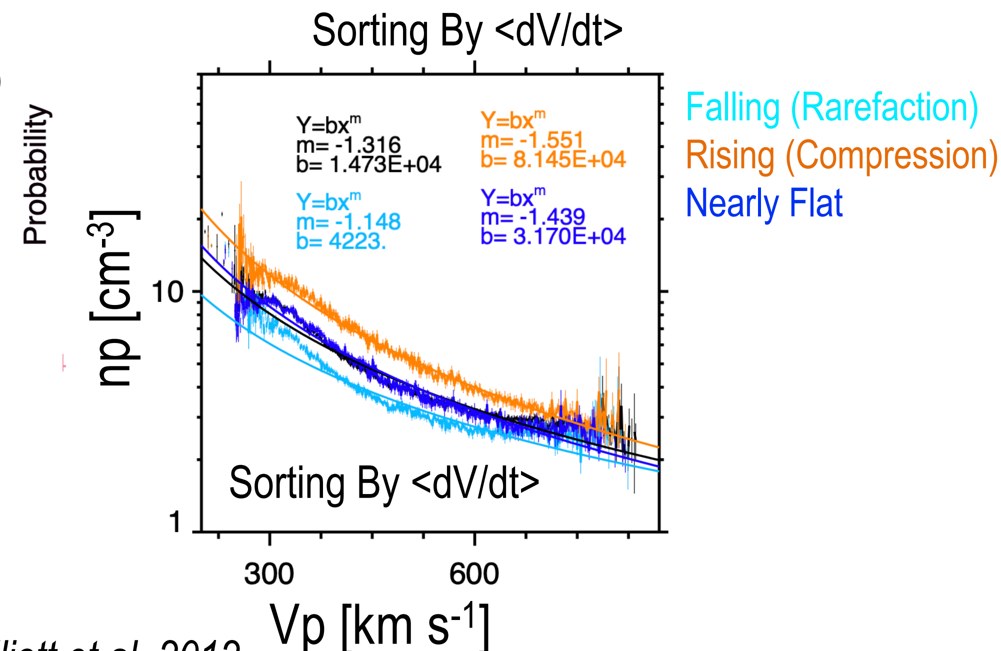
Extension of Elliott et al. 2012

- **Linear** relationship between T and V.
- Sorting by the 2-day average of $<dV/dt>_{2day}$ improves the ability to reproduce T and V.

- Rising profiles (orange) $<dV/dt>_{2day}$ > 7000km/s/year
- Falling profiles (light blue) $<dV/dt>_{2day}$ < - 7000km/s/year
- Flat profiles (dark blue) $|<dV/dt>_{2day}| \leqq$ 7000km/s/year
- All the data (black)

Density-Speed Relationship

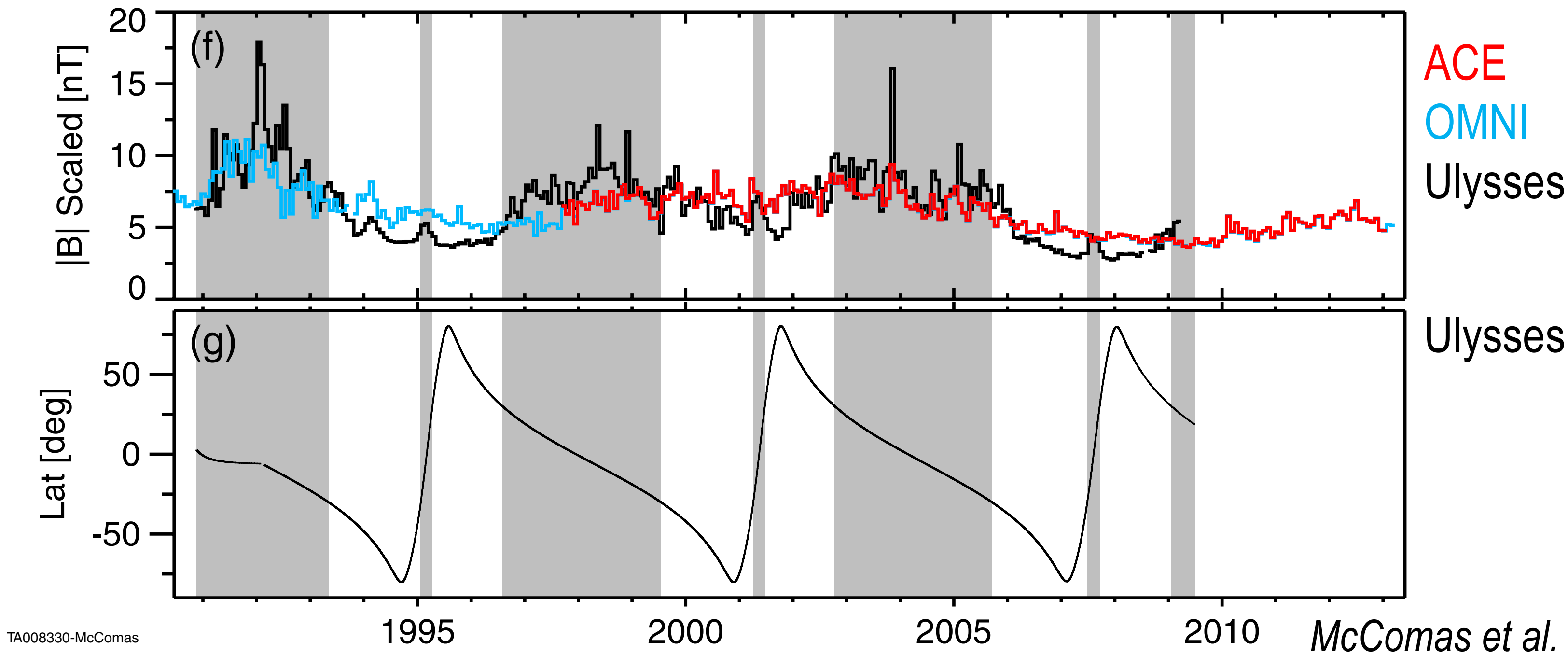




Extension of Elliott et al. 2012

- **Power Law** relationship between n and V.
- Sorting by the 2-day average of $<dV/dt>_{2day}$ improves the ability to reproduce T and V.
- Rising profiles (orange) $<dV/dt>_{2day}$ > 7000km/s/year
- Falling profiles (light blue) $<dV/dt>_{2day}$ < - 7000km/s/year
- Flat profiles (dark blue) $|<dV/dt>_{2day}| \leqq$ 7000km/s/year
- All the data (black)

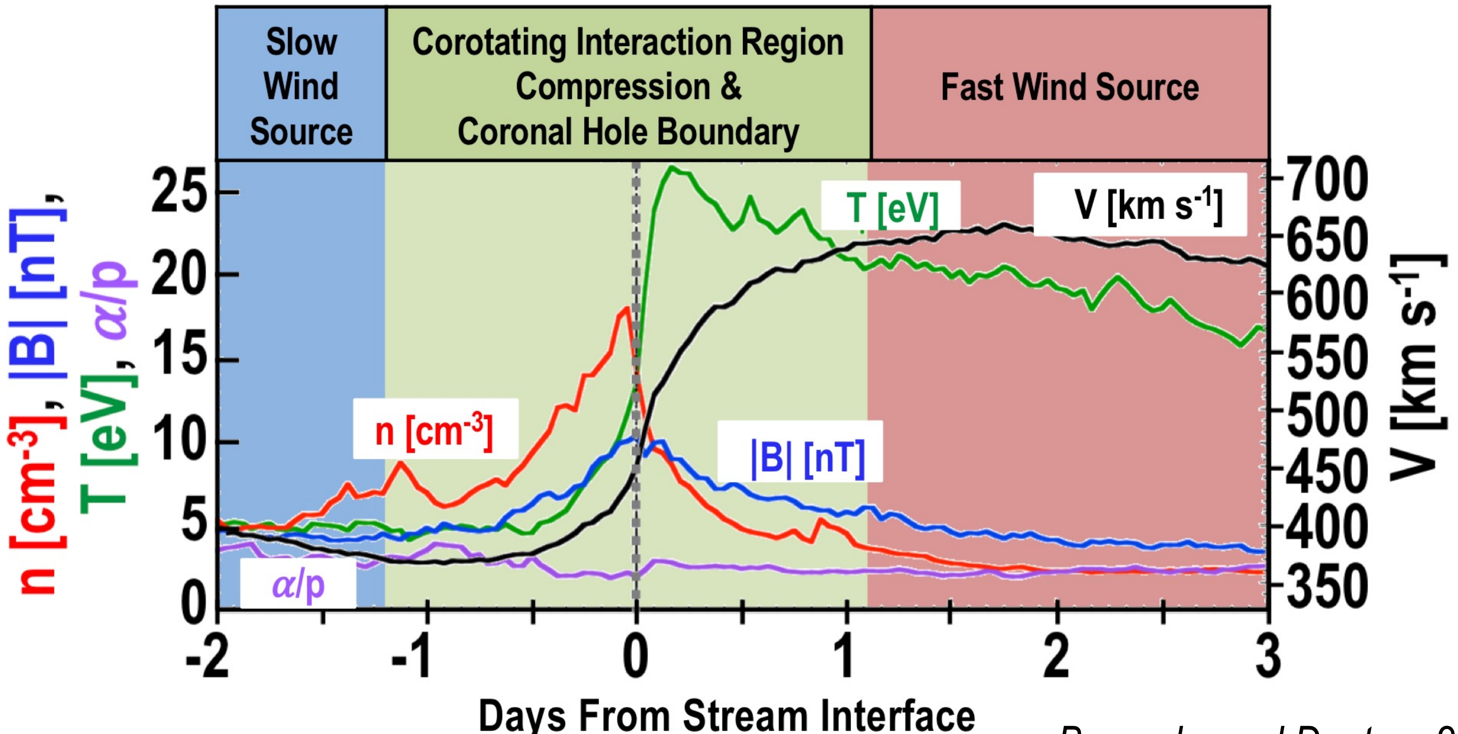
Long Term Trends in IMF Field Strength (|B|)



McComas et al. 2013

- The magnitude of the field |B| has some long term trends that track the long term trends for the Sun.
- These means there are long term baseline trends in |B| that affect the baseline field strength.
- Other variations in |B| observed in situ reflect the field from an individual structure and a dynamic interactions.

Dynamic Interactions and Source Properties

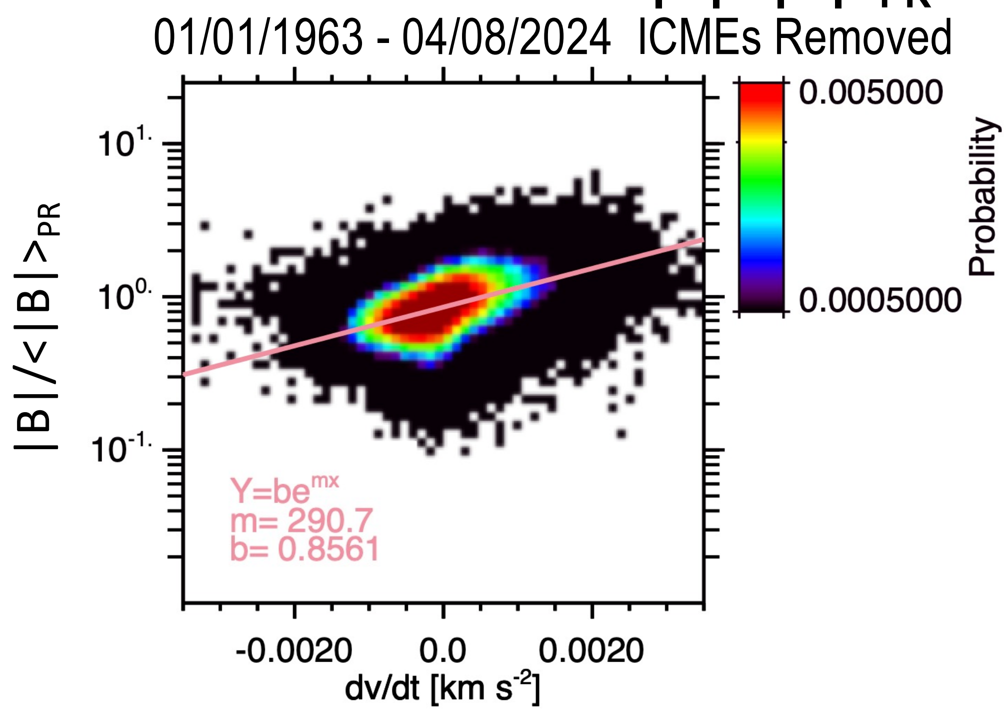


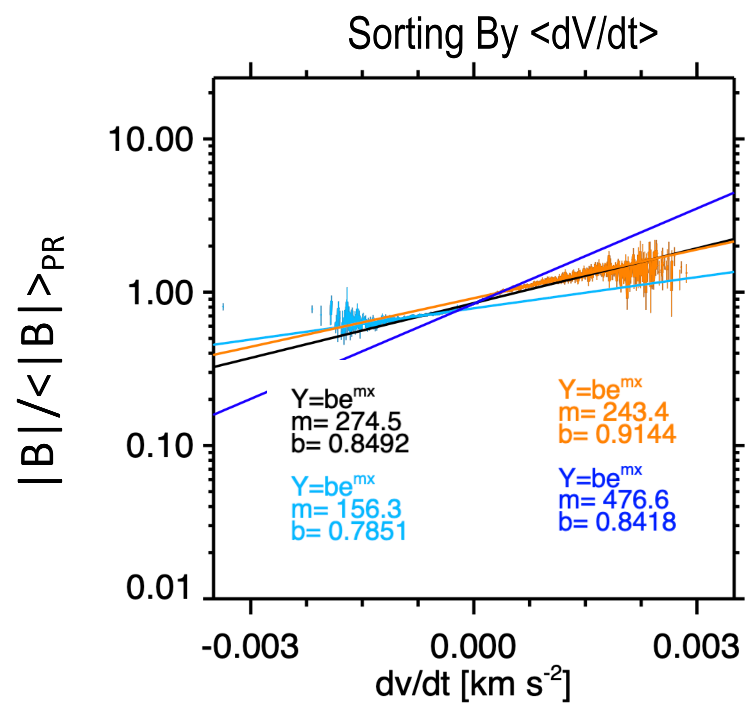
Borovsky and Denton, 2010

Superposed epoch analysis of 27 CIRs illustrates contributions of source properties and dynamic interactions, which produce correlations amongst solar wind and IMF parameters.

Estimate the Field Strength Using the Steepness in the Speed-Time Profile

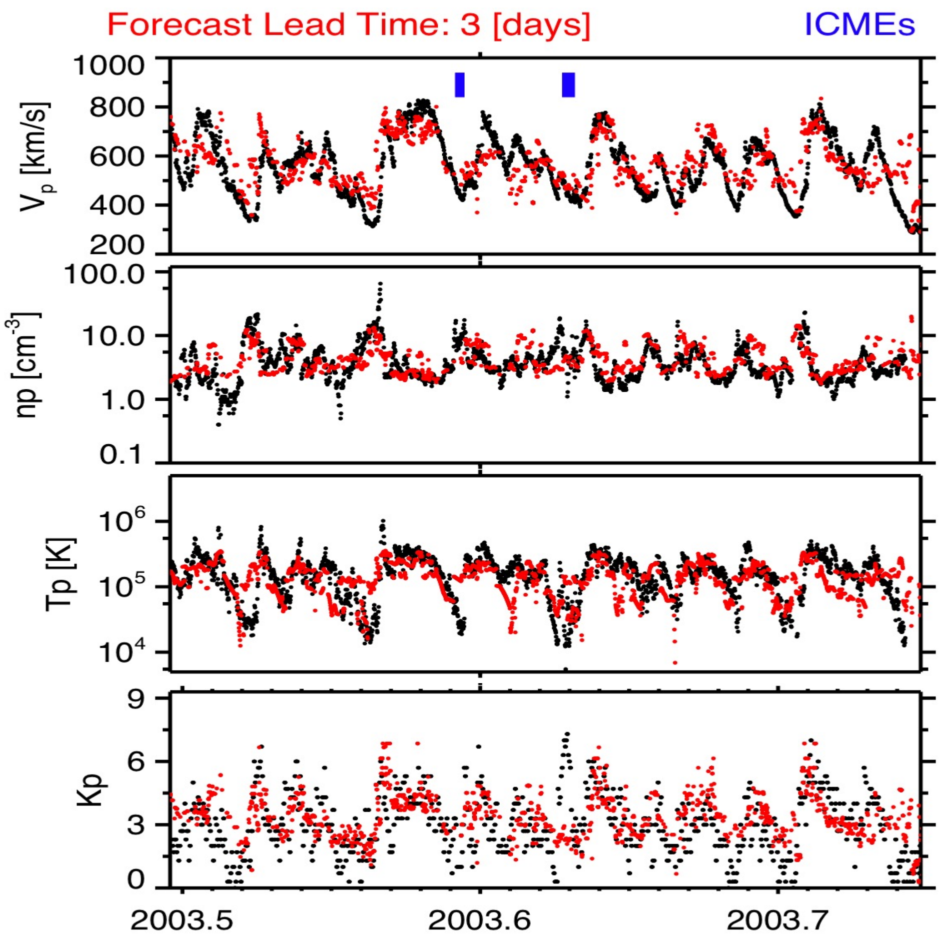
$|B|/\langle|B|\rangle_{PR}$ vs. $\langle dV/dt\rangle$



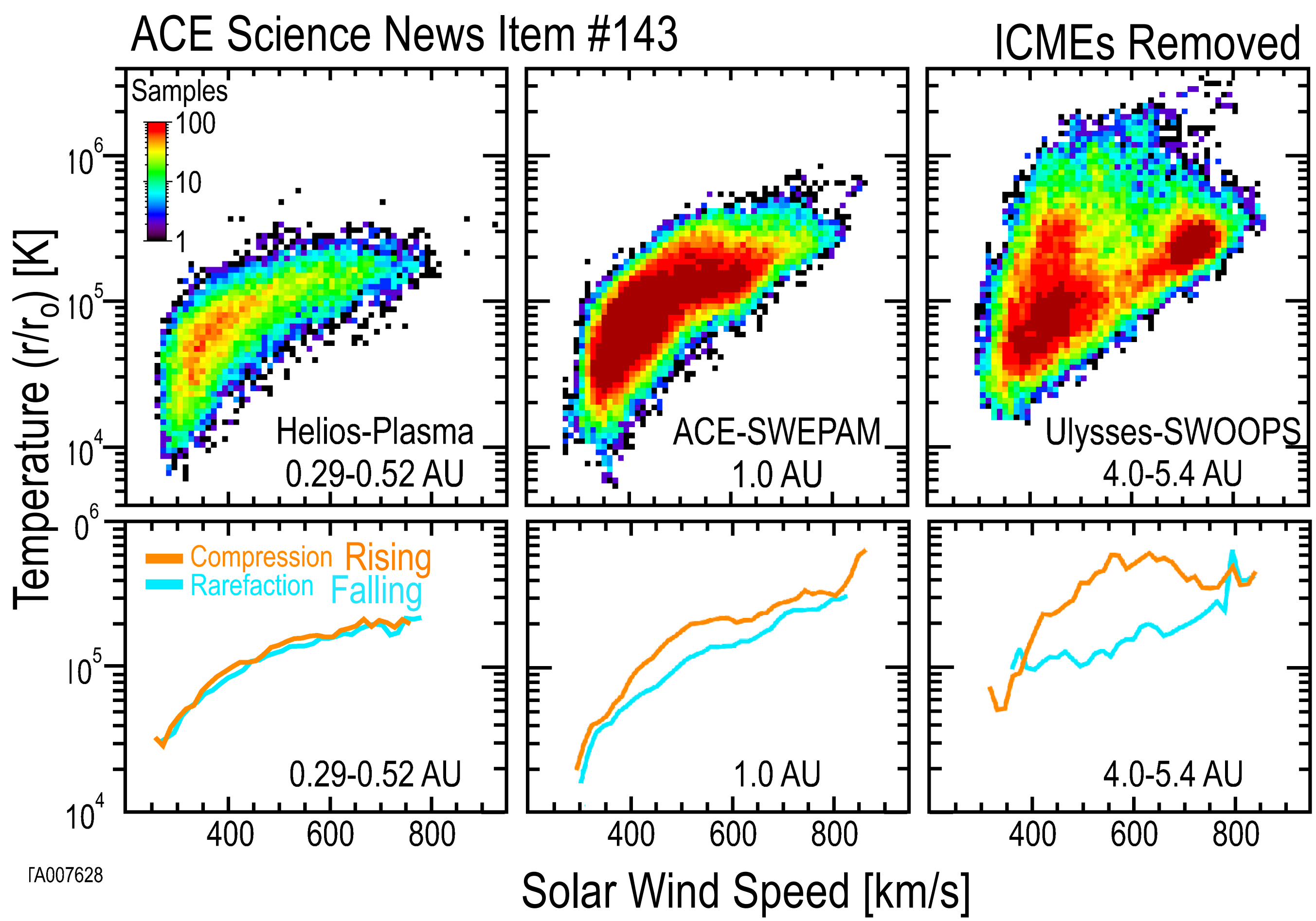


- Normalize interplanetary magnetic field strength (|B|) by the average value over the prior solar rotation to remove most of the very long term trends (solar cycle and greater) present in |B|.
- $|B|/\langle|B|\rangle_{\text{prior rot}}$ is plotted vs $\langle dV/dt\rangle_{2day}$ since we know that |B| typically peaks when in the middle of the rise in speed.

Forecast Test Using Corrected Speeds & Statistical Relationships (Zoom)

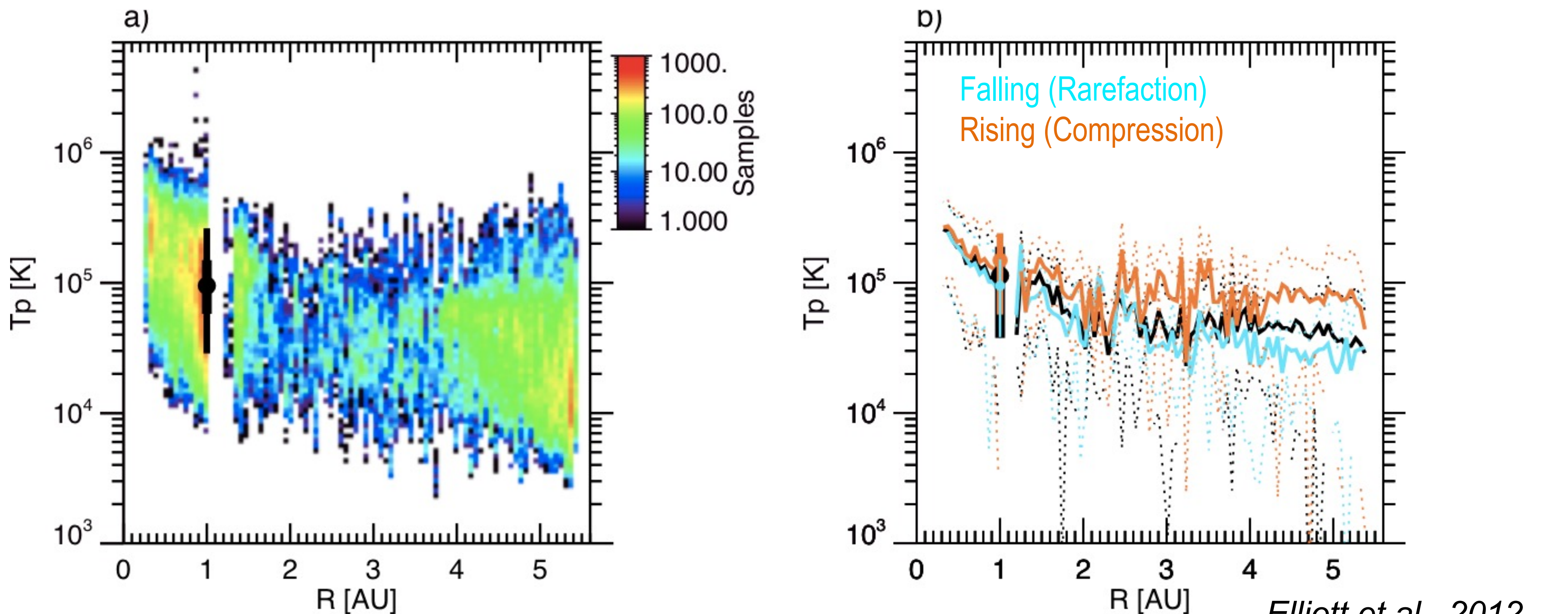


Radial Trends In T-V Relationship
Intermediate Wind Heated in Rises/Compressions



Adapted from Elliott et al., 2012

Temperature Radial Profile

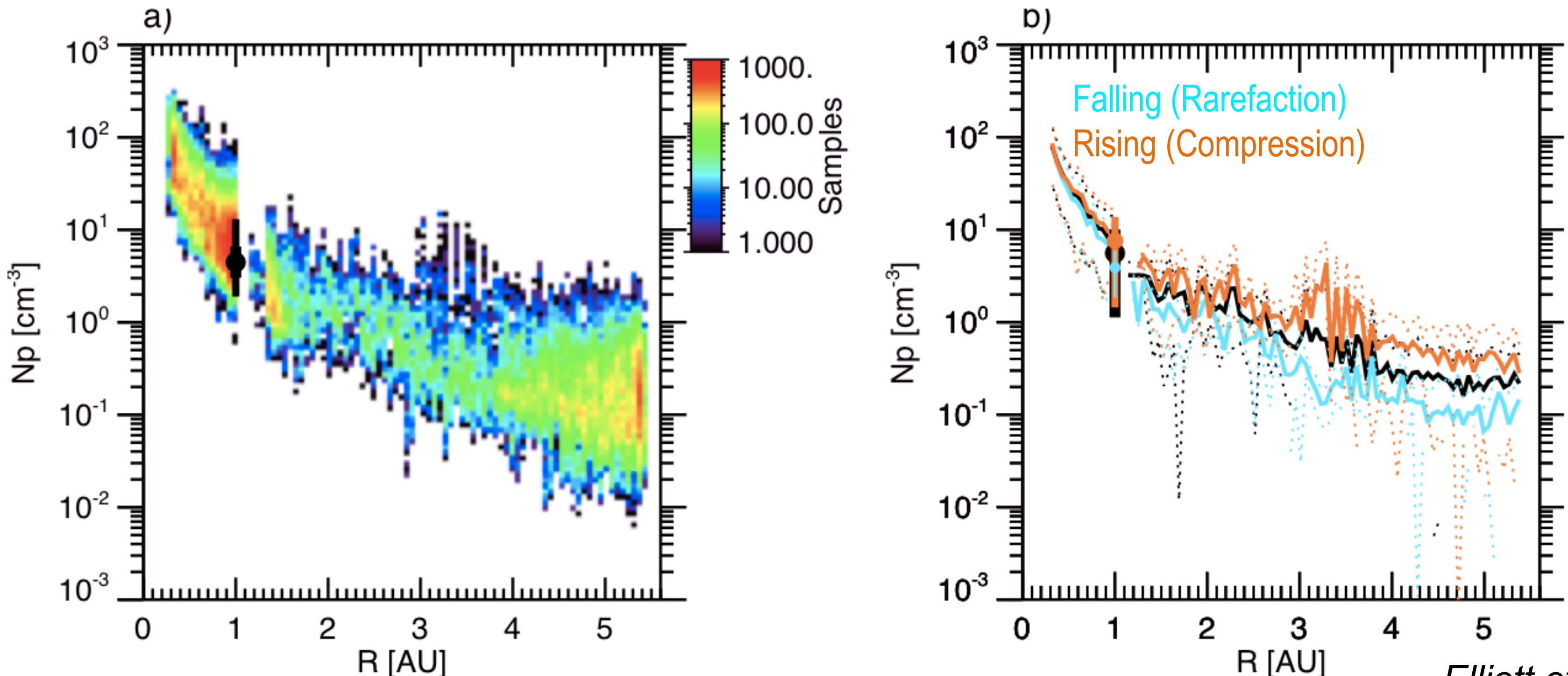


Elliott et al., 2012

- ICMEs removed from all data sets
- Polar coronal holes removed from Ulysses

- Impact of dynamic interaction is more apparent beyond 2 au.
  - Rising intervals are hotter
  - Falling intervals are cooler

Density Radial Profile



Elliott et al., 2012

- ICMEs removed from all data sets
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- Impact of dynamic interaction is more apparent beyond 2 au.
  - Rising intervals are hotter
  - Falling intervals are cooler

Inner Heliosphere: Summary and Conclusions

1. The solar wind primarily moves in the radial direction.

2. The radial motion of the solar wind and solar rotation cause spiral magnetic field lines as the solar wind carries the magnetic field.

3. The spiral density enhancements are caused by fast wind running into slow wind.

4. The relationships between solar wind parameters arise from a combination of source properties and dynamic interactions that happen as the solar wind propagates away from the Sun.

5. The dynamic interactions between faster and slower moving parcels caused the solar wind to evolve in the inner heliosphere.