Possible Evolution of Minifilament-Eruption-Produced Solar Coronal Jets, Jetlets, and Spicules, into Magnetic-Twist-Wave “Switchbacks” Observed by the Parker Solar Probe (PSP)

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Abstract.
Many solar coronal jets result from erupting miniature-filament ("minifilament") magnetic flux ropes that reconnect with encountered surrounding far-reaching field. Many of those minifilament flux ropes are apparently built and triggered to erupt by magnetic flux cancelation. If that cancelation (or some other process) results in the flux rope’s field having twist, then the reconnection with the far-reaching field transfers much of that twist to that reconnected far-reaching field. In cases where that surrounding field is open, the twist can propagate to far distances from the Sun as a magnetic-twist Alfvénic pulse. We argue that such pulses from jets could be the kinked-magnetic-field structures known as “switchbacks,” detected in the solar wind during perihelion passages of the Parker Solar Probe (PSP). For typical coronal-jet-generated Alfvénic pulses, we expect that the switchbacks would flow past PSP with a duration of several tens of minutes; larger coronal jets might produce switchbacks with passage durations ~1 hr. Smaller-scale jet-like features on the Sun known as “jetlets” may be small-scale versions of coronal jets, produced in a similar manner as the coronal jets. We estimate that switchbacks from jetlets would flow past PSP with a duration of a few minutes. Chromospheric spicules are jet-like features that are even smaller than jetlets. If some portion of their population are indeed very-small-scale versions of coronal jets, then we speculate that the same processes could result in switchbacks that pass PSP with durations ranging from about ~2 min down to tens of seconds.
1. Introduction

Solar coronal jets are transient features in the Sun’s outer atmosphere, the corona, that were first studied in detail using observations from the X-ray telescope on the Yohkoh satellite ([1, 2]), which was launched in 1991. They grow to be long and narrow (typically around $50,000 \times 10,000$ km) over a short period of time $\sim 10$ min, for those occurring in polar coronal holes ([3, 4]). They are also common in quiet Sun and active regions. Since Yohkoh, they have been observed extensively in X-rays from the X-ray telescope (XRT) on Hinode, and in various EUV filters from the Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory (SDO) satellite. They have also been studied with other instruments and in different wavelength ranges. Their properties have been reviewed elsewhere ([5, 6, 7]).

Switchbacks are localized structures in the solar wind where the magnetic-field direction undergoes large variation. Although detected and discussed previously (e.g., [8, 9, 10]), they have recently become of wider interest due to a series of detailed in situ observations by the Parker Solar Probe (PSP) very close to the Sun, during its perihelion passages of $\sim 35 R_\odot$ in 2018 November and 2019 April. The kinks in the magnetic field of the switchbacks are sometimes extreme enough for the field’s radial component to reverse for a period of time. They are possibly Alfvénic pulses that are propagating in the solar wind, whereby they pass PSP as they move outward from the Sun riding on the solar wind. Their durations vary widely, with PSP-crossing times ranging from less than one second to over an hour ([11]).

Here we consider how coronal jets and similar features might be the source of the PSP switchbacks, as mentioned previously ([12, 11]), and discussed in more detail in [13]. Much of the presentation here is based on the investigation in [14]. Although not addressed further here, we point out that there are other ideas under discussion for switchback production (e.g., [11]).

2. From Minifilament Eruptions to Solar Coronal Jets

Early models of jets assumed that they formed when new magnetic flux emerging from the photosphere reconnected with encountered far-reaching coronal field ([1, 15]). Later observations however showed that jets, especially those in coronal holes and quiet regions, frequently originate from sites of flux convergence rather than emergence (e.g., [16, 17, 18, 19]), and that they frequently occur as a result of eruption of a miniature filament (“minifilament”) (e.g., [17, 19]). [20] showed that polar coronal hole jets commonly result from minifilament eruptions. Subsequent work (e.g., [21, 22, 23, 24]) argues that flux cancelation builds the minifilament flux rope and triggers its eruption in most cases. (Work of [25] confirms that many coronal hole jets result from minifilament eruptions, but argues that the eruptions often result from flux convergence and/or shearing motions rather than cancelation.)

A minifilament-eruption-model, schematically presented by [20], describes how the minifilament flux-rope eruption can drive the jet and concurrently explain a brightening that often appears at the base of the jet and off to one side of the spire (Fig. 1). They argue that the jet is a small-scale version of the better-known larger filament eruptions that often produce coronal mass ejections (CMEs), and that the base-edge brightening is a small-scale version a typical solar-flare brightening (i.e. the brightening from the flare arcade that forms in the wake of larger-scale filament eruptions that sometimes produce CMEs). Numerical modeling confirms the plausibility of this schematic ([26, 27]).

In active region coronal jets, minifilament eruptions are sometimes not as obvious as in many jets in quieter solar regions. Nonetheless, flux cancelation leading to minifilament flux-rope eruptions that make jets appears to be the basic process driving many active region jets also (e.g., [28, 29, 30, 31, 32, 33, 34, 35]). The lack of obvious erupting minifilaments (and some other features) in some active region jets might be a consequence of the complex magnetic field arrangement and rapid evolution in those regions compared to quieter regions [29].

Jets also frequently show twisting motions (e.g. [36, 37, 38, 39, 40, 41, 42, 43, 21, 44, 45]).
Figure 1. Schematic showing the minifilament eruption model for coronal jets; originally presented in [20], this version is from [14]. This represents a near-limb 2D cross-sectional view of the jetting region, with the yellow curve representing the solar limb. Black lines represent magnetic field lines prior to magnetic reconnection, and red lines represent reconnected field lines. In the most general jet model the vertical lines can represent either open or far-reaching closed field, but here we only consider the open-field case since we are assuming that the jet effects extend into the distant heliosphere. (a) A minifilament (blue disk) is in a magnetic bipole, pictured here as residing on the right-hand side of a larger bipole (see the plus- and minus-polarities at the bottom of the panel). The curled field line encircling the minifilament indicates non-potential twist in the field holding the minifilament material. (b) The minifilament field erupts, running into and undergoing interchange reconnection with opposite-polarity open field, leading to new field lines (dotted) including new open field that guides a hot jet (shaded region), and with field below the minifilament undergoing reconnection (“internal reconnection” [20]) and forming a frequently observed brightening on one side of the jet’s base (thick red semicircle). (c) As the minifilament eruption progresses, the interchange reconnection can eat into the minifilament flux rope enough to release cool minifilament material to travel outward along the jet spire. That interchange reconnection also transfers twist that is in the erupting minifilament flux rope to the open field, resulting in a frequently observed spinning jet spire. See [20, 28, 29, 49] for more details. This picture has been modeled numerically ([26, 27]).

The minifilament eruption model (Fig.1) is consistent with this if twist first builds up in the minifilament flux rope prior to its eruption, and then some of that twist is transferred onto the open field via magnetic reconnection ([46, 47, 48]).

3. From Solar Coronal Jets to PSP Switchbacks
From the above discussion, we can say that: Coronal jets are frequently produced by minifilament flux-rope eruptions, the minifilament flux ropes often appear to be made by magnetic flux cancelation, and the eruptions apparently are at least many times triggered by flux cancelation. It is plausible that canceling sheared fields form minifilament flux ropes containing twist, and that when the minifilament flux rope erupts and makes the jet, it transfers some of that twist to the open coronal field via magnetic reconnection. This puts an Alfvénic twist wave onto the jet-spire field, resulting in the frequently observed jet-spire rotation.

A plausible interpretation of switchbacks observed by PSP is that they are propagating Alfvénic twist-wave packets riding on the solar wind. Here we consider whether the just-described twists of the jets could become switchbacks.

First we consider evidence that effects of coronal jets extend beyond the inner corona and into the outer corona and inner heliosphere.

Several studies (e.g., [50, 51, 52, 53, 54, 47, 28]) show that coronagraph-observed “narrow
CMEs” (of width from Sun-disk center of $\lesssim 5^\circ$), also called “white-light jets,” originate from coronal jets. Similar features extending from coronal jets have been observed in eclipse images ([55, 56]). Coronal jets (or coronal-jet remnants) have been detected well into the heliosphere (a large fraction of an AU) via 3D reconstructions using Solar Mass Ejection Imager (SMEI) observations ([57, 58]). They have also been detected in interplanetary space from the Hi1 Heliospheric Imager on the STEREO spacecraft [14]. This is strong evidence that the influence of at least some coronal jets can persist out to the distances of PSP perihelia, and beyond.

A natural follow-up question is: Which particular jets are most likely to persist out to PSP locations? While we cannot yet supply an exact answer to this question, work by [47] found that the coronal jets that showed up as white-light jets in SOHO/LASCO C2 coronagraph images were those that tended to display comparatively larger twisting motions in SDO/AIA 304 Å He ii images. More specifically, in earlier studies of random polar jets, [41] found that $\sim 80\%$ of the 29 polar coronal hole jets they studied displayed spinning amounts of $\lesssim 0.5$ turns; in contrast, the 14 polar coronal hole jets known to be counterparts of white-light jets all had twist amounts of between 0.5 and 2.5 turns. Thus, this suggests that the jets with relatively large twist are most likely to make detectable white-light jets. Moreover, [47] found evidence that the twists of the coronal jets persisted out into the LASCO C2 corona as swaying motions in the corresponding white-light jets.

Under the assumption then that a minifilament flux rope that contains twist erupts to produce a jet on reconnected coronal field that extends out into the heliosphere, we can expect that much of the twist of the minifilament field is transferred onto the open field. This twist may then continue to propagate outward, driving a density enhancement, and appearing as a white-light jet and a density enhancement in interplanetary space. (Our basic argument here is independent of whether the erupting minifilament field contains cool minifilament material. It might be that the addition of cool, denser, minifilament material is required in order for the feature to appear as a white-light jet, but this is not yet established.)

The twist that has been transferred to the open field should then propagate outward as a magnetic-twist pulse at the Alfvén speed. In the inner heliosphere, the Alfvén speed ($=B/(4\pi \rho)^{0.5}$, where $B$ is the field strength and $\rho$ the plasma mass density) decreases with distance from the Sun. In the corona we can expect an Alfvén speed of 1000 km s$^{-1}$ (e.g. in coronal holes), while PSP found an Alfvén speed of $\sim 100$ km s$^{-1}$ at its perihelion of $\sim 35$ R$_\odot$ ([12]), confirming a substantial gradient in the Alfvén speed with distance from the Sun.

The effect of this gradient is that an Alfvén-wave pulse of finite length will feel different local Alfvén speeds along its extent. An Alfvén wave packet propagates at different speeds between its ends: faster nearer the Sun and slower farther from the Sun. The result is a contraction, or “steepening,” of the pulse packet wave with distance (and hence time) as it moves out from the Sun (Fig. 2).

Following [14], taking a coronal Alfvén speed of 1000 km s$^{-1}$ and a typical jet lifetime of 10 min, we can expect the time for the minifilament flux rope to transfer its twist to the open coronal field to be $\sim 600$ s, so that the length of the Alfvén twist-wave pulse in the corona would be $\sim 600,000$ km. During the first PSP perihelion, the solar wind speed at PSP was $\sim 300$ km s$^{-1}$ ([59]). With the jet-produced Alfvén pulse riding on the wind at the local Alfvén speed of 100 km s$^{-1}$, the pulse will pass PSP at $\sim 400$ km s$^{-1}$. So if there were negligible contraction of the pulse between the corona and PSP we would expect the time for the passage to be about 25 min; with contraction, it is less than this.

4. A Possible Source for Shorter-Duration Switchbacks: Smaller-scale “Coronal Jets.”

From the above arguments, and given the variety of jet-lifetime durations (100—2000 s according to [60]), and with the expected contraction of the Alfvén pulse with travel time, it is plausible
Figure 2. This figure is from [14]. Schematic showing a Parker spiral heliospheric field (blue lines) that are curved relative to a radial line (black) extending out from the Sun (yellow circles). This is an extension of Fig. 1, where the twist transferred to the reconnected open coronal field through the interchange reconnection in Figs. 1(b) and 1(c) is the twist that is shown here in the open field, and which propagates outward as an Alfvénic pulse. In (a), the twist transferred to the open field becomes the red disturbance, that appears as a low-pitch twist wave packet moving outward (when launched from a coronal jet the radial extent of the twist packet is estimated be comparable to a solar radius, and so its extent is exaggerated by a factor of a few times compared to the Sun in this schematic representation). Panel (b) shows how the pitch of the disturbance could increase, as described in the text, as it moves further from the Sun and into a regime of lower Alfvén speed compared to that lower in the corona. In (c), this pitch-angle steepening of the impulse continues as it moves even further from the Sun. We suggest that this Alfvénic disturbance could appear as a “switchback” by the time it encounters PSP.

that coronal jets from minifilament eruptions could explain switchbacks of durations lasting a few minutes to a few tens of minutes. Given arguments that many larger-scale eruptions occur in circumstances similar to coronal jets (e.g., [61, 62]), we can expect that there will also be some longer-duration switchbacks ejected to the PSP perihelion location. As mentioned in §1, however, switchbacks durations range over less than one second to over an hour; if typical coronal jets account for switchbacks of a few minutes or tens of minutes, then somewhat-larger-scale coronal jets (or small-scale solar eruptions) might account for switchbacks of durations ~1 hr. Could the same scenario explain shorter-duration switchbacks? It turns out that there is some evidence that frequently occurring jets that are smaller-scale versions of typical coronal jets do occur on the Sun. We now briefly discuss those in the context of switchbacks.
4.1. A Possible Jetlet-Switchback Connection

“Jetlets” are jet-like features that occur on a smaller scale than coronal jets. They were identified ([63]) in AIA EUV images at the base of coronal plumes, occurring at sites where magnetic minority polarity elements cancel with surrounding field. That [63] study argued that the jetlets and other cancelation-induced transients are the main energy source for the plumes. Subsequently, [64] examined ten jetlets, using both EUV images from AIA and UV images from the Interface Region Imaging Spectrograph (IRIS) spacecraft. They found that the jetlets occurred at the boundaries of the magnetic network, and that they were not restricted to plume locations. According to [64], jetlets have on average widths of about 3000 km and live about 3 min, values that are about three-times smaller than the corresponding values for typical coronal jets ([4]). Jetlet speeds of \(~70 \text{ km s}^{-1}\) ([64]) are comparable to those found for coronal jets (\(~70—100 \text{ km s}^{-1}\), [65, 23]). [64] found them to have average maximum spire lengths of 27,000 km and 16,000 km when measured respectively in EUV (AIA 171 Å) and UV (IRIS S IV slit-jaw images); which is substantially shorter than typical spire lengths of coronal jets observed in X-rays (50,000 km, [4]).

[64] and [66] argue that many jetlets are small-scale version of coronal jets. Although no minifilament eruption has been observed at their base, they do share other similarities with jets, including evidence that they occur at sites of magnetic flux cancelation, and that brightenings are frequently observed at the base of the jetlets near the time of their onset. There are also hints that some jetlet spires may show spinning motions as they grow.

Building on this evidence that jetlets are small-scale coronal jets, if we further assume that they are produced as described in §2, that is, cancelation of sheared magnetic flux builds a twisted flux rope that erupts and produces the jetlet (Fig. 1) and imparts spin to it, then we can speculate that the jetlets might also be a source for switchbacks. (N. Raouafi (2019, private communication) speculated that jetlets are the source of switchbacks; also see [12].) Following the discussion in §3, we can estimate the maximum size and PSP-passage duration of the jetlet switchbacks. With a 3-min lifetime and coronal Alfvén speed of 1000 km s\(^{-1}\), a \(~180,000 \text{ km Alfvénic pulse packet would be expected to be loaded onto the low-coronal open field at the site of the jetlet’s formation. A pulse of this size will pass PSP in 7.5 min, even without any contraction; with contraction we can expect the durations of the jetlet-generated switchbacks to be of order a few minutes.

4.2. A Possible Spicule-Switchback Connection

Could switchbacks be made the same way on even smaller-size scales than jetlets? Extending the same concept of jetlets being coronal jets occurring on reduced size scales, it could be that at least some chromospheric spicules are made in a similar manner as jets but on a size scale even smaller than jetlets, and hence produce switchbacks of even shorter PSP-passage durations.

Spicules have been observed for a long time with a wide variety of instruments. They are jet-like features, but even delineating their properties has been a challenge, as those observed properties are dependent on both the instruments and wavelengths used, also on the resolution and time cadence of any particular instrument. Some general approximate numbers are that they have maximum lengths of a few thousand kms, widths of a few hundred km, and lifetimes of a few minutes, as discussed in several reviews and summary papers (e.g., [67, 68, 69, 70, 7, 71]). There are many ideas for how they are created, as discussed in the same review papers, while some more recent investigations include [72] and [73].

It has been suggested ([74]) that at least some spicules might be small-scale versions of coronal jets. Recent high-resolution on-disk spicule observations ([71, 75]) furthered this argument. It has long been suspected (e.g., [76]) that some spicules spin, and now this has been shown for some spicules spectroscopically ([77]). Also, recent high-resolution observations by [71] show that magnetic activity, at least some of which might be flux cancelation, occurs at the base
of at least some spicules. These two aspects - spin and possible flux cancelation - along with their general jet-like appearance, are qualities of spicules that are similar to many coronal jets. “Microfilament” eruptions making spicules, potentially corresponding to the minifilament eruptions that often make coronal jets, have not been compellingly detected, and therefore the idea that spicules are scaled-down coronal jets is still speculative. Nonetheless, a simple extrapolation of number of erupting filament-like features on the Sun as a function of the size of those erupting filaments ([74]) suggests that at least some coronal-jet-like features of the spicule-size category could be present in the chromosphere, independent of the question of whether that mechanism would make up a majority of spicules or only a small fraction of the total spicule population.

If some spicule-like features are produced by microfilament eruptions by the same process that makes many coronal jets (Fig. 1), then we can ask what a corresponding switchback might look like from that population of spicules. A spicule’s microfilament eruption timescale might be 30 s—1 min, based on the candidate erupting microfilaments identified in [75]. This gives a twist-pulse length in the corona of ~30,000—60,000 km. Sticking with our earlier assumptions and just considering a pulse of this size, it would pass PSP in just 75—150 s, and so ~2 min. With contraction as envisaged in Fig. 2, this time period - at least for the part of the pulse displaying the most rapid magnetic-field-direction changes - would be ~1 min, down to perhaps as short as a few tens of seconds.

It has already been proposed that a reconnection-like process simultaneously produces spicules and generates propagating coronal waves within plumes ([78, 79]), which could be consistent with our view in Fig. 2. In addition, high spatial- and temporal-resolution studies show that incompressible transverse motions occur ubiquitously in mottles/spicules ([80, 81, 82, 83, 84, 85, 86]); whether these motions result from dynamics such as low-altitude reconnections and twist transfer as envisioned in Fig. 1 is a topic for future investigation.

5. Discussion and Conclusions
There is now excellent evidence that many quiet Sun and coronal hole jets are made by minifilament eruptions. There is good evidence that in many cases the minifilament flux rope is built and triggered to erupt by magnetic flux cancelation. In many cases, active region jets develop and form the same way, but the process can be complicated by the more-complex and rapidly evolving magnetic environment of active regions compared to quieter solar regions. If the so-formed minifilament flux rope has twist prior to its eruption, then via the scenario of Fig. 1, it will transfer much of that twist to the open field with which it reconnects, inducing the often-observed twisting motion of the jet spire. We have argued that the twist plausibly could propagate out to PSP-perihelia locations as an Alfvénic twist-wave pulse. Alfvén-speed decrease in the heliosphere with radial distance from the Sun could then lead to a steepening of the kink in the magnetic field in the pulse as it travels away from the Sun along a Parker spiral, as depicted in Fig. 2. For the case of coronal jets, we have argued that PSP could see the passage of that kinked Alfvénic pulse as a switchback of likely duration of several tens of minutes. Larger jets, and larger (but still small-scale) filament eruptions, might result in switchbacks with passage times of ~1 hr.

If jetlets work in the same way as these coronal jets, then they could similarly produce PSP-observed switchbacks of likely duration of the order of several minutes. If we further speculate that some portion of the spicule population are similarly produced scaled-down jets, then they could result in PSP-observed switchbacks of likely duration of a couple of minutes, down to a few tens of seconds.

Our work here does not directly explain very short duration switchbacks, down to a few seconds or even less than a second. It should be expected however that PSP sometimes skirts by (nicks the edge of) a jet-induced switchback (rather than encountering the full wave packet
along the packet’s direction of travel), substantially shortening the encounter duration. In this sense, the durations that we have derived above can be viewed as upper limits to the expected duration of the switchbacks encountered by PSP.

At this point in time, as the scale size decreases our story becomes more speculative. For example, we have not unquestionably detected the equivalent of a cool-material minifilament eruption in jetlets or spicules. This however could be a natural limitation of current observational capabilities. Future investigations with current and future instruments should address further the question of the origin of these features.

Also, future numerical simulations should address how Alfvénic twist-wave pulses launched in the low solar atmosphere will evolve as they propagate out to PSP locations. Numerical simulations by [87] show that Alfvénic impulses can indeed maintain their integrity for estimated distances of tens of $R_\odot$ in the solar wind, given calm-enough solar-wind conditions. Codes such as that of [87], and others, for example codes those of [88] and [89] that model magnetic connections between the photosphere and the heliosphere, might be appropriate for investigations into the ideas discussed here, provided such codes include modeling of the minifilament-field eruption that drives the jet.

Our schematic in Fig. 2 explains how the twist pulse might steepen into a $\sim$90-degree swing in field direction from the solar radial direction (it might be slightly larger than 90 degrees from radial, due to the Parker-spiral angle). It does not however picture an “extreme” switchback, of swing angle substantially greater than 90 degrees. Such large-angle switchbacks are relatively uncommon, but seemingly more frequent further from the Sun ([90]). It is possible that the twist wave that we envision might evolve into such a state on small-enough length scales, where the wave pulse encounters a local solar wind inhomogeneity, for example. Numerical simulations incorporating appropriate solar-wind physics might be able to address this question. On the other hand, recent PSP investigations show that the typical switchback field-rotational angle increases with radial distance from the Sun ([90]), which is consistent with the picture of Fig. 2.

If coronal jets and similar jet-like features are the source of the switchbacks, then we would expect the rate of switchbacks encountered by PSP with closer and closer perihelia continually to remain high or increase, while the average swing angle continually decreases. If other ideas for switchback origin predict different trends of switchback frequency and swing angle with distance from the Sun (for example, some ideas might predict the switchbacks to start at a certain radial distance from the Sun, while our idea predicts their existence from the low-corona outward), then the findings from upcoming PSP perihelia might be used to help narrow candidate ideas for switchback generation.

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