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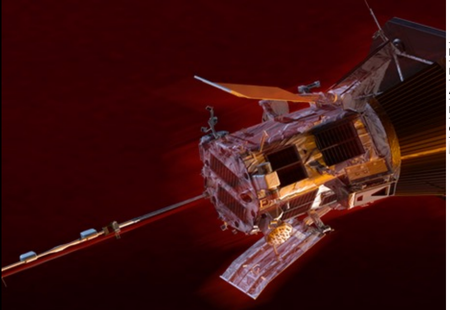
A MISSION TO TOUCH THE SUN



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Magnetic Reconnection as the Driver of the Solar Wind

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Article

Interchange reconnection as the source of the fast solar wind within coronal holes

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The fast solar wind that fills the heliosphere originates from deep within regions of open magnetic field on the Sun called 'coronal holes'. The energy source responsible for accelerating the plasma is widely debated; however, there is evidence that it is ultimately magnetic in nature, with candidate mechanisms including wave heating[1,2] and interchange reconnection[3–5]. The coronal magnetic field near the solar surface is structured on scales associated with 'supergranulation' convection cells, whereby descending flows create intense fields. The energy density in these 'network' magnetic field bundles is a candidate energy source for the wind. Here we report measurements of fast solar wind streams from the Parker Solar Probe (PSP) spacecraft[6] that provide strong evidence for the interchange reconnection mechanism. We show that the supergranulation structure at the coronal base remains imprinted in the near-Sun solar wind, resulting in asymmetric patches of magnetic 'switchbacks'[7,8] and bursty wind streams with power-law-like energetic ion spectra to beyond 100 keV. Computer simulations of interchange reconnection support key features of the observations, including the ion spectra. Important characteristics of interchange reconnection in the low corona are inferred from the data, including that the reconnection is collisionless and that the energy release rate is sufficient to power the fast wind. In this scenario, magnetic reconnection is continuous and the wind is driven by both the resulting plasma pressure and the radial Alfvénic flow bursts.

Development of a structured, turbulent solar wind as a result of interchange reconnection

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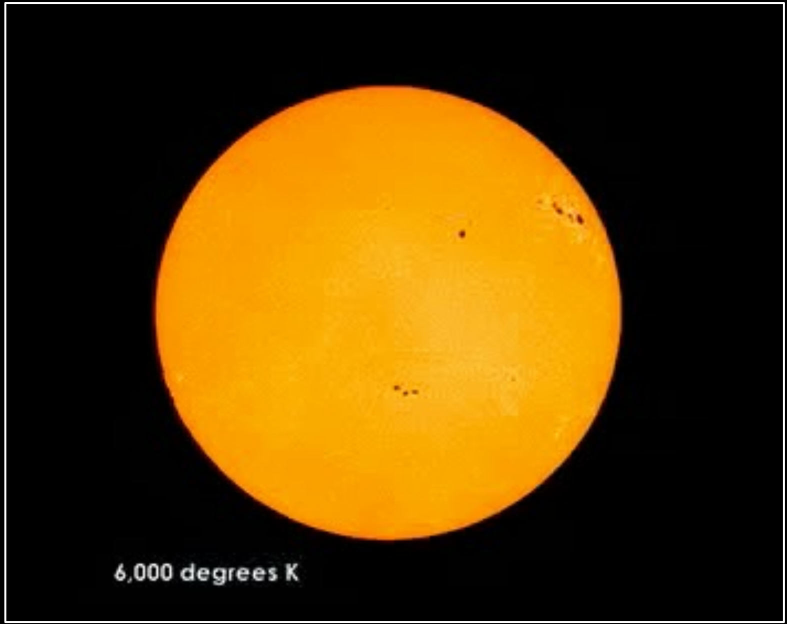
ABSTRACT

The role of interchange reconnection as a drive mechanism for the solar wind is explored by solving the global magnetic-field-aligned equations describing wind acceleration. Boundary conditions in the low corona, including a reconnection-driven Alfvénic outflow and associated heating differ from previous models. Additional heating of the corona associated with Alfvén waves or other MHD turbulence, which has been the foundation of many earlier models, is neglected. For this simplified model a sufficient condition for interchange reconnection to overcome gravity to drive the wind is derived. The combination of Alfvénic ejection and reconnection-driven heating yields a minimum value of the Alfvén speed of the order of 350-400km/s that is required to drive the wind. Recent evidence based on Parker Solar Probe (PSP) observations suggests that this threshold is typically exceeded in the coronal holes that are the source regions of the fast wind. On the other hand, since reconnection in the coronal environment is predicted to have a bursty character, the magnitude of reconnection outflows can be highly variable. The consequence is a highly non-uniform wind in which in some regions the velocity increases sharply to super-Alfvénic values while in adjacent regions the formation of an asymptotic wind fails. A simple model is constructed to describe the turbulent mixing of these highly-sheared super-Alfvénic flows that suggests these flows are the free-energy source of the Alfvénic turbulence and associated switchbacks that have been documented in the PSP data in the near coronal environment. The global wind profiles are presented and benchmarked with Parker Solar Probe (PSP) observations at 12 solar radii.

PUNCH-4, Boulder, CO, July 6-7, 2023

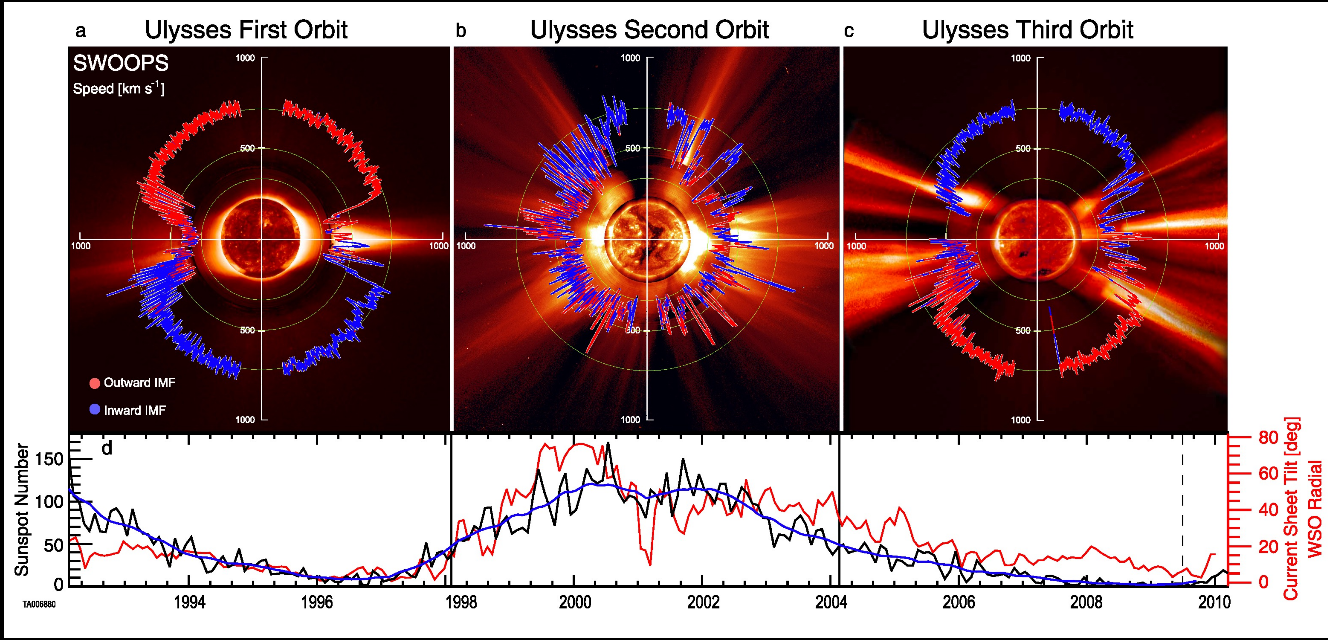
Long-Standing Mysteries of the Solar Corona



How is the corona heated to >300 times hotter the photosphere

How the solar wind is accelerated to hundreds of km/sec to escape to bearing solar gravity?

Solar Wind Origins

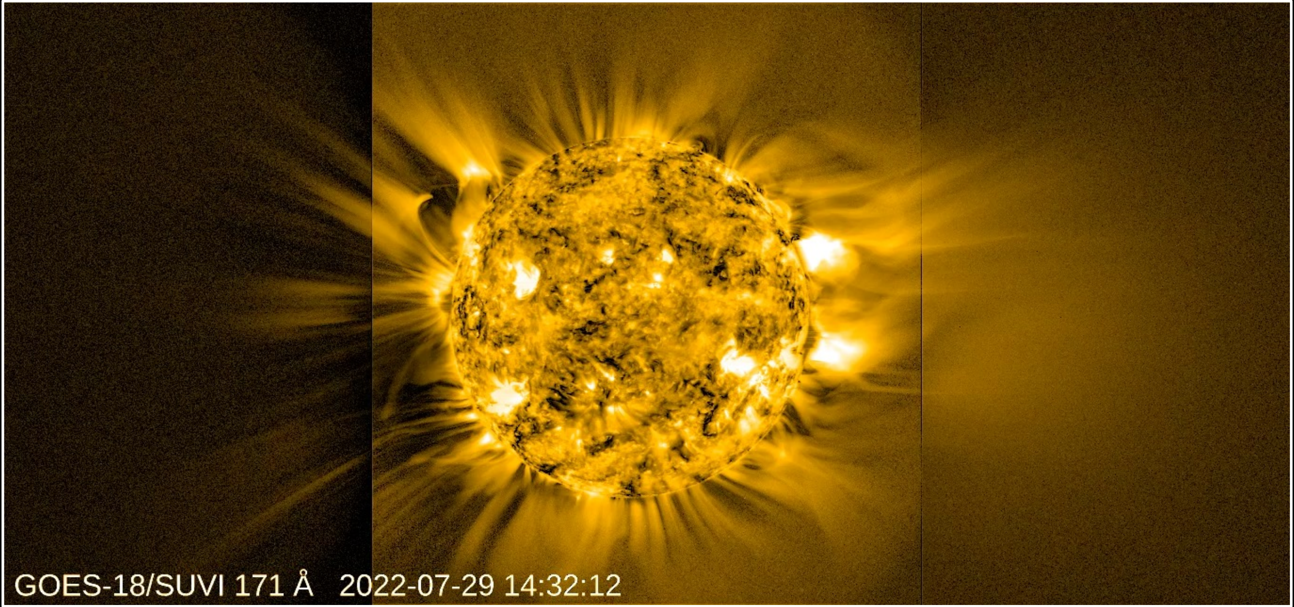


McComas et al. (2008)

Fast solar wind (> 500 km s[-1])
Steady; Alfvénic; Emerges from open field regions (coronal holes)

Slow solar wind (< 500 km s[-1])
Highly variable; mostly non-Alfvénic at 1 AU; potential sources: boundaries of CHs, ARs, & quiet sun.

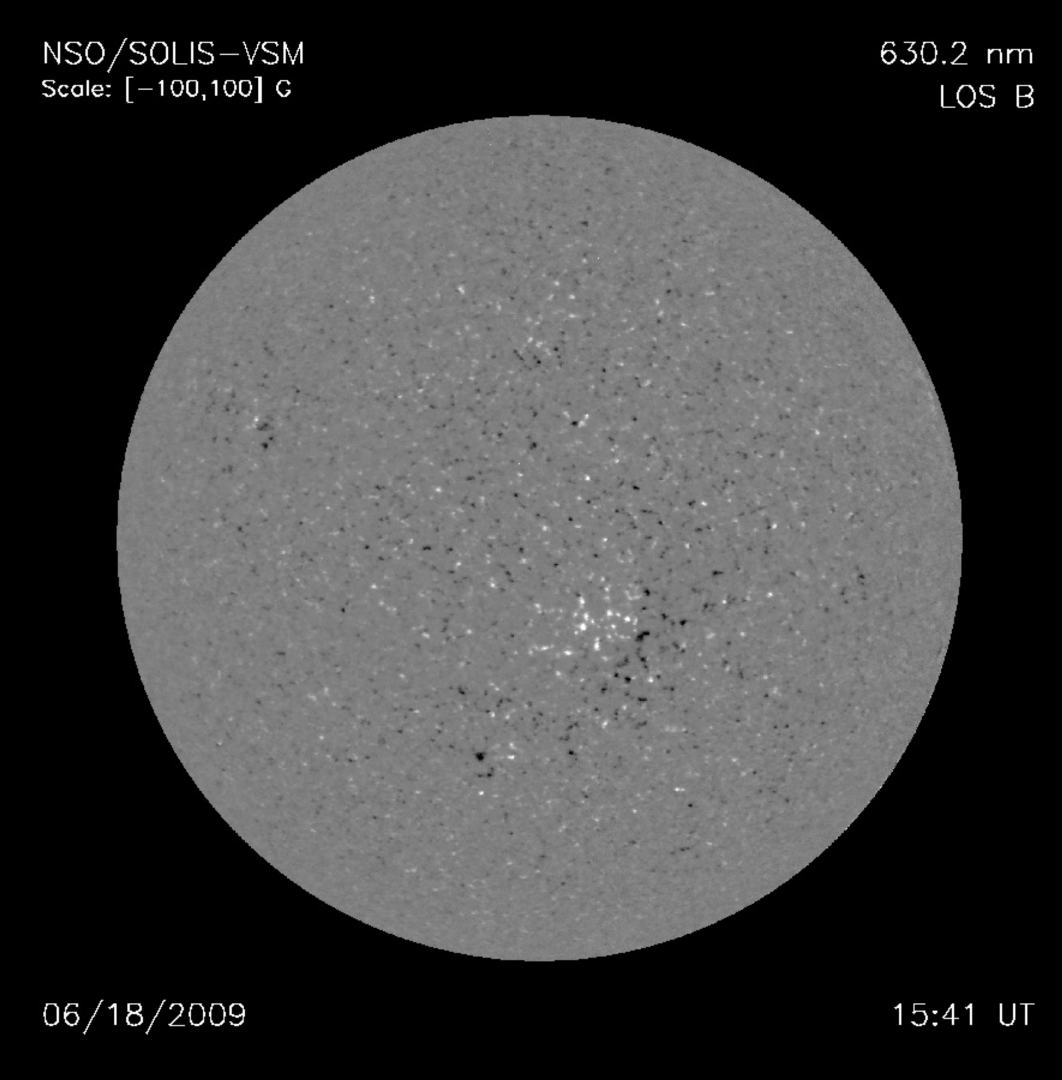
Solar Wind: Open Questions



What are the physical processes that give birth to different regimes of the solar wind?

What is the nature of the solar wind at the source (i.e., continuous vs. intermittent)?

What are the processes that energize the solar wind to escape the Sun’s gravity? (Drake’s paper on ArXiv)

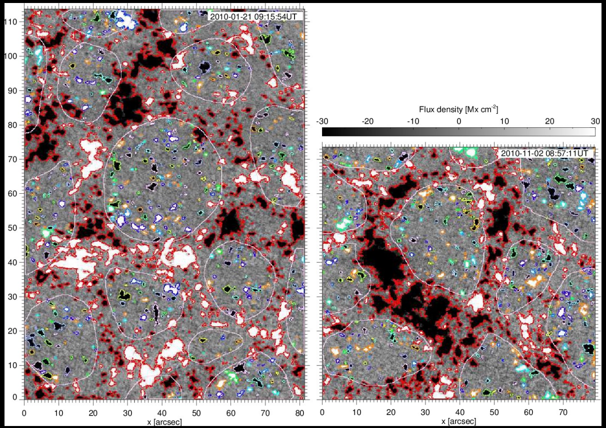


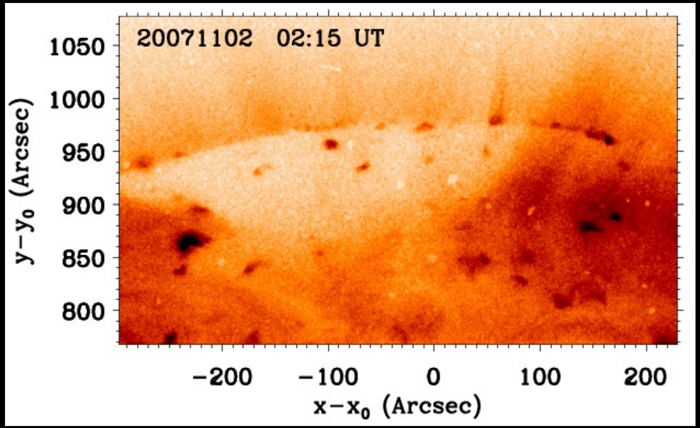
- The solar wind is omnipresent regardless of the phasing of the solar cycle.
- At solar minima, active regions are rare. Yet, the hot solar wind is still blowing.

➔ **Active regions cannot the primary source of the solar wind.**

➔ **Small-scale magnetic activity is also omnipresent and could be the main source of the solar wind.**

Small-Scale Solar activity



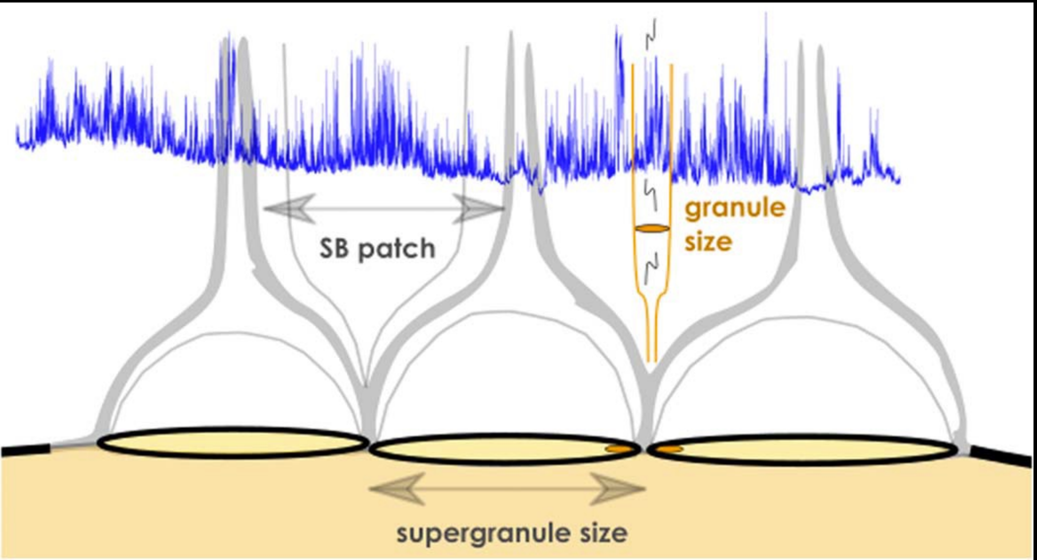


Magnetic Field Network

Coronal Jets

Coronal Plumes

Switchbacks & Potential Connection to the Solar Corona



Bale+2021
Fargette+2021

- The SB patches correlate with the supergranule scale size

➔ Is this a hint for a coronal origin of at least one flavor of SBs?

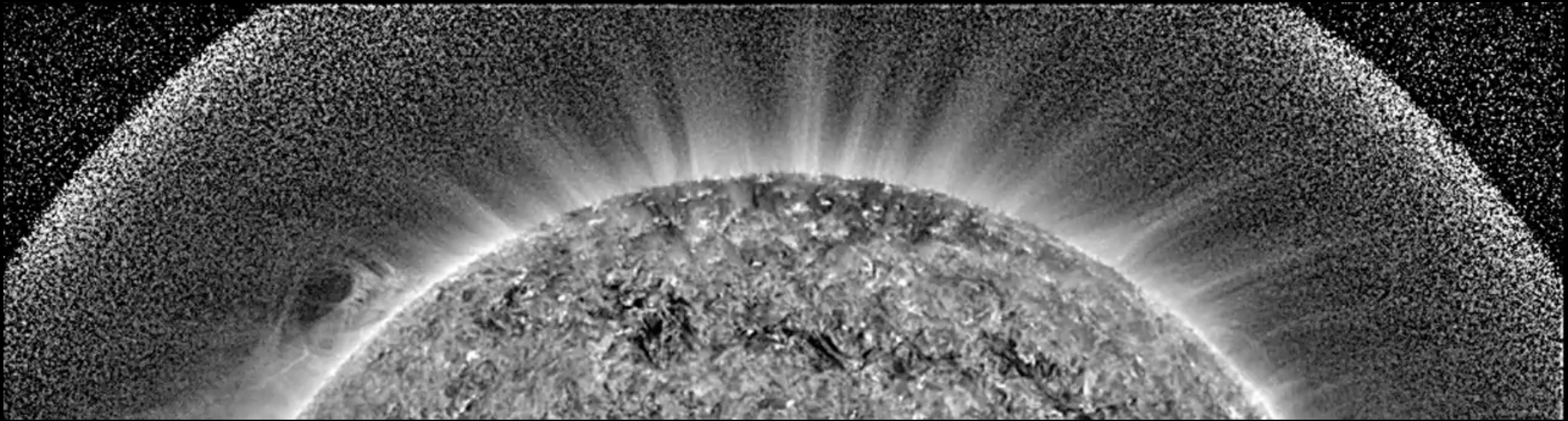
- Solar wind observed by PSP is predominantly Alfvénic

➔ Are slow & fast solar wind driven by the same physical processes?

Ubiquitous Coronal Jetting – Jetlets

Raouafi & Stenborg (2014) & Raouafi et al. (2023)

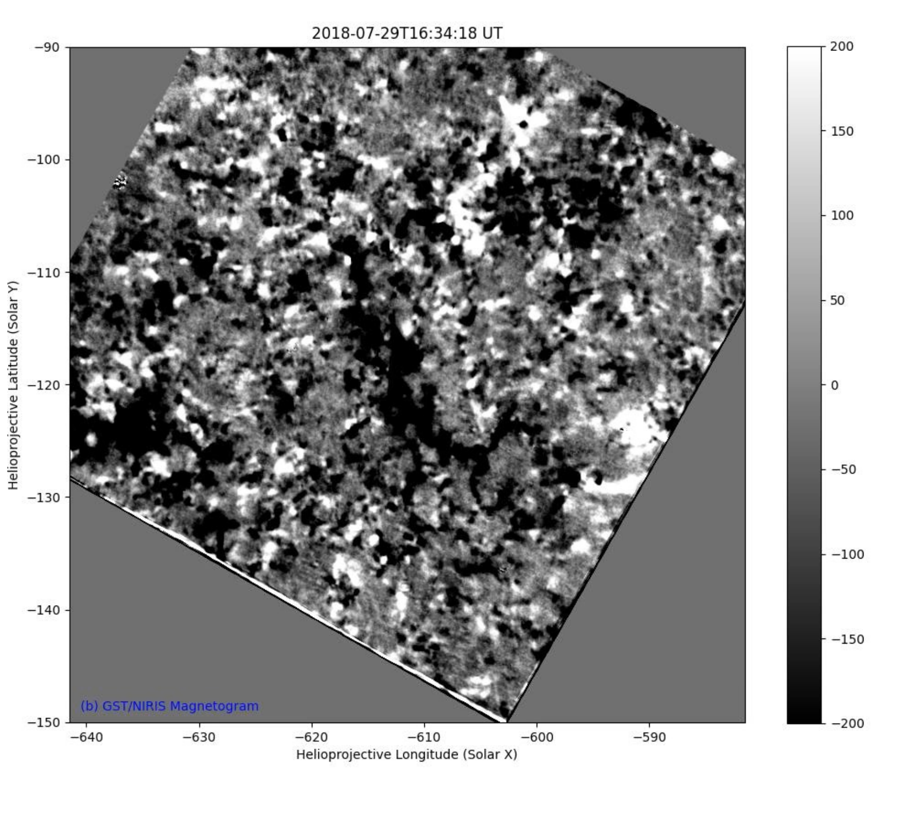
Observing the Solar Wind Genesis



The dynamics at the base of the solar corona are dominated by small-scale plasma jets (jetlets)

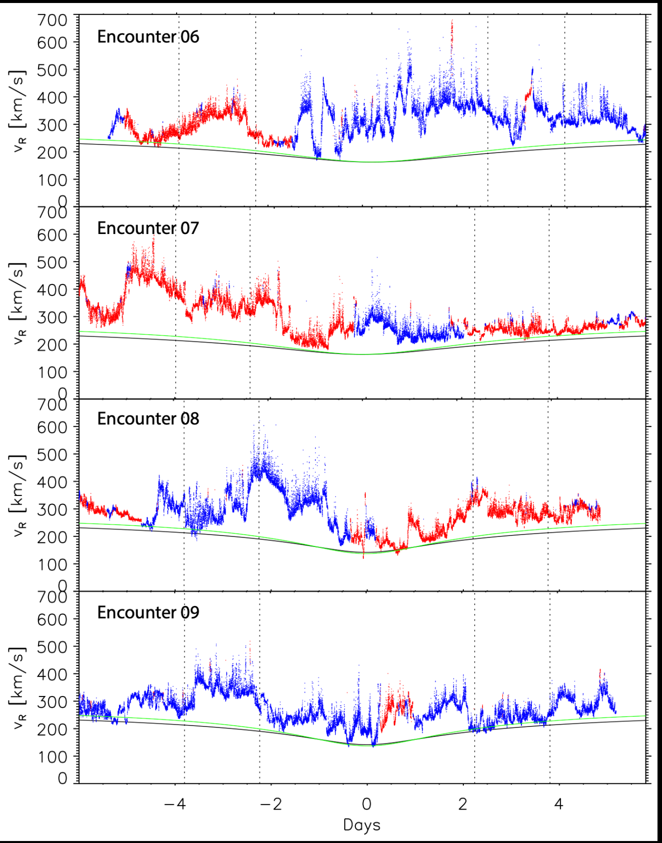
Are we observing the solar wind being born?

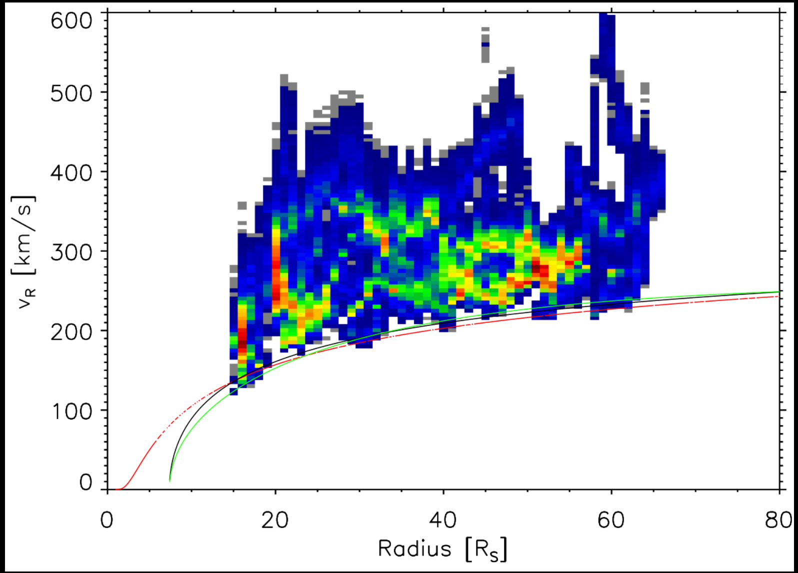
Ubiquitous Magnetic Reconnection



- BBSO/GST magnetogram
- Spatial resolution: 0″.2
- FOV: 70″×70″
- Observation time: 90 minutes
- Number of cancelling bipoles: >1400
- 61 events were rooted in network field concentrations.
- 7 of these produced EUV jetlets
- Each jetlet provides **~1×10^{35} protons** and **5×10^{22} erg s^{-1}**

Highly Structuring Solar Wind





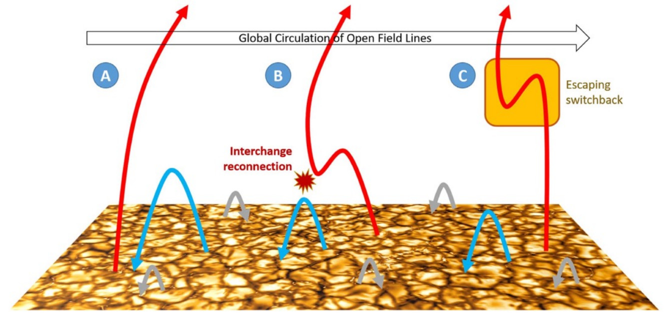
Bale+23

SW structured as a ‘baseline’ Parker-like flow beneath smaller-scale microstreams that emerge from supergranulation cell boundaries.

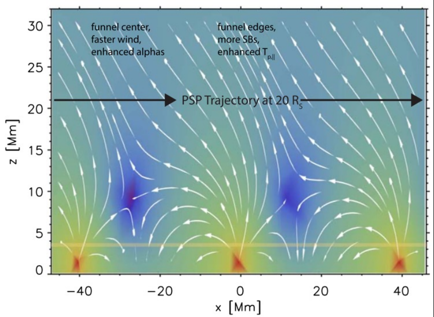
How do the SBs Form?

SB models have to explain several aspects of the SBs: frequency, Alfvénicity, patchiness, etc.

Coronal origin

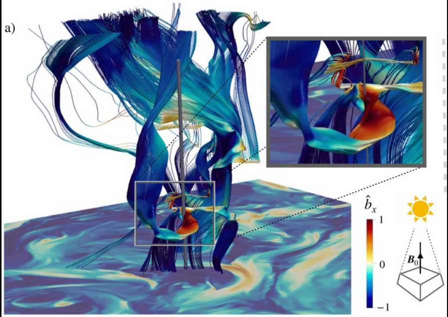


Fisk & Kasper21

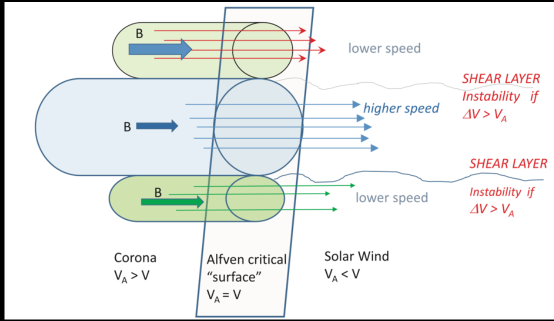


Bale+21

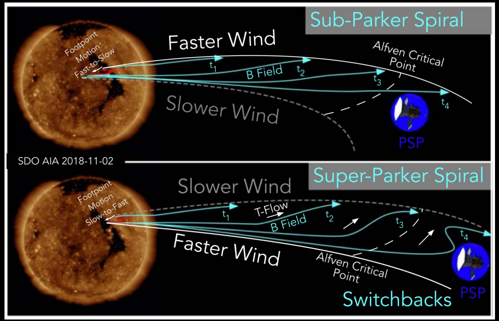
In situ



Squire+20



Ruffolo+20



Schwadron & McComas+21

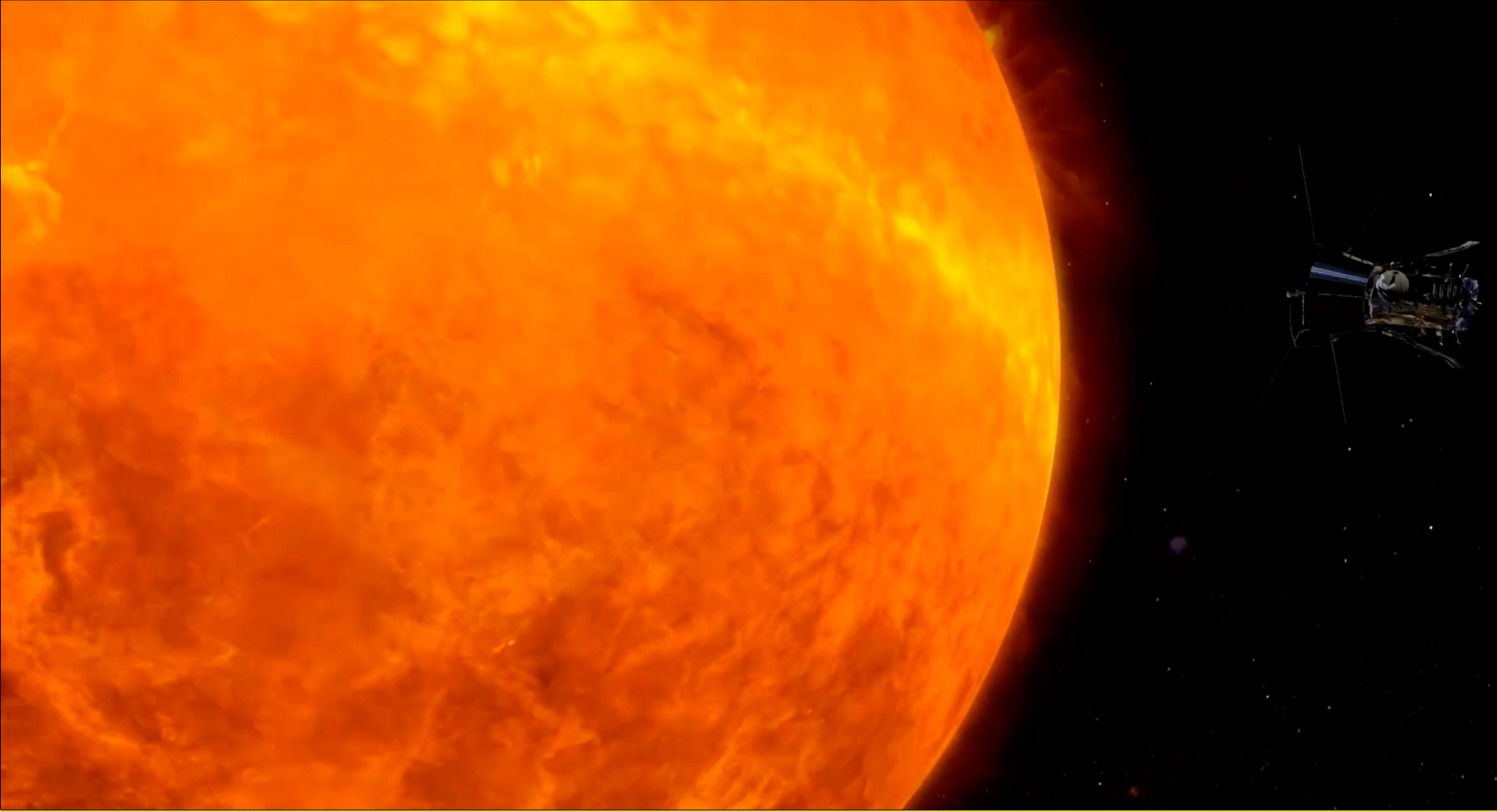
Mass and Energy input to the corona and solar wind

- The entire solar wind loss of 6×10^{35} protons s^{-1} requires roughly 2×10^{3} jetlets to be active at any instant and 6 jetlets s^{-1} to be initiated over the full Sun.
- If 2×10^{3} jetlets are active at any instant, the total jetlet kinetic-energy injection rate is 1×10^{26} erg s^{-1}.
- By comparison, the overall solar kinetic-energy loss rate (assuming an asymptotic flow speed of 500 km s^{-1}) is about 1×10^{27} erg s^{-1}.
- Clearly the injected jetlet plasma must be accelerated further by the coronal thermal & wave pressure to reach the asymptotic solar wind speed.

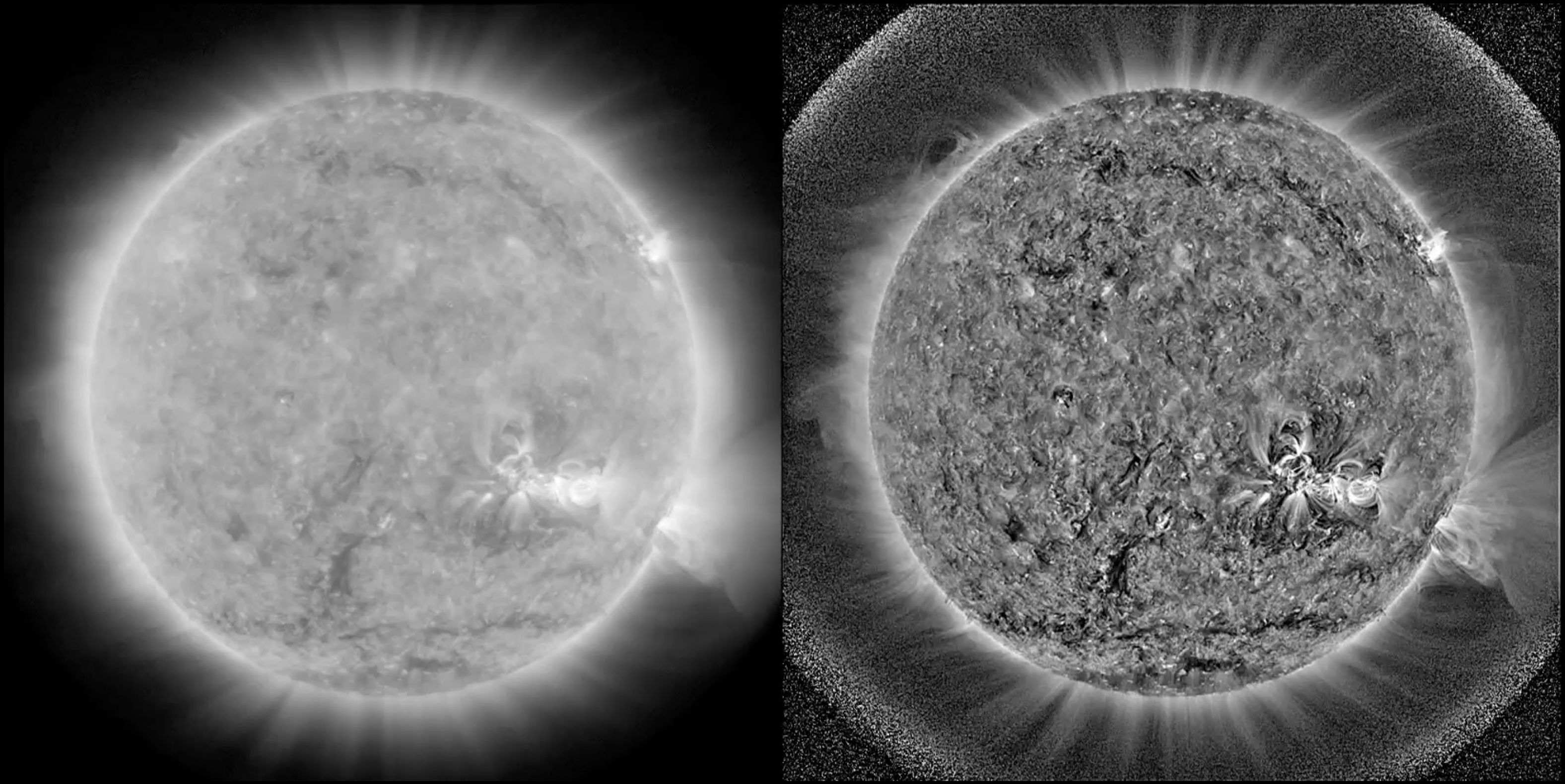
Do we have enough jetlets to power the solar wind?

The BBSO/GST and EUV data suggest 5×10^{3} jetlets to be active at any instant over the full Sun. That is > $2\times$ what is needed to drive the solar wind.

Magnetic reconnection is the driver of the plasma thermodynamics in the lower solar atmosphere, and also provides the energy for other processes occurring in the solar wind.



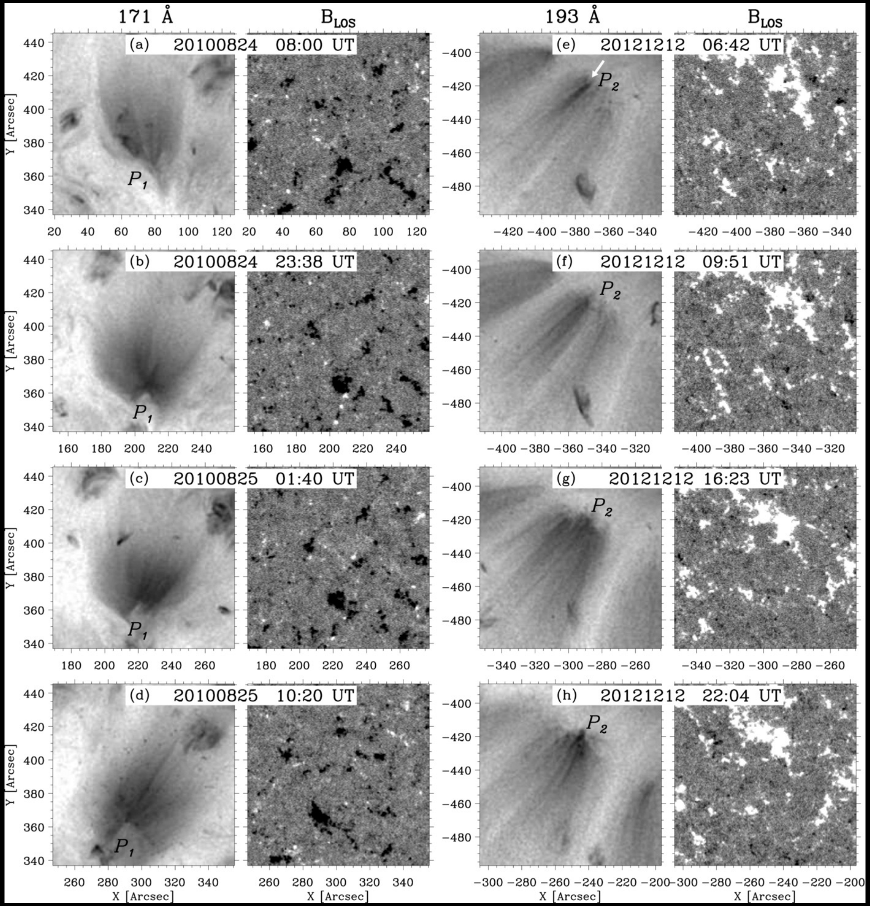
Ubiquitous Coronal Jetting – Jetlets

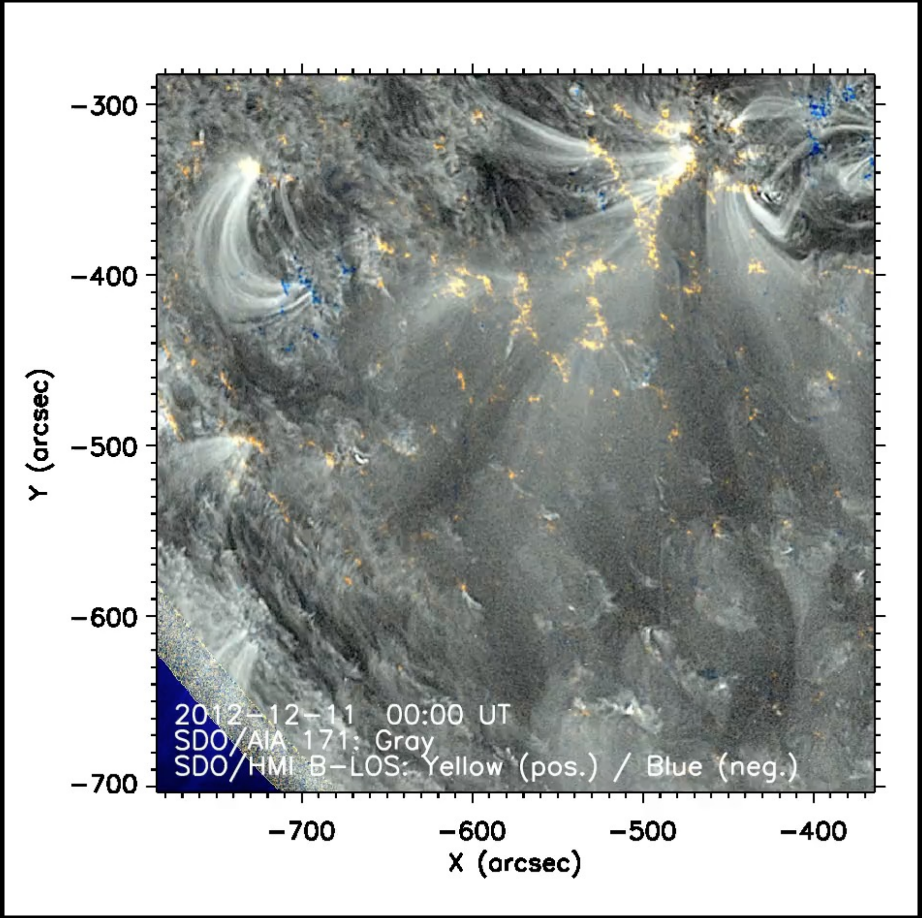


Raouafi & Stenborg (2014) & Raouafi et al. (2023)

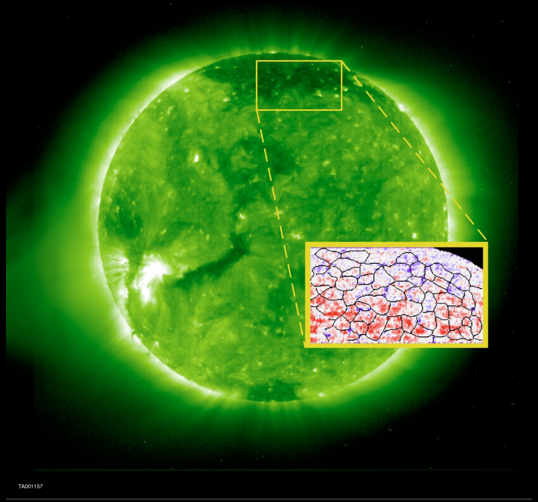
Coronal Jetlets

Raouafi & Stenborg (2014)



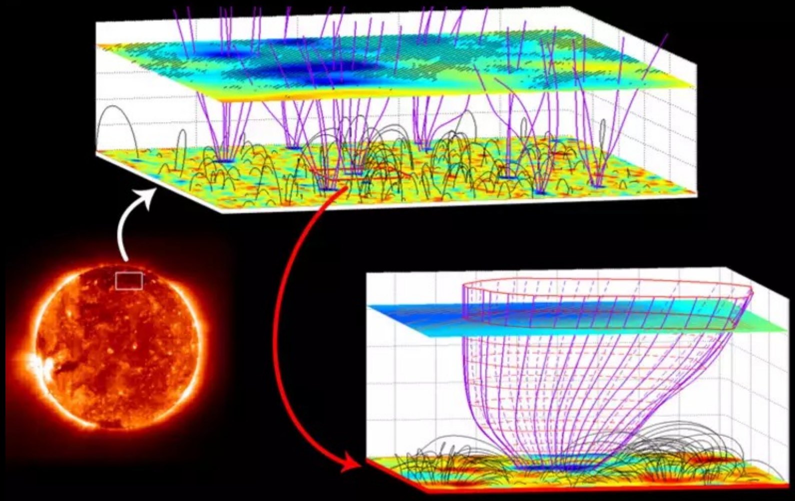


Doppler Shifts from the Chromospheric Network



SOHO/SUMER observations of the solar-wind source regions and magnetic structure of the chromospheric network.

Hassler *et al.* (1999)



Doppler flows: SOHO/SUMER
Magnetic field lines: SOHO/MDI extrapolation
Solar image: SOHO/EIT

Tu & Marsh (2005)

Small-Scale Activity Effects in the Heliosphere

Raouafi et al. (2008): close causality relation between coronal jets and plumes. Coronal plume formation is preceded by jet eruptions.

Neugebauer (2012): coronal jets could explain the properties of the solar wind microstreams.

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EVIDENCE FOR POLAR X-RAY JETS AS SOURCES OF MICROSTREAM PEAKS IN THE SOLAR WIND

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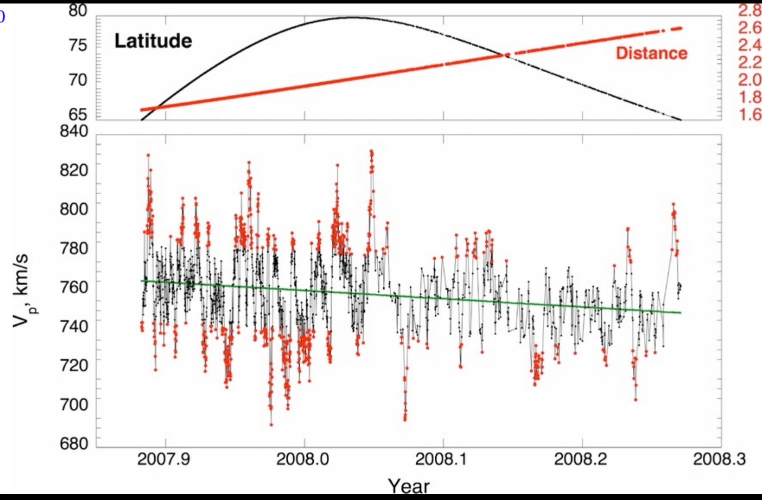
ABSTRACT

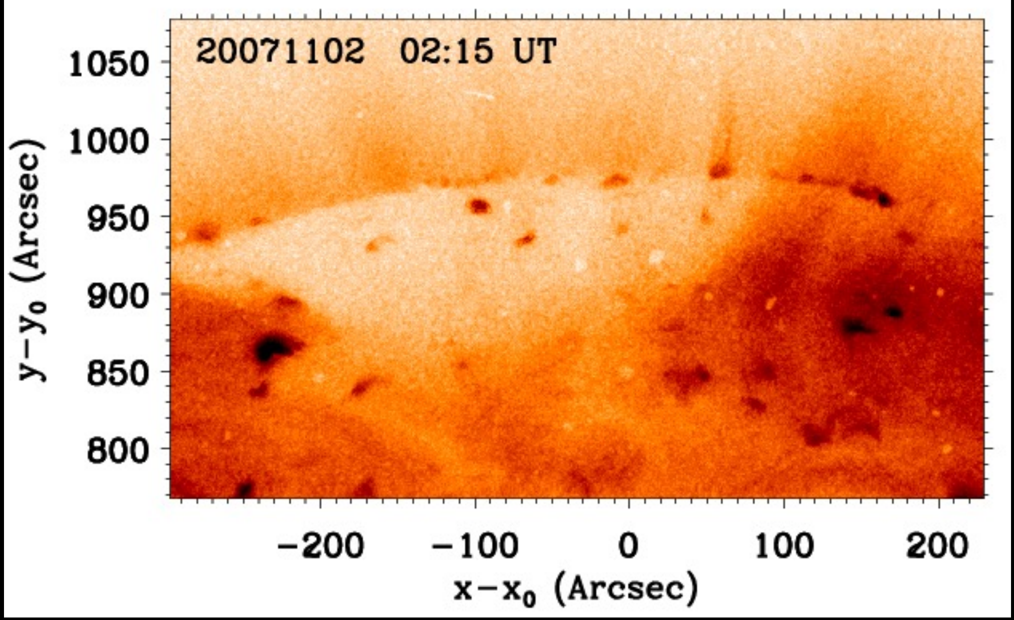
It is proposed that the interplanetary manifestations of X-ray jets observed in solar polar coronal holes during periods of low solar activity are the peaks of the so-called microstreams observed in the fast polar solar wind. These microstreams exhibit velocity fluctuations of ± 35 km s^{-1}, higher kinetic temperatures, slightly higher proton fluxes, and slightly higher abundances of the low-first-ionization-potential element iron relative to oxygen ions than the average polar wind. Those properties can all be explained if the fast microstreams result from the magnetic reconnection of bright-point loops, which leads to X-ray jets which, in turn, result in solar polar plumes. Because most of the microstream peaks are bounded by discontinuities of solar origin, jets are favored over plumes for the majority of the microstream peaks.

Key words: solar wind – Sun: X-rays, gamma rays



Coronal Plumes

Coronal Jets



- Prominent at the polar during solar cycle minima
- Can also form within equatorial CHs
- Rooted within the magnetic network

- Impulsive hot plasma ejections in the corona and solar wind
- Driven by magnetic reconnection
- ~300 events day^{-1} $hemisphere^{-1}$