Shear-Driven Transition to Isotropically Turbulent Solar Wind Outside the Alfvén Critical Zone

การเปลี่ยนแปลงที่ขับเคลื่อนโดยการเฉือนสู่ลมสุริยะที่ปั่นป่วนแบบไอโซทรอปิกภายนอกเขตวิกฤติอัลฟ์เวน

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Motivated by prior remote observations of a transition from striated solar coronal structures to more isotropic "flocculated" fluctuations, we propose that the dynamics of the inner solar wind is powered by the relative velocities of adjacent coronal magnetic flux tubes. We suggest that large-amplitude flow contrasts are magnetically constrained at lower altitude but shear-driven dynamics are triggered as such constraints are released above the Alfvén critical zone, as suggested by global magnetohydrodynamic (MHD) simulations that include self-consistent turbulence transport. We argue that this dynamical evolution accounts for features observed by Parker Solar Probe (PSP) near initial perihelia, including magnetic "switchbacks," and large transverse velocities that are partially corotational and saturate near the local Alfvén speed. Large-scale magnetic increments are more longitudinal than latitudinal, a state unlikely to originate in or below the lower corona. We attribute this to preferentially longitudinal velocity shear from varying degrees of corotation. Supporting evidence includes comparison with a high Mach number three-dimensional compressible MHD simulation of nonlinear shear-driven turbulence, reproducing several observed diagnostics, including characteristic distributions of fluctuations that are qualitatively similar to PSP observations near the first perihelion. The concurrence of evidence from remote sensing observations, in situ measurements, and both global and local simulations supports the idea that the dynamics just above the Alfvén critical zone boost low-frequency plasma turbulence to the level routinely observed throughout the explored solar system.

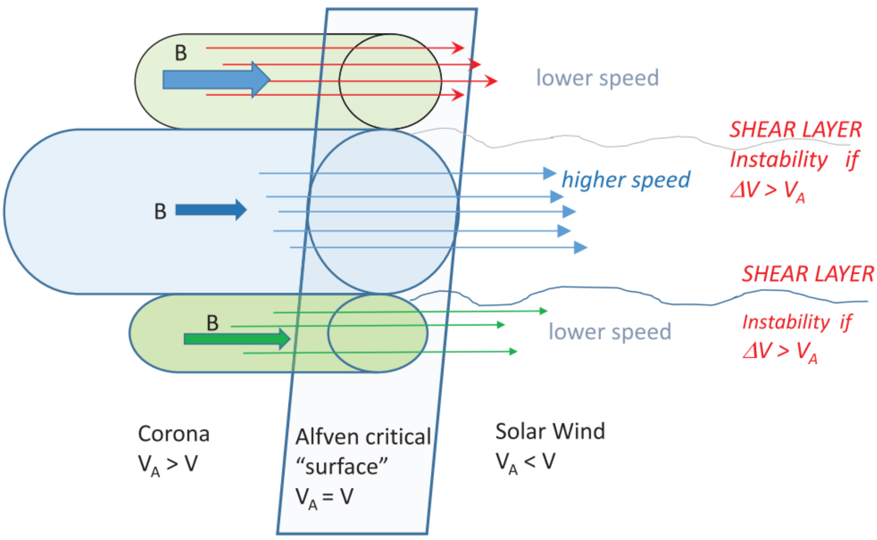

Figure 1: Sketch describing our proposed hypothesis. In the corona, the strong magnetic field regulates the dynamics of the nascent solar wind. Each flux tube may contain differing radial speeds and different radial field

strengths due to processes at lower altitudes. Beyond the Alfvén critical zone, the magnetic field is no longer capable of constraining the dynamics and the energy in the velocity contrasts becomes available to drive nonlinear magnetized Kelvin–Helmholtz-like dynamics, including magnetic field amplification and directional change, with associated deflection of velocities into the transverse directions. This may explain the transition from striation to flocculation in STEREO images such as that in Figure 1 and, in the present work, we point out characteristics of PSP data that are consistent with this picture of how shear-driven dynamics at and above the Alfvén critical zone boosts low-frequency turbulence to the levels observed throughout the heliosphere.

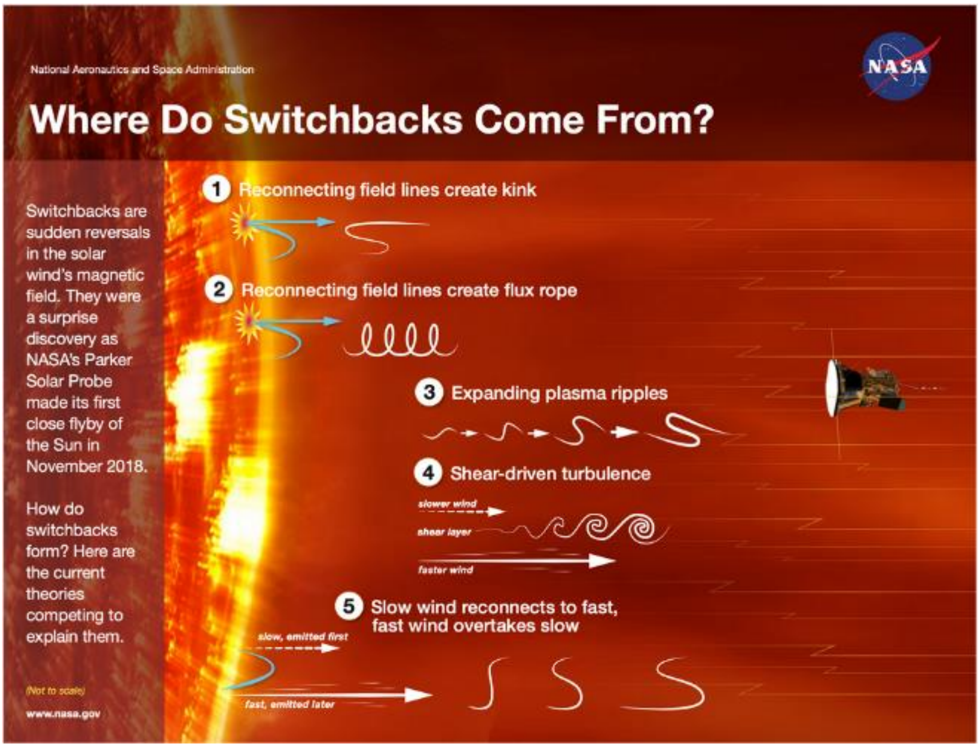

Figure 2: NASA graphic, from https://www.nasa.gov/feature/goddard/2021/switchbacks-science-explaining-parker-solar-probe-s-magnetic-puzzle, summarizing our mechanism of shear-driven turbulence (#4) and other mechanisms to explain switchbacks in data from Parker Solar Probe.