Suprathermal electron flux peaks at stream interfaces: Signature of solar wind dynamics or tracer for open magnetic flux transport on the Sun?

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Suprathermal electron flux peaks at stream interfaces: Signature of solar wind dynamics or tracer for open magnetic flux transport on the Sun?

N. U. Crooker,[1] E. M. Appleton,[1] N. A. Schwadron,[1,2] and M. J. Owens[3]

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[1] The high variability of the intensity of suprathermal electron flux in the solar wind is usually ascribed to the high variability of sources on the Sun. Here we demonstrate that a substantial amount of the variability arises from peaks in stream interaction regions, where fast wind runs into slow wind and creates a pressure ridge at the interface. Superposed epoch analysis centered on stream interfaces in 26 interaction regions previously identified in Wind data reveal a twofold increase in 250 eV flux (integrated over pitch angle). Whether the peaks result from the compression there or are solar signatures of the coronal hole boundary, to which interfaces may map, is an open question. Suggestive of the latter, some cases show a displacement between the electron and magnetic field peaks at the interface. Since solar information is transmitted to 1 AU much more quickly by suprathermal electrons compared to convected plasma signatures, the displacement may imply a shift in the coronal hole boundary through transport of open magnetic flux via interchange reconnection. If so, however, the fact that displacements occur in both directions and that the electron and field peaks in the superposed epoch analysis are nearly coincident indicate that any systematic transport expected from differential solar rotation is overwhelmed by a random pattern, possibly owing to transport across a ragged coronal hole boundary.

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1. Introduction

[2] Suprathermal electrons (>80 eV at 1 AU) continually stream outward from the Sun along magnetic field lines. Their intensities in the heliosphere are highly variable, and several studies that address that variability have focused upon their solar source. For example, solar energetic electron bursts often extend down to suprathermal energies, creating distinctive time variations in intensity [e.g., *Gosling et al.*, 2003], and spatial variations of suprathermal electron sources on the Sun are thought to be responsible for differences in intensity observed on either side of the heliospheric current sheet [*Gosling et al.*, 2004]. The focus in this paper, instead, is on changes in suprathermal electron intensity associated with solar wind dynamics, specifically, with stream interaction regions. As will become apparent, however, we note at the outset that it is not clear whether stream interactions are the direct cause of the changes.

[3] As is well-established [e.g., *Pizzo*, 1978], stream interaction regions form in the spiral geometry of the heliospheric magnetic field where fast solar wind from coronal holes runs radially outward into slow wind from the streamer belt, creating a pressure ridge at the interface between them. The pressure ridge, often characterized by a peak in magnetic field magnitude, spirals out from the Sun, and the flow away from it generated by the pressure gradient is responsible for the well-known east–west deflection signature. The compressed plasma constitutes the stream interaction region, which corotates with the Sun. Section 2 of this paper uses superposed epoch analysis to demonstrate that the stream interaction region contains a strong signal in the time variation of suprathermal electron intensity.

[4] Superposed epoch analysis of electron parameters derived from models fit to distribution functions measured across stream interaction regions was performed some time ago by *Gosling et al.* [1978] and *Feldman et al.* [1978]. Their results, discussed in section 3.1, combined with our analysis of case studies in section 2 raise the possibility of a solar source for the suprathermal electron intensity profile in stream interaction regions. That possibility is discussed in section 3.2 in terms of potential implications for open

[1]Center for Space Physics, Boston University, Boston, Massachusetts, USA.
[2]Now at Space Science Center, University of New Hampshire, Durham, New Hampshire, USA.
[3]Space Environment Physics Group, Department of Meteorology, University of Reading, Reading, UK.

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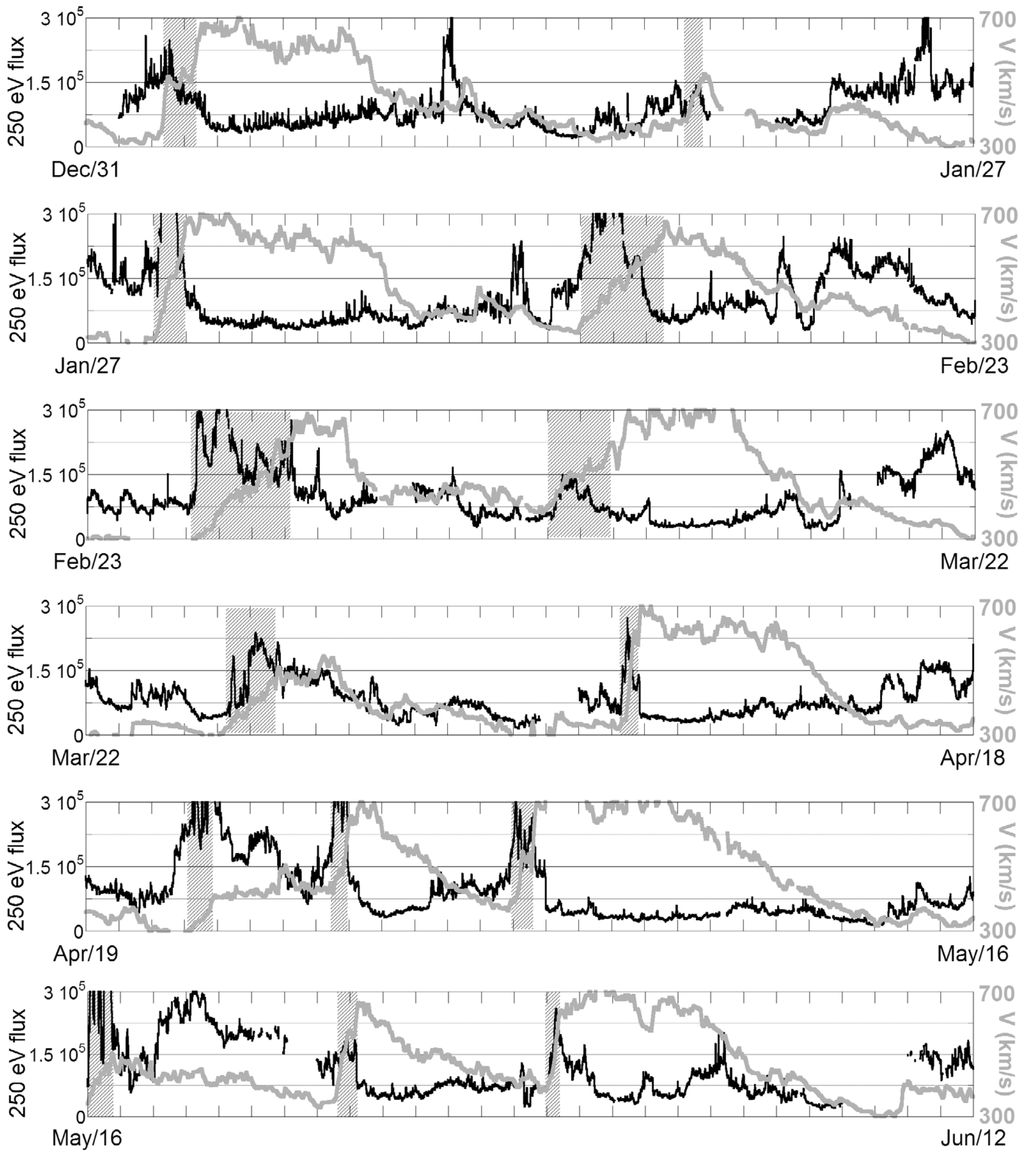

Figure 1. Twenty-seven-day recurrence plots of 250 eV electron number flux integrated over pitch angle in units of cm^{-2} s^{-1} sr^{-1} (black) and solar wind speed (gray) observed by Wind in 1995. Hatched intervals show flux peaks coincident with rising speed in stream interaction regions.

magnetic flux transport on the Sun. Open flux transport occurs when interchange reconnection takes place, that is, when an open field line, rooted on the Sun at only one end, reconnects with a closed field line, a loop rooted at both ends [e.g., *Fisk et al.*, 1999; *Crooker et al.*, 2002]. The result is that the foot of the open field line saltates (jumps) to the point which originally lay at the far foot of the loop [e.g., *Merkin and Crooker*, 2008].

[5] Open magnetic flux transport by interchange reconnection at the Sun presumably can be sensed at 1 AU by comparing suprathermal electron and plasma signatures of the same boundary [*Borovsky*, 2008]. Since suprathermal electrons travel to 1 AU along the magnetic field in only a few hours whereas plasma, convecting radially outward at the solar wind speed, takes 4–5 d, it follows that any change in boundary location owing to flux transport during those ~4–5 d might be detected as a displacement between the electron and plasma signatures of the boundary at 1 AU. The solar boundary relevant to the results presented here is the coronal hole boundary, which, in some views [e.g., *Fisk et al.*, 1999], maps out to stream interfaces and separates open from closed magnetic flux on the Sun. Changes in the coronal hole boundary by open flux transport should yield a displacement between suprathermal electron and plasma signatures of the interface. Open flux transport at the coronal hole boundary is thought to be the means by which the boundary moves rigidly with the Sun in the presence of global differential rotation [e.g., *Nash et al.*, 1988; *Wang and Sheeley*, 2004], and flux transport across the boundary has been predicted as a means of closing large-scale circulation cells of magnetic foot points in the photosphere set up by differential rotation in the presence of a dipole axis tilted with

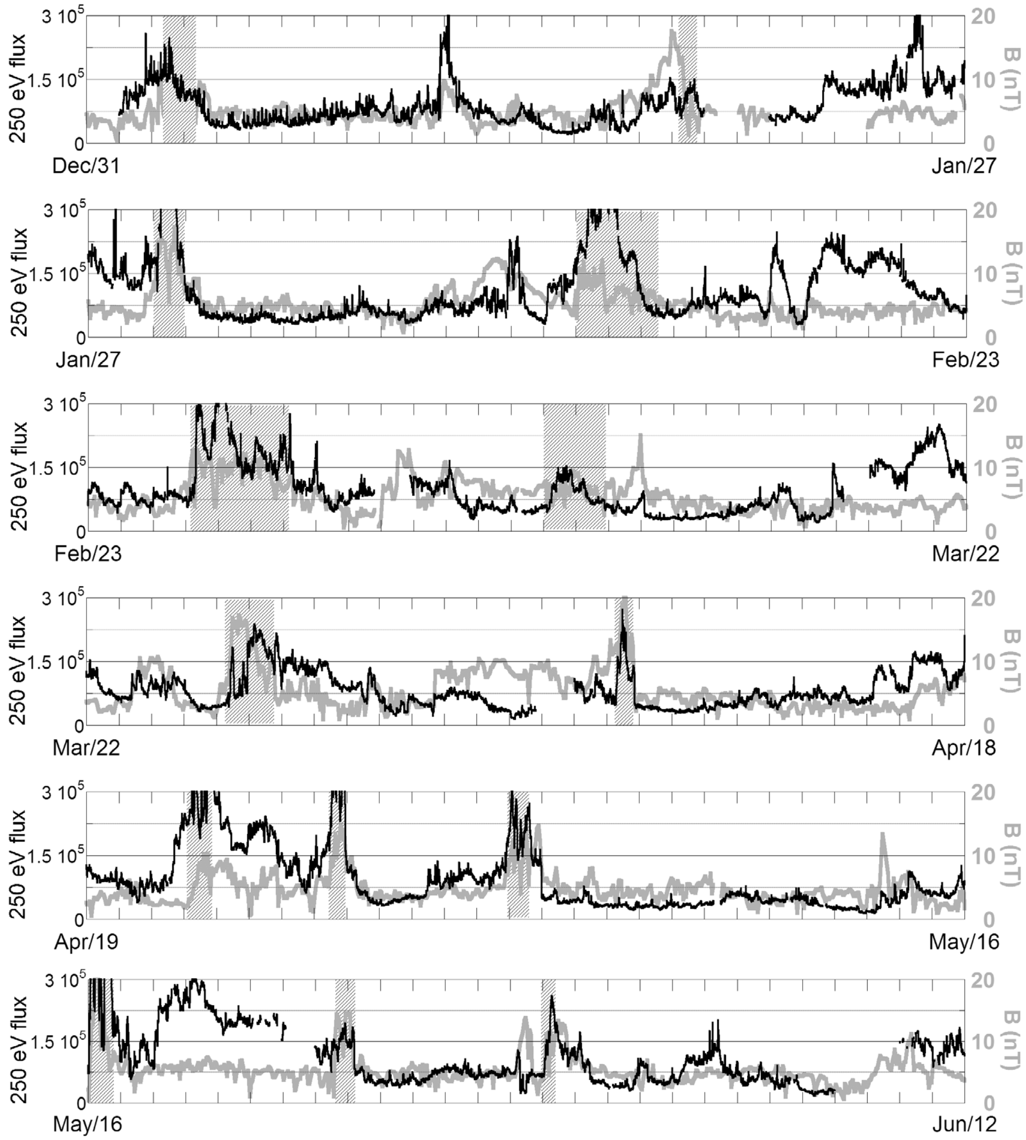

Figure 2. Twenty-seven-day recurrence plots of 250 eV electron number flux integrated over pitch angle in units of $cm^{-2}\ s^{-1}\ sr^{-1}$ (black) and magnetic field magnitude (gray) observed by Wind in 1995. Hatched intervals show flux and field peaks in stream interaction regions.

respect to the rotation axis [*Fisk et al.*, 1999]. Section 3.2 discusses these ideas in light of apparent interface signature displacements.

2. Analysis

[6] The parameter we use to characterize suprathermal electron intensity is number flux integrated over pitch angle in an energy band central to the suprathermal range, in this case, centered on ~250 eV [cf. *Pagel et al.*, 2005; *Crooker and Pagel*, 2008]. Time variations of 10 min averages of this electron flux measured by the 3-D plasma and energetic particle instrument [*Lin et al.*, 1995] on the Wind spacecraft are shown in black in Figure 1 for six successive Carrington Rotations of the Sun in 1995. High variability is evident.

[7] To some extent the variability of electron flux in Figure 1 is ordered by solar wind speed. During the period shown, the solar wind displayed a pattern of recurrent high-speed streams [e.g., *Crooker et al.*, 1996], as can be seen in the time variations of hourly averages of speed plotted in gray in Figure 1, from measurements by the Solar Wind Experiment [*Ogilvie et al.*, 1995] on the Wind spacecraft. Whenever the gray trace rises above the 500 km/s level, midway up the scale, the black trace dips to low, steady values, resulting in a characteristic pattern of separation between the traces. Thus, in the high-speed flow, the electron flux tends to be low, and its time variation tends to be smooth. These qualities have also been noted for electron heat flux, which is carried by the suprathermal electrons, and for suprathermal electron temperature [*Feldman et al.*, 1978]. In the slow wind, the electron flux tends to be elevated and much more variable. At the end of each interval of variability, there is a noticeable tendency for the flux to peak on the leading edge of the approaching high-speed stream, where speed is rising rapidly. Each of these intervals of rising speed is indicated by hatching in

Table 1. Times of Stream Interface Passage at the Wind Spacecraft in 1995[a]

Date	UT	Date	UT
02 Jan	0929	30 May	0646
18 Jan	0341	19 Jun	0952
29 Jan	0600	25 Jun	1933
11 Feb	0906	16 Jul	1627
26 Feb	1102	07 Aug	1956
09 Mar	1015	14 Aug	0145
26 Mar	1102	05 Sep	1517
07 Apr	1235	02 Oct	1604
22 Apr	1800	18 Oct	1956
26 Apr	1933	30 Oct	1454
02 May	0623	05 Nov	1321
16 May	0952	27 Nov	0929
23 May	1650	24 Dec	0906

[a]Courtesy R. L. McPherron.

Figure 1. They identify the stream interaction regions described in section 1, where fast wind runs into slow wind and creates a pressure ridge.

[8] Since an excellent signature of the pressure ridge in stream interaction regions is a peak in magnetic field strength, from the pattern in Figure 1 one might expect some correlation between field strength and electron flux. This is evident in Figure 2, plotted in the same format as Figure 1. Hourly averages of field strength from measurements by the Magnetic Field Investigation [*Lepping et al.*, 1995] show peaks that tend to coincide with peaks in electron flux, particularly in the hatched interaction regions which have been transferred from Figure 1. *Scime et al.* [1994] reported a similar match between field strength and electron heat flux.

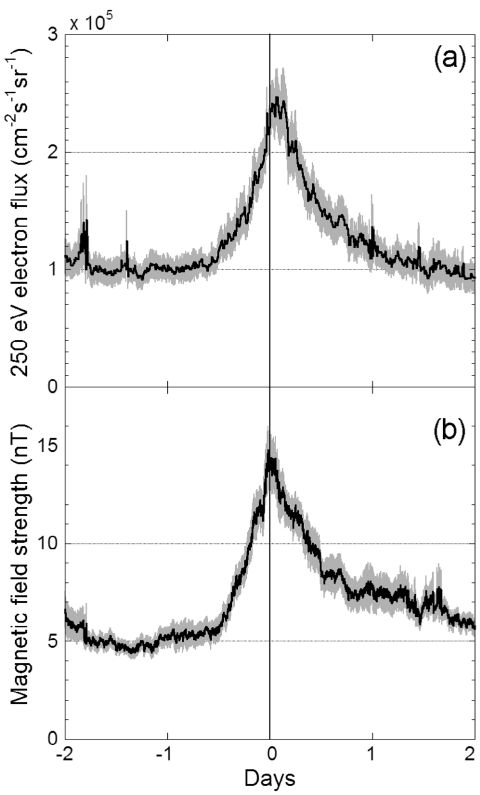

Figure 3. Results of superposed epoch analysis centered on 26 stream interfaces. The gray band shows the extent of the standard error of the mean. (a) The suprathermal electron flux peaks ~1.5 h after the interface, and (b) the field magnitude peaks at the interface.

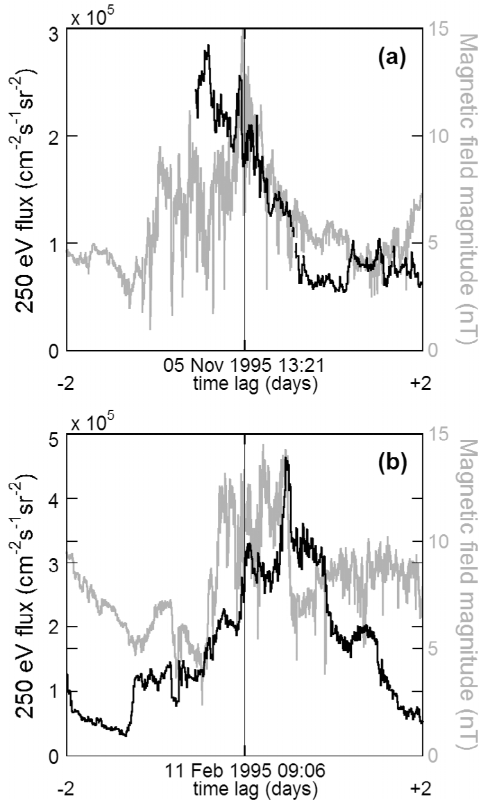

Figure 4. Time variations of suprathermal electron flux (black) and magnetic field magnitude (gray) across two interfaces. In Figure 4a the flux leads the field, and in Figure 4b the flux lags the field.

[9] To confirm what seems evident by eye in Figure 2, we performed a superposed epoch analysis on 1995 Wind data centered on 26 stream interfaces identified by *McPherron and Siscoe* [2004] and *McPherron et al.* [2005] based on their distinctive east–west flow deflections. The interface times are listed in Table 1, and the results of the superposed epoch analysis are displayed in Figure 3. Figure 3a shows a remarkably pronounced peak in the 10 min averages of 250 eV electron flux. It is nearly coincident with the interface, lagging by ~1.5 h. Since the ordinate scale in Figure 3a spans the same range as in Figures 1 and 2, it is clear that a substantial amount of the electron flux variability in those figures (Figures 1 and 2) is associated with stream interaction regions, as discussed further in section 3.1. Figure 3b shows a pronounced peak in 1 min averages of magnetic field strength, as expected. The peak is centered on the interface, reflecting the pressure ridge there.

[10] A detailed comparison of the time variations of electron flux and field strength for each case reveals much variability compared to the smoothed results of the superposed epoch analysis. Many cases show multiple mismatched peaks in the vicinity of the stream interface, reflecting complicated structure [cf. *Wimmer-Schweingruber et al.*,

1997]. Two cases are shown in Figure 4. In Figure 4a, the magnetic field strength peaks at the interface, whereas the electron peak precedes the field peak at the interface by 10 h. In Figure 4b, the signatures are more structured. The field peak is broad, slightly offset from the interface, and topped with multiple smaller peaks. The electron flux displays a comparably broad peak offset from the field peak by ~10 h and topped by a spike offset from the interface by 11 h. Despite these complications, the overall impression is that Figure 4b is the converse of Figure 4a, with the electron peak lagging rather than leading the field peak by ~10 h. The possible significance of the displacements between the peaks in electron flux and field strength is discussed in terms of open flux transport in section 3.2.

3. Discussion

3.1. Electron Flux and Solar Wind Dynamics

[11] The similarity between the amplitude of the suprathermal electron flux peak at the stream interface in the superposed epoch analysis result in Figure 3a and the amplitude of flux variations as a function of time in Figures 1 and 2 indicates that interplanetary dynamics is at least associated with if not responsible for a major component of the time variability in electron flux. Although changes owing to time variations in solar source may dominate at phases of the solar cycle in which high-speed streams are less prevalent, the relative strength of the peak in Figure 3a is somewhat surprising.

[12] It may seem like the obvious cause of the peak in electron flux at the interface is interplanetary dynamics, that is, the compression there from the interacting streams, but one cannot rule out the possibility of a solar source. If suprathermal electrons spiraling along field lines are viewed as beads along strings, then one would expect that increasing the density of the strings through compression would also increase the density of the beads. The earlier results of *Gosling et al.* [1978] and *Feldman et al.* [1978], however, suggest otherwise, that temperature rather than density may be the cause of the flux peak. Although these authors used a now outdated core-halo model of the electron distribution that inadequately accounts for the directed strahl, in their superposed epoch analysis of model parameters they found interface-associated peaks in heat flux, which is carried by the suprathermal electrons, and in the temperature of the halo (suprathermal) electrons. Specifically, *Gosling et al.* [1978] show a pronounced peak in the halo temperature centered on the interface, but the halo density there barely rises above noise level. Since a rise in temperature without a larger rise in density implies an increase in entropy that cannot be the result of compression, we consider the possibility that this pattern has a solar origin.

[13] A feature that is even more suggestive of a solar origin is the displacement of the electron flux peaks from the interfaces in Figure 4. The electron peaks clearly were not generated by the local compression at the interface, as identified by the flow deflection there and reflected in the field peaks. While one can always argue that some time variation in the flux of electrons from the Sun was responsible for the misalignment of the electron flux peak with the region of compression, the next section considers the possibility that instead the peak is a spatial signature of the coronal hole boundary.

3.2. Implications for Open Flux Transport

[14] As described in section 1, following *Borovsky* [2008], a displacement between suprathermal electron and plasma boundaries observed at 1 AU may be a signature of open flux transport by interchange reconnection back at the Sun. Here we address possible transport across the coronal hole boundary at the Sun, assuming that the coronal hole boundary maps out to the stream interface at 1 AU, as in models where slow flow originates from closed fields on the Sun. For the purpose of this discussion, we further assume that the observed peak in flux at the stream interface is the suprathermal electron signature of the coronal hole boundary and compare this signature with the peak in magnetic field magnitude there, which we use as a well-established proxy for the plasma signature of the boundary. (The compression that creates the field peak is local, of course, but what creates the compression is understood to be the solar configuration of the source of fast flow abutting the source of slow flow at the coronal hole boundary.) We note that while the assumption of peak electron flux at the coronal hole boundary is central to our interpretation, the cause of the peak is left as an open question.

[15] Some of the 26 cases of interface crossings used in this study show displacement between the electron and field interface signatures that imply flux transport in both directions. For example, the ~10 h lag of the electron peak behind the field peak in Figure 4b implies eastward displacement of the interface across ~6° of longitude, assuming a 27 d solar rotation rate. Figure 5 illustrates how this displacement could be the outcome of interchange reconnection on the Sun. Figure 5 places *Borovsky*'s [2008] Figure 16 in the context of stream interaction regions, where his pink and green volumes now represent fast and slow flow, respectively. The two views represent the configuration before (Figure 5a) and after (Figure 5b) reconnection. Two field lines rooted in the coronal hole in Figure 5a reconnect with the oppositely directed legs of two of the adjacent loops in the streamer belt. The first field line to reconnect is the heavy line at the coronal hole boundary that traces out to the stream interface. It is shown in its new configuration in Figure 5b as a dashed heavy line, with its foot point now deep inside the streamer belt, adjacent to the helmet streamer at the foot of the heliospheric current sheet. Out in the heliosphere the dashed line still threads the pressure ridge where the field peaks between the fast and slow flow, but the peak suprathermal electron flux now follows the trailing (solid, heavy) field line that traces back to the new coronal hole boundary. This field line will thread the new interface once the plasma at its foot point convects out to the observing point. Reconnection of the second field line rooted in the coronal hole in Figure 5a is shown as just having occurred in Figure 5b, with a sharp kink indicating proximity to the reconnection site. As a result of the reconnection, Figure 5b shows that two new loops appear adjacent to the new coronal hole boundary, the boundary itself has been displaced eastward, and two open field lines have saltated westward, from the coronal hole into the streamer belt. For eastward saltation and westward displacement of the boundary, corresponding to the case in Figure 4a (and to

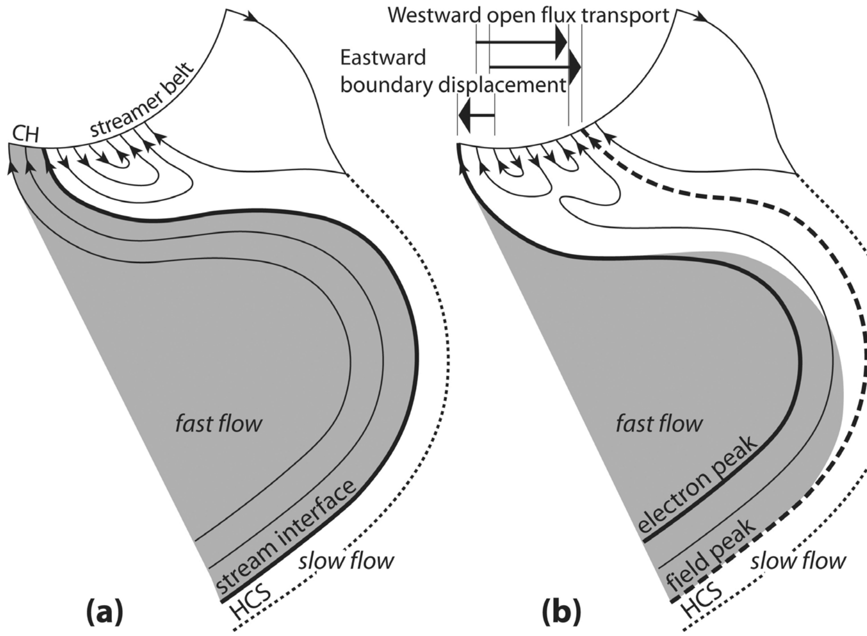

Figure 5. Schematic cross section of the magnetic field configuration in the ecliptic plane (a) before and (b) after interchange reconnection transports open flux from the coronal hole (CH) to the streamer belt. In the heliosphere, the magnetic field peak marking the pressure ridge at the stream interface remains at the boundary between fast flow (gray) from the CH and slow flow (white) encompassing the heliospheric current sheet (HCS), but after reconnection the field-aligned suprathermal electrons immediately stream out from the newly displaced CH boundary marked by a field line that trails the pressure ridge. The magnetic field line that originally connected the interface to the CH boundary (heavy curve, solid in Figure 5a, dashed curve in Figure 5b) has saltated deep into the streamer belt.

the predictions of the model by *Fisk et al.* [1999] discussed below), one begins with nested loops with polarity opposite to that drawn in Figure 5a and reconnects their inner legs with open field lines adjacent to the helmet streamer, in essence reversing the illustrated reconnection process.

[16] We note that interchange reconnection across the coronal hole boundary, as illustrated in two dimensions in Figure 5, requires an intrusion of open flux into a region of closed fields. In three dimensions under steady conditions, however, regions of open flux must be topologically connected [e.g., *Crooker and Siscoe*, 1990; *Antiochos et al.*, 2007]. Thus, strictly speaking, the newly transported open flux in Figure 5b does not lie as an open island within the closed streamer belt but rather lies in the cross section of a lobe of open field that extends from the coronal hole. This caveat plays a role in the interpretation of our results, as discussed below, but for convenience we continue to describe flux transport in terms of crossing the coronal hole boundary.

[17] While the displaced peaks in Figure 4 give evidence of interchange reconnection on a case-by-case basis, the near-coincidence of the two interface signatures in the superposed epoch analysis in Figure 3 indicates that, on average, there is essentially no systematic transport in a given direction across the coronal hole boundary. As mentioned in section 1, the possibility of systematic flux transport was proposed by *Fisk et al.* [1999] as a means of closing circulation cells in the model by *Fisk* [1996]. The proposed pattern of flow is specific about the direction of flux transport across the coronal hole boundary with respect to the pattern of stream interactions. From the schematic diagram of *Fisk et al.* [1999] (their Figure 3), one can deduce that flux should move from the coronal hole to the streamer belt in regions of rarefaction, where slow flow trails fast flow, and from the streamer belt to the coronal hole in regions of compression, like those analyzed here (opposite to the direction shown in Figure 5). This sense of transport would reveal itself as peak field strength lagging peak electron flux at the interface, as in the case shown in Figure 4a, but there is no evidence of this lag in the superposed epoch analysis in Figure 3. Even if the ~1.5 h lag there is treated as significant, it goes in the wrong direction. More recently, based on constraints deduced from composition observations, *Zhao and Fisk* [2010] have proposed that the circulation resulting from the model of *Fisk* [1996] closes just poleward of a newly defined streamer stalk boundary, with no transport across it. If the streamer stalk boundary is treated as the coronal hole boundary, then the new view sounds consistent with the results presented here. This is not true, however, because the streamer stalk boundary lies within the source of slow flow and separates completely closed fields from the mix of open and closed fields undergoing interchange reconnection. *Zhao and Fisk* [2010] thus separate the streamer stalk boundary from the boundary between fast and slow flow, and flux transport across the fast-slow boundary remains systematically westward at the base of stream interaction regions. In the context of their model, our results pertain to the fast-slow boundary and so remain inconsistent with the model prediction of systematic transport.

[18] We offer two possible explanations for the lack of an observed signature of the systematic transport expected from the Fisk models. First, the signature may be missing in the 1995 data because the Sun was not configured in the idealized tilted dipolar pattern used in the model. A quadrupolar field dominated, as was evident in the four-sector structure [*Crooker et al.*, 1996; *Wang and Sheeley*, 2009]. A considerably more intriguing explanation, however, lies in the recent work of S. K. Antiochos et al. (A model for the sources of the slow solar wind, submitted to *The Astrophysics Journal*, 2010) and related work of *Edmondson et al.* [2010], based on the topological concepts discussed by *Antiochos et al.* [2007]. They argue that the boundary between closed and open flux is highly irregular, suffused with small-scale convolutions. It is thus likely that the convolutions are created by interchange reconnection, that the poleward boundary of the band of finite width formed by the convoluted boundary is a ragged, fast-slow boundary, similar to the configuration proposed by *Zhao and Fisk* [2010], and that any signature of systematic flux transport across that boundary would be overwhelmed by a random signal owing to its irregular shape.

[19] Finally, we discuss the expectation of a signature of systematic flux transport across the coronal hole boundary from interchange reconnection that maintains the rigid rotation of coronal holes [e.g., *Nash et al.*, 1988]. This signature should be present independent of whether the dipolar or quadrupolar field dominates. As illustrated in Figure 9 of *Wang and Sheeley* [2004], the pattern of global differential rotation requires a prevailing westward drift of the coronal hole boundary at higher latitudes to keep up with the faster rotation rate at lower latitudes, and the westward drift should be accomplished by systematic flux transport from the streamer belt to the coronal hole along those segments of the coronal hole boundary that generate regions of compression in the solar wind. This is the same systematic transport required by the Fisk models, which is not observed, possibly owing to the irregular nature of that boundary, as discussed above. On the other hand, for coronal hole extensions that reach equatorial latitudes and rotate at the speed of midlatitude active regions, the boundaries drift eastward, with systematic flux transport from the coronal hole to the streamer belt. Since the Wind spacecraft orbits near the equatorial plane, it is possible that the observations are dominated by solar wind from low-latitude coronal hole extensions and that the ~1.5 h lag of the electron flux peak behind the stream interface in the superposed epoch analysis reflects that systematic eastward drift.

4. Conclusions

[20] We have used Wind data from 1995, when high-speed streams were prevalent in the solar wind, to identify a suprathermal electron signature of interfaces between slow and fast flow that takes the form of a peak in 250 eV number flux integrated over pitch angle. During 1995, peaks in electron flux at interfaces account for a surprisingly substantial amount of the observed time variability in flux at 1 AU, which is typically ascribed instead to time variations in solar source. The peaks may be generated by local compression, but occasional displacements from the local pressure ridge leave open the possibility that they arise from the coronal hole boundary on the Sun. If so, they can be used as remote sensors of interchange reconnection and consequent open flux transport. Case studies would then imply that transport occurs in both directions across the boundary. The results of a superposed epoch analysis of 26 cases, however, give little evidence of the systematic transport predicted by models that address the effects of differential solar rotation. An interesting possibility for this discrepancy is that any signal of systematic transport may be overwhelmed by a pattern of random transport created by recently postulated, small-scale convolutions in the boundary.

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E. M. Appleton and N. U. Crooker, Center for Space Physics, Boston University, 725 Commonwealth Ave., Boston, MA 02215, USA. (crooker@bu.edu)

M. J. Owens, Space Environment Physics Group, Department of Meteorology, University of Reading, Earley Gate, PO Box 243, Reading RG6 6BB, UK.

N. A. Schwadron, Space Science Center, University of New Hampshire, 354 Morse Hall, 8 College Rd., Durham, NH 03824-3525, USA.