Interchange reconnection as the driver of the fast solar wind

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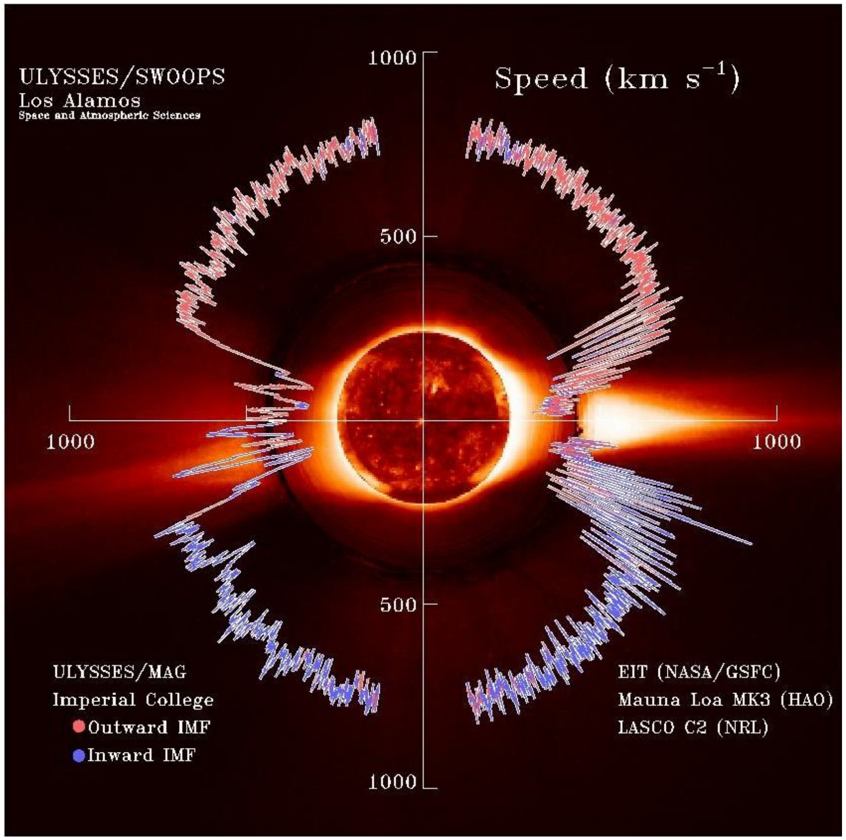
and the Parker Solar Probe science team

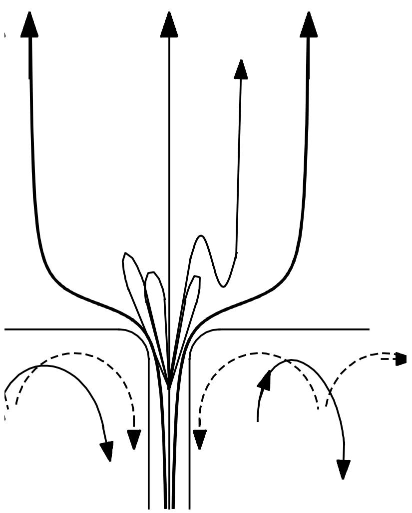
Solar wind basics

- The solar wind components
  - Fast wind at high latitudes from coronal holes (regions of open magnetic flux)
  - Slow wind at low latitude from the streamer belt
- Focus today on the fast wind from coronal holes



Solar wind modeling basics

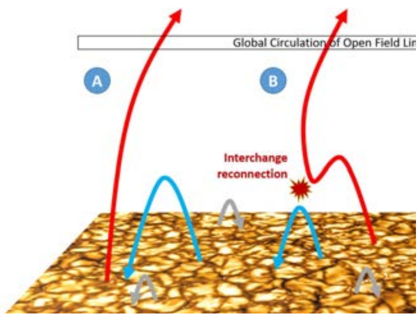
- Eugene Parker first predicted that a hot corona (around 200eV) would drive a supersonic outflow
  - Confirmed by Mariner 2 observations (Neugebauer & Synder ‘62)
- Alfven wave model of coronal heating and wind drive
  - “Furnace model” -- magnetic reconnection in the chromosphere drives Alfven wave turbulence that heats the corona and drives the wind (Gabriel ’76; Dowdy ’86; Axford & McKenzie ’92 - ’97)
  - The convection zone is also a source of Alfven waves (De Pontieu+ ‘07)



Axford+ ‘99

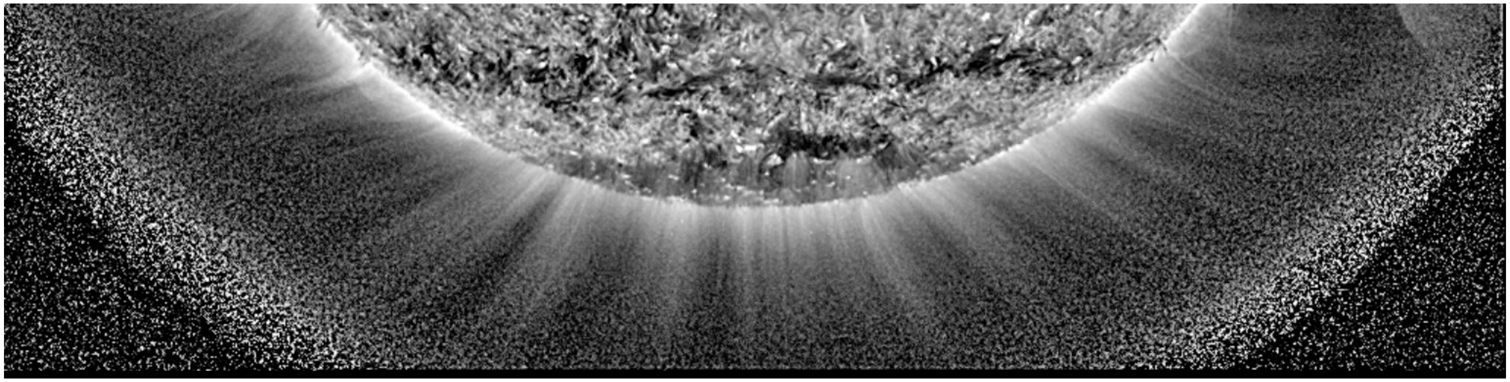
Solar wind modeling basics

- Reconnection between open and closed magnetic flux might directly drive the fast solar wind (Fisk+ ‘99)



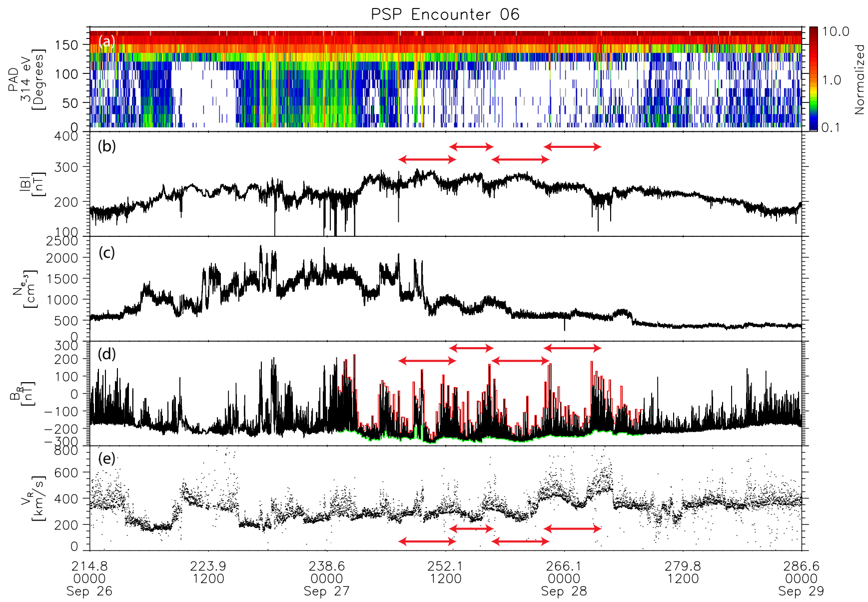
- Direct observation of large numbers of bursty outflows from the solar surface support the reconnection drive picture (Raouafi+ ‘23)

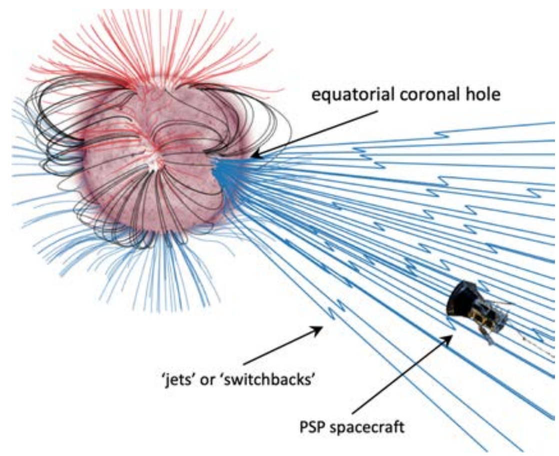
SDO/AIA



Emergence of a bursty solar wind close to the sun

- The solar wind becomes increasingly bursty close to the sun
  - Bursty radial wind velocity (Kasper+ '19, Bale+ '19)
  - Local reversals in the radial magnetic field – "switchbacks"
    - Source of switchbacks continues to be discussed (Squire+ '20, Fisk+ '20, Drake+ '21)



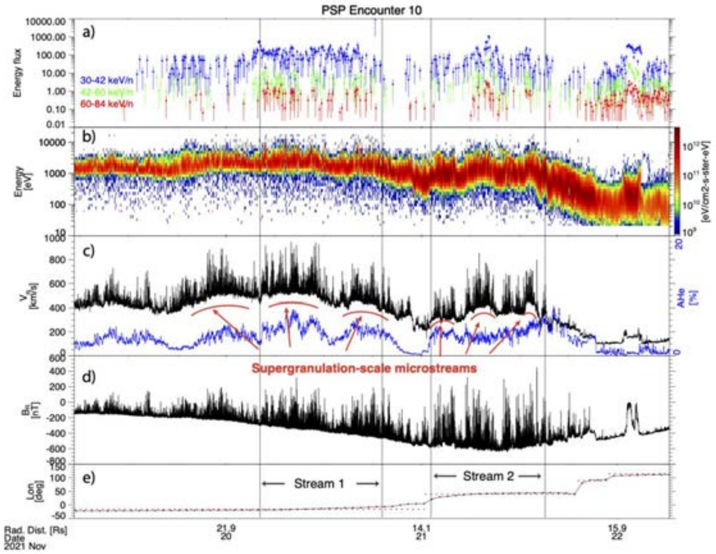


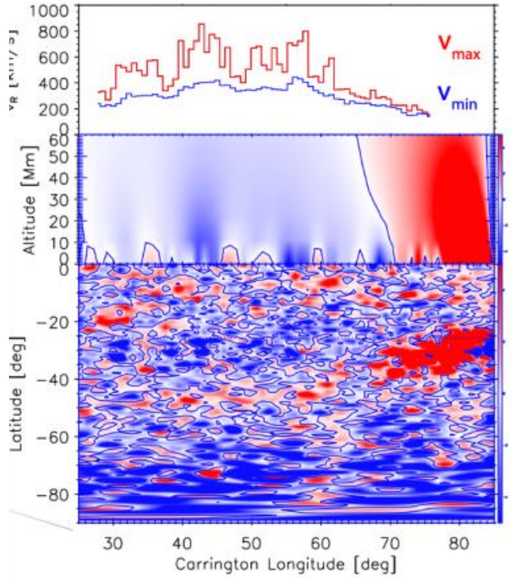
Bale+ '21

Linkage of patches of flow bursts and switchbacks to the sun's surface magnetic field

- Phase correlation of switchback bursts with the surface mixed polarity magnetic field (Bale+ '21, '23)
- Height of mixed polarity field of the order of 10Mm
- Magnetic field of around 4G with characteristic periodicity lengths of 6×10^4km $\Longrightarrow 10^o$

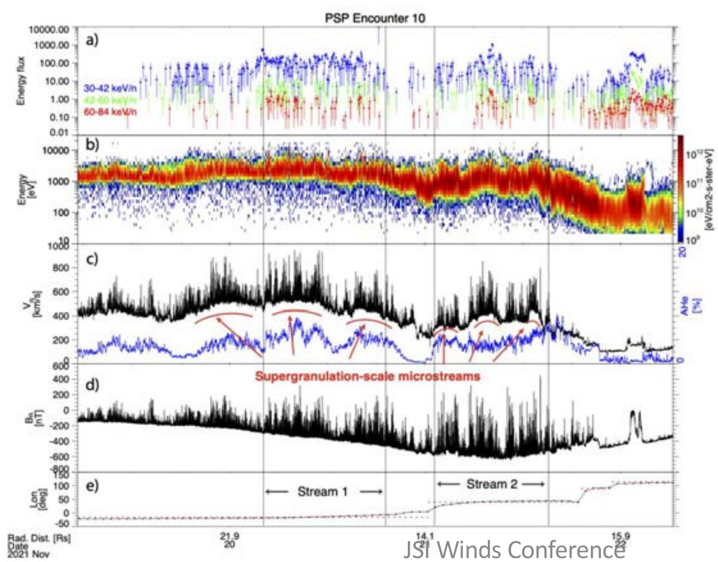
Bale+ '23





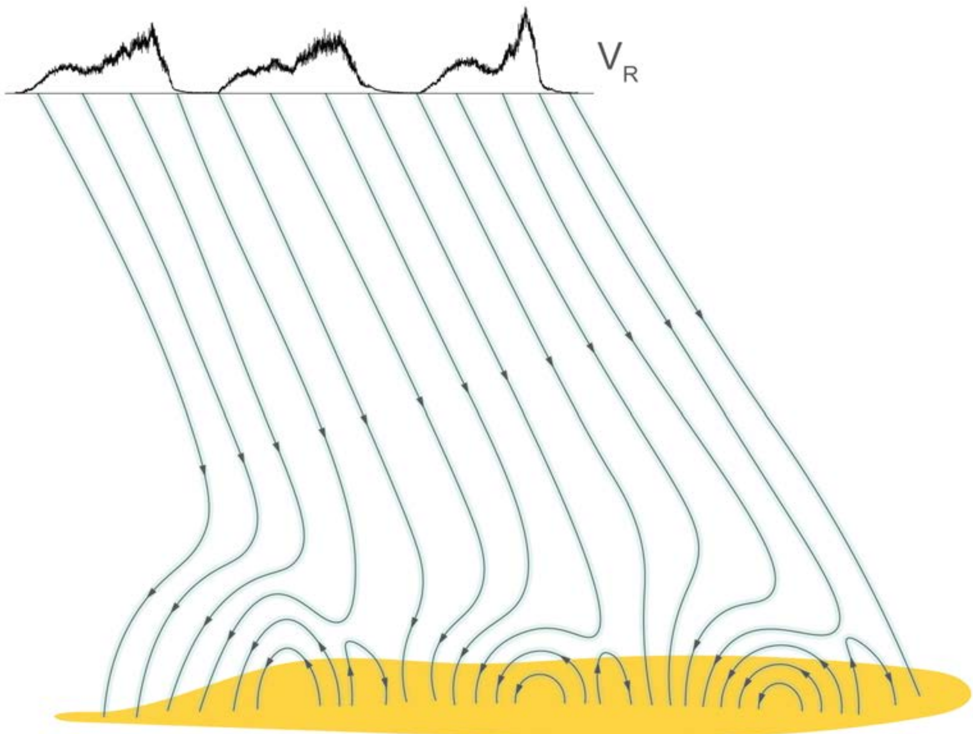
Interchange reconnection as the driver of the bursty wind

- Characteristics of the solar wind modulations
  - Bursty flows on top of increased ambient solar wind
    - Reconnection is expected to be bursty in the coronal environment
  - Increased plasma density and pressure in the bursts
  - Reduced magnetic pressure
  - Bursts of energetic ions
- All are signatures of outflows from interchange reconnection



Continuous interchange reconnection picture

- The data suggests that the open magnetic flux from coronal holes is undergoing continuous reconnection with closed flux regions
  - The unidirectional picture of coronal holes is overly simplistic
- The open magnetic flux is instead undergoing continuous reconnection with closed flux to drive the outflow
- The open magnetic flux sweeps across the closed flux regions, undergoing continuous reconnection



Linking PSP observations from E10 with the characteristics of interchange reconnection

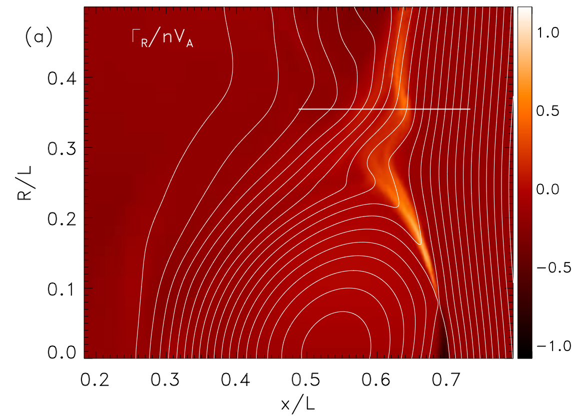
- Strength of the reconnection magnetic field at the solar surface
  - Magnetic field of 600nT at 13.4R_s projects to around 4 G at the solar surface
    - Consistent with solar surface measurements
- Reconnection inflow velocity
  - Observations of continuous bursts at PSP suggest that the reconnection time of a surface blob is comparable to the transit time to PSP at 13.4R_s
  - V_{rec}~ 3km/s
- Reconnection electric field exceeds the Dreiser runaway field by many orders of magnitude
  - Reconnection is collisionless
    - Consistent with measurements of energetic ions
- Rate of energy release sufficient to drive the wind

$$\dot{W} \sim V_{rec} \frac{B_{rec}^2}{4\pi} \sim 5\times 10^5 ergs / cm^2 \sec$$

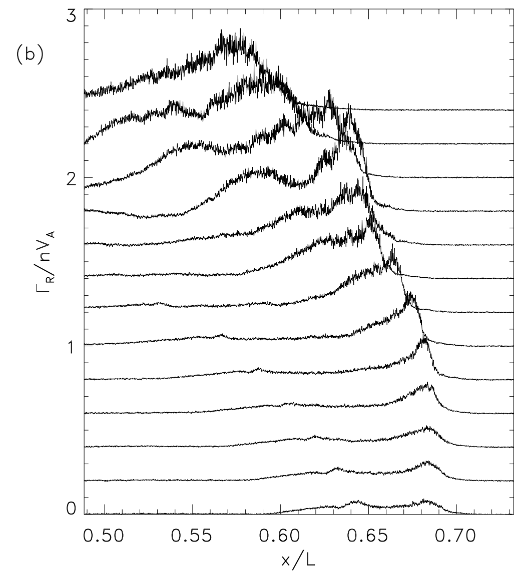
Simulation of interchange reconnection

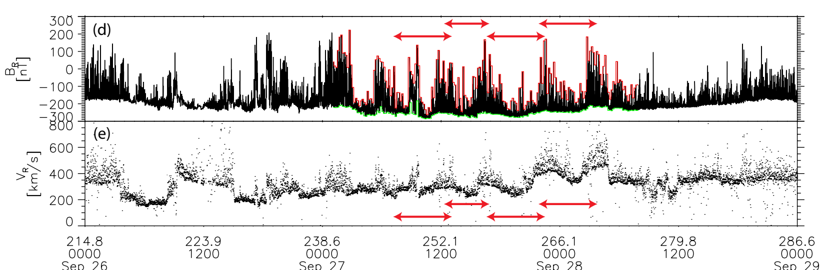
- Interchange reconnection simulations to explore the structure of the exhaust
- The exhaust exhibits the bursty behavior and time asymmetry seen in the PSP data

Radial flux



Cuts of radial flux across exhaust

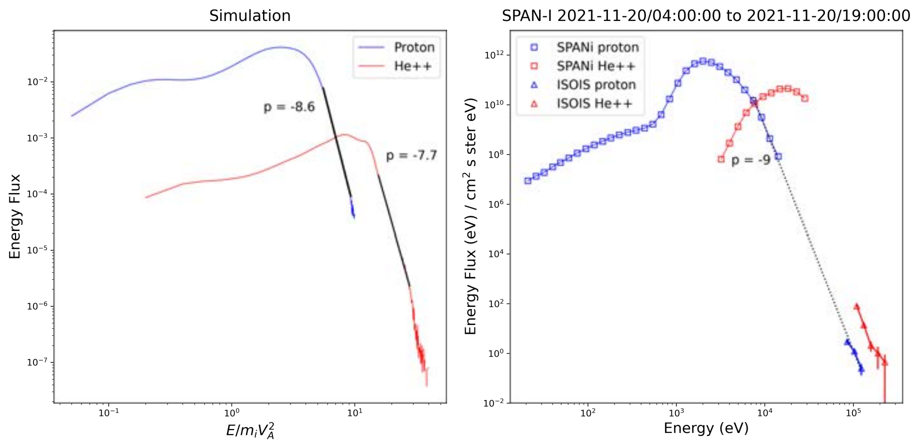




Interchange reconnection drives an energetic wind

- A major surprise are the bursts of energetic ions that are a component of the wind
  - Their presence further supports the reconnection drive hypothesis
  - Powerlaw slopes of protons and alphas from simulation and data match
  - Matching the lower edge of the powerlaw in SPANi protons to the simulation yields the characteristic Alfven speed associated with the reconnection drive

$$m_i V_A^2 = 1.4 keV \Rightarrow V_A \sim 370 km/s$$



A reconnection solar wind drive mechanism

- How does reconnection drive the solar wind?
  - Bulk Alfvenic outflow that forms the reconnection exhaust
  - Direct deposition of magnetic energy into plasma pressure and energetic particles
  - Ejection of MHD turbulence as Poynting flux as a source of coronal heating
- Observations of reconnection in the Earth space environment suggest that the MHD Poynting flux from reconnection is much smaller than the bulk flow kinetic energy and enthalpy flux (Eastwood+ 2013, 2023)
- PIC simulations of interchange reconnection also reveal that the Poynting flux is small
- Explore reconnection driven bulk outflow and ambient plasma heating as the dominant solar wind drive – discard Poynting flux

A reconnection solar wind drive mechanism

- The outflow velocity at the Alfven speed combined with the ambient heating from reconnection combine to drive the fast wind
  - Reconnection energy per particle: $W_B = \frac{1}{n}\frac{B^2}{4\pi} = m_i V_A^2$
  - Half into bulk kinetic energy: $\frac{1}{2} m_i V_A^2$
  - Half into thermal energy: $\frac{3}{2} T = \frac{1}{2} m_i V_A^2 \Rightarrow C_s^2 = \frac{5}{9} V_A^2$
  - Note that the Alfven speed V_{A0} exceeds the sound speed C_{s0} at the solar surface
    - Required to produce a wind solution

A reconnection solar wind drive mechanism

- In the absence of an additional source of coronal heating the magnetic field aligned energy flux F_w is a constant
  - Bulk flow and pressure must exceed the gravitational potential

$$F_w = \frac{1}{2}V^2 + \frac{5}{2}\frac{P}{\rho} - \frac{GM_\odot}{R} = const.$$

- Require $F_w > 0$ for a wind solution
- For a reconnection drive this reduces to a condition on the Alfven speed of the reconnecting field at the solar surface V_{A0}

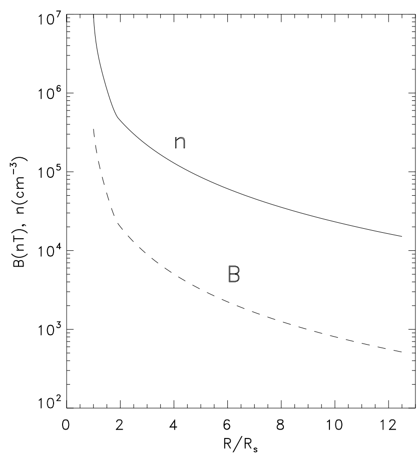
$$V_{A0} > \sqrt{3/8}V_{esc} = 377\,km/s$$

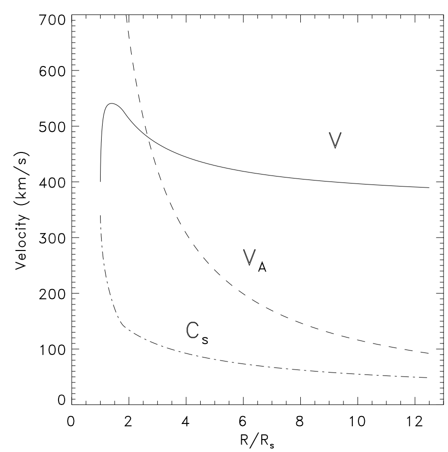
Drake+ '23

  - V_{esc} = 615km/s is the sun's escape velocity

Matching wind profiles with PSP measurements at $12R_s$

- The standard wind equations can be directly integrated with solar surface values based on inferred interchange reconnection parameters and a magnetic field profile from the coronal hole

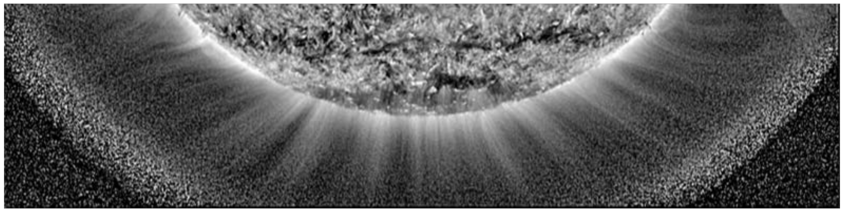




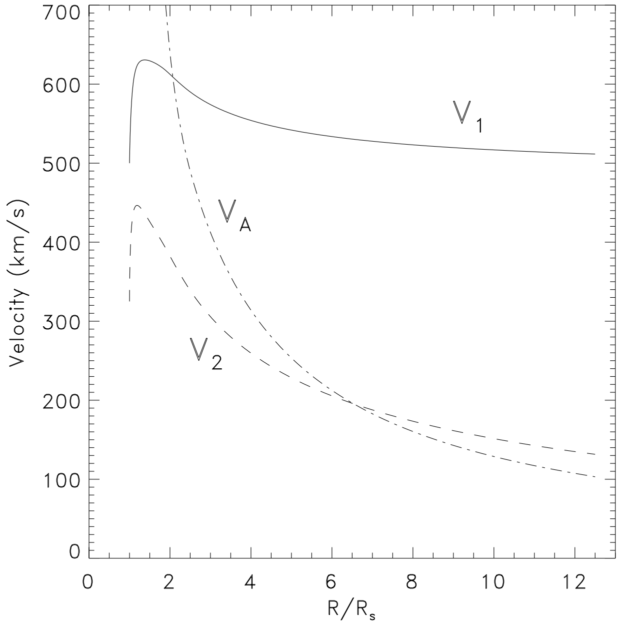
- Note that the wind velocity peaks close to the solar surface because of the rapid expansion of B from the coronal hole
- The Alfven critical point where $V = V_A$ is just above 2 R_s

Development of a spatially structured solar wind

- Because reconnection is bursty, reconnection driven outflows and heating are highly variable
  - The wind velocity in nearby spatial locations will differ and will result in a highly structured wind



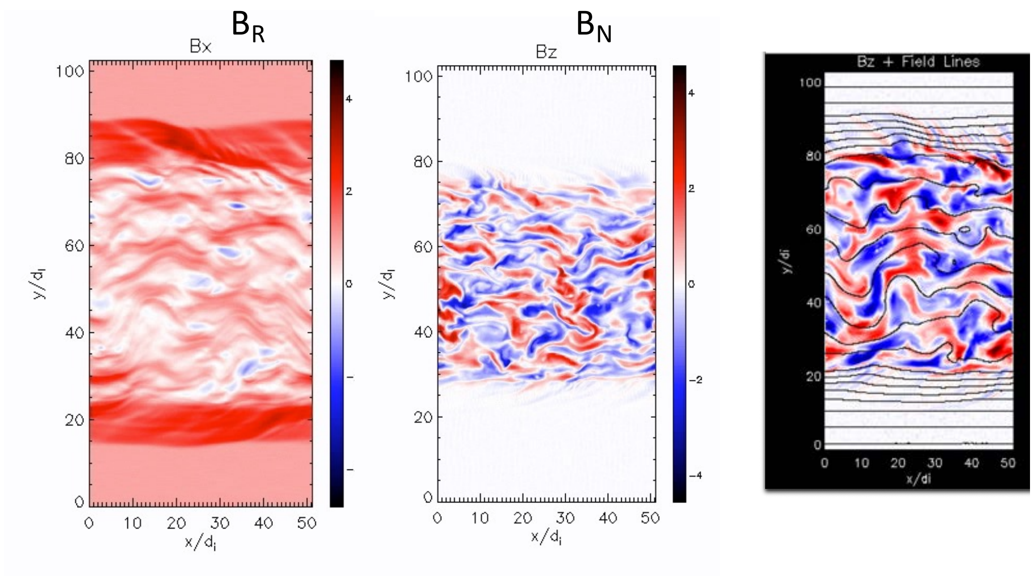
- Because of the rapid drop in the Alfven speed away from a coronal hole the velocity variation will greatly exceed local Alfven speed
- The resulting highly structured wind has sufficient free energy to drive strong magnetic turbulence
  - Expect turbulence from both super-Alfvenic beams and sheared flow
  - Can turbulence generated in the corona replace the hypothetical Alfven wave source at the solar surface?



Magnetic turbulence in the young solar wind

- PIC simulations reveal that strong turbulence results from a combination of Weibel-like and super-Alfvenic sheared flow instabilities

B_N



Field lines with B_N

Swisdak+ '23

- Reversals in the radial magnetic, generation of a strong out-of-plane magnetic field – possible source of switchbacks?
- Are sheared flow instabilities the dominant source of solar wind turbulence rather than Alfven waves propagating upward from the solar surface? Stay tuned.

Conclusions

- Bursty behavior of the wind measured by PSP close to the sun is consistent with crossings of interchange reconnection exhausts
- Reconnection simulations of interchange reconnection reveal powerlaw distributions of protons and alphas with powerlaws that are consistent with SPANi and ISOIS data
  - The solar wind has an energetic component produced by reconnection
- The Alfvenic outflow combined with the ambient heating from interchange reconnection near the solar surface is sufficient to drive the fast solar wind
  - The profiles of the wind velocity differ greatly from the conventional wisdom
  - The bursty behavior of reconnection drives a highly structured wind with enormous free energy to drive magnetic turbulence