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BRIEF REPORT

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Key Points:

- We use a new tool to help identify flows from streamers and pseudostreamers
- Both have plasma and composition signatures characteristic of slow solar wind
- Pseudostreamer signatures are slightly weaker than streamer signatures

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Comparison of interplanetary signatures of streamers and pseudostreamers

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Abstract If the source of the slow solar wind is a web comprising pseudostreamer belts connected to the streamer belt, then one expects the properties of interplanetary pseudostreamer flows to be similar to those of streamer flows. That expectation is tested with data from the slow wind preceding stream interfaces in stream interaction regions at 1 AU, where the interfaces separate what was originally slow and fast wind. Pseudostreamer cases were separated from streamer cases with the aid of the streamer identification tool developed by Owens et al. (2013), and superposed epoch analysis was performed to compare the patterns of a number of plasma and composition parameters. The results reveal that pseudostreamer flows have all of the slow-wind characteristics of streamer flows except that they are slightly less pronounced than streamer characteristics when compared to fast wind. The results are consistent with the concept that the solar wind displays a continuum of dynamic states rather than only slow and fast states.

1. Introduction

Recent studies indicate that slow solar wind comes from a web of connected streamer and pseudostreamer belts [*Antiochos et al.*, 2011; *Riley and Luhmann*, 2012; *Crooker et al.*, 2012], where the streamer belt encases the heliospheric current sheet (HCS) and the pseudostreamer belts lack current sheets. To analyze the interplanetary composition of this slow wind, *Crooker and McPherron* [2012] used data from the ACE spacecraft at 1 AU to perform a superposed epoch analysis of passage through 258 stream interfaces, which mark the boundaries between what was originally fast and slow flow. Stream interfaces presumably map back to the vicinity of the coronal hole boundary on the Sun [e.g., *Crooker et al.*, 2010]. Consistent with earlier studies [e.g., *Geiss et al.*, 1995; *Wimmer-Schweingruber et al.*, 1997; *Fisk et al.*, 1998], *Crooker and McPherron* [2012] concluded that all slow wind has ionic and elemental composition characteristic of the streamer belt (the "streamer stalk" wind of *Zhao and Fisk* [2011]). In particular, the result implied that slow wind from pseudostreamers, which can be located quite far from the HCS [*Antiochos et al.*, 2012; *Crooker et al.*, 2012], has the same composition as slow wind from the streamer belt. To test this implication directly, *Crooker and McPherron* [2012] performed a limited superposed epoch analysis on a select subset of stream interfaces separated according to whether the slow wind had a streamer (14 cases) or pseudostreamer (11 cases) source. They found that pseudostreamer flow had slightly higher speeds and lower O^{7+}/O^{6+} ratios than streamer flow, but the O^{7+}/O^{6+} ratio was high enough to meet the criterion for slow flow determined by *Zhao et al.* [2009].

This report expands upon that limited study by overcoming the difficulty of identifying pseudostreamer flows at interfaces. From interplanetary data alone, one can only identify pseudostreamer cases as those that lack a magnetic polarity reversal on the slow-flow side of the interface, since pseudostreamers contain no current sheet. The problem with this criterion is twofold. First, the criterion does not distinguish pseudostreamer cases from streamer cases in which the spacecraft skims the streamer belt without passing through it and thus does not encounter the polarity reversal signaling the HCS. Second, even if the spacecraft passes through the streamer belt, if it does so obliquely, the interface might trail so far behind the HCS crossing that it becomes unclear whether the two features are associated with each other. For this study we use a pseudostreamer identification method developed by *Owens et al.* [2013] that avoids these ambiguities and allows us to quadruple the number of pseudostreamer cases analyzed, thus improving the statistical reliability of the results. Cumulative distribution functions (as opposed to the simple averages in the limited study) are presented for the full complement of composition and plasma parameters, separated according to pseudostreamer or streamer source.

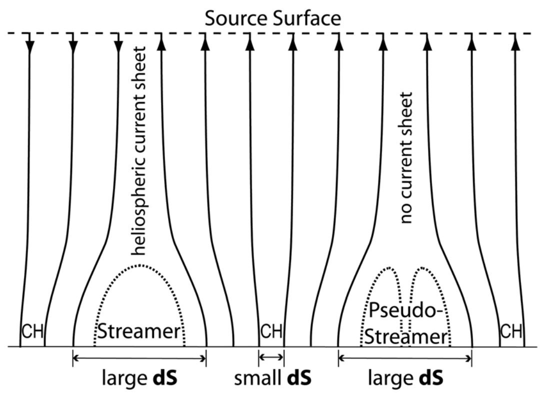

Figure 1. Schematic diagram illustrating the streamer identification parameter dS, the distance between the foot points of evenly spaced field lines on the source surface mapped down to the Sun's surface. Large values indicate streamers encasing the heliospheric current sheet or pseudostreamers with no current sheet, and small values indicate coronal holes (CH).

2. Analysis

To compare the properties of slow solar wind from streamers with slow wind from pseudostreamers, we began with the list of 258 stream interfaces provided by *Crooker and McPherron* [2012]. These span the period from March 1998 through December 2009 and were selected for their robust signatures of azimuthal velocity shear arising from the pressure ridge created by the fast wind running into the slow wind. The list was then reduced to those 128 cases that occurred during 69 Carrington Rotations (CRs) for which the uncertainty in the streamer identification parameter dS was reasonably low, following *Owens et al.* [2013, 2014].

The streamer identification parameter dS is illustrated in Figure 1. It is the distance between the photospheric foot points of evenly spaced field lines on the surface of a potential field source surface model. Small values of dS indicate mapping to coronal holes, and large values indicate mapping to the base of either streamers or pseudostreamers. These are distinguished from each other by the presence or absence of a change in polarity signaling a current sheet. Streamers separate the polar coronal holes of opposite polarity and encase the heliospheric current sheet. Sometimes they are called "dipolar streamers," to distinguish them from "pseudostreamers," the latter named by *Wang et al.* [2007], which separate coronal holes of like polarity and contain no current sheet.

Figure 2a shows a plot of the time variation of ln dS in the ecliptic plane at the Sun's central meridian during CR2007 in 2003. The dS values, in arbitrary units, were calculated from the two-dimensional formulation used

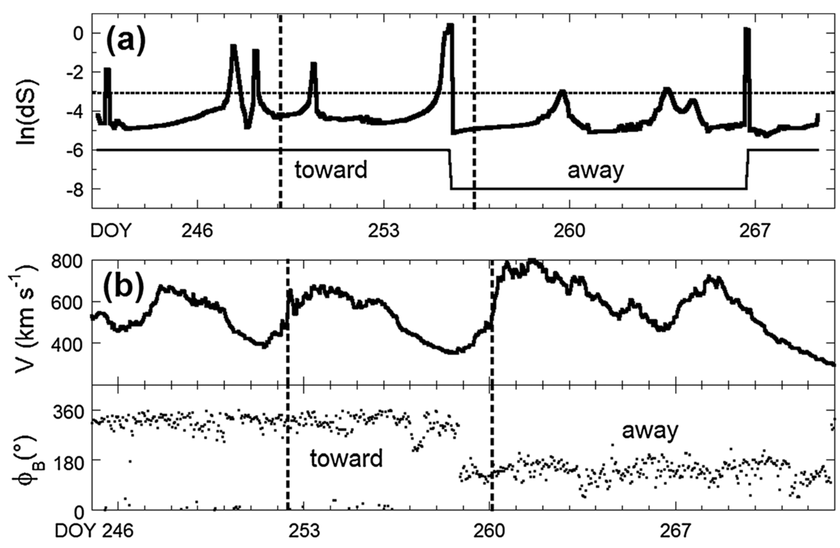

Figure 2. Analysis of the solar source of slow wind preceding two stream interfaces, marked by vertical dashed lines, observed by ACE at 1 AU on 9 September (day of year (DOY) 252) and 17 September (DOY 260) in 2003, during CR2007. (a) Time variations of the natural logarithm of the streamer identification parameter dS and of the magnetic polarity (thin line) at central meridian on the Sun in the ecliptic plane, calculated from a potential field source surface model. Stream interface locations were ballistically mapped back to the Sun from 1 AU. The first falls in the middle of a toward sector, implying that the peaks in ln dS there must indicate a pseudostreamer source. The second follows a sector boundary, implying that the peak in ln dS preceding it indicates a streamer source. (b) Time variations of solar wind speed V and longitude angle ϕ_B of the magnetic field in the ecliptic plane at 1 AU. The time scale is shifted by 3 days to account for solar wind travel time to 1 AU.

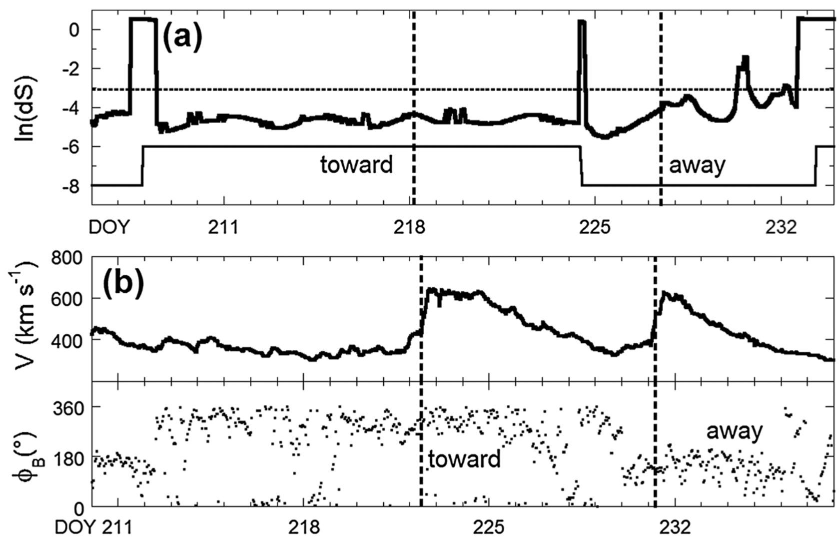

Figure 3. Analysis of the solar source of slow wind preceding two stream interfaces observed by ACE at 1 AU on 9 August (DOY 222) and 18 August (DOY 231) in 2008, during CR 2073, in the same format as Figure 2. Although the first interface falls in the middle of a toward sector, as in Figure 2a, in this case there is no preceding peak in ln dS indicating a pseudostreamer source. Instead, the source of the slow wind must have been the preceding streamer traversed obliquely.

by *Owens et al.* [2014], an improvement over the one-dimensional version first used by *Owens et al.* [2013]. The horizontal dashed line at ln dS = −3 marks the threshold above which peaks in ln dS locate streamers and pseudostreamers. The peaks typically lie between −2 and +0.5, while elsewhere the values are typically −5. Thus, the typical distance dS between field line foot points in streamers or pseudostreamers is on the order of 100 times the distance between foot points in coronal holes (much larger than illustrated in Figure 1).

Of particular interest in Figure 2 are the peaks immediately preceding the two vertical dashed lines marking the locations of two of the selected stream interfaces, which were ballistically mapped back to the Sun from 1 AU. These peaks lie on the slow-wind side of the interfaces. To test whether these peaks represent streamers or pseudostreamers, we check to see if they align with a magnetic polarity change, where polarity is indicated by the thin line below the ln dS curve. The double peak on days 247–248, preceding the first dashed line, falls in the middle of the sector with polarity pointing toward the Sun. We thus classify this case as a pseudostreamer source (although the double peak suggests an even more complicated structure). The peak on day 255, preceding the second interface, marks a streamer source because it clearly aligns with a polarity change.

The plots in Figure 2b provide context for the plots in Figure 2a. They show time variations of solar wind speed V and magnetic longitude angle ϕ_B in the ecliptic plane at 1 AU. There are two high-speed streams per sector rather than the generic single stream per sector [cf. *Crooker et al.*, 1996], consistent with mid-sector slow wind from pseudostreamers [cf. *Neugebauer et al.*, 2004]. The time scale is shifted by 3 days relative to Figure 2a to roughly account for solar wind travel time to 1 AU. The vertical dashed lines marking the two interfaces of interest fall on the leading edges of high-speed streams, as expected. The preceding slow wind contains a polarity reversal in the second case but not in the first, consistent with streamer and pseudostreamer sources, respectively.

In the cases shown in Figure 2, one would correctly deduce the sources from interplanetary data alone. This is not true for the cases shown in Figure 3, where the dS parameter plays a decisive role. Like Figure 2a, Figure 3a shows the first of two mapped interfaces falling near the middle of a toward sector, but in this case there is no preceding peak in ln dS that lacks a polarity reversal. The nearest peaks, on days 207–208 and 224, occur at polarity reversals marking the streamers at either end of the toward sector. With no ln dS peak in the middle of the sector, we must conclude that the slow wind preceding the interface did not arise from a pseudostreamer. Since the only other source of slow wind is a streamer, the

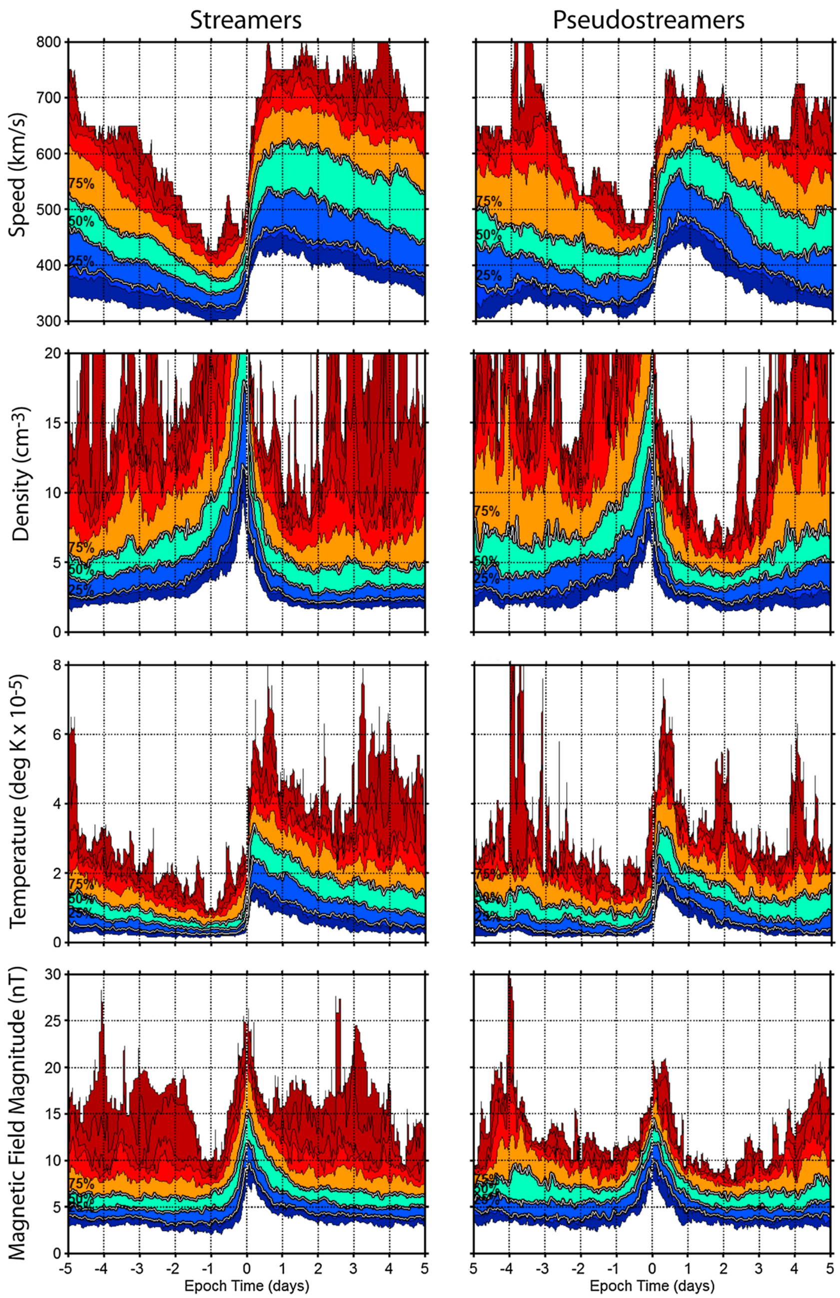

Figure 4. Cumulative distribution functions for plasma parameters across stream interfaces bounding slow flow from streamers compared to pseudostreamers. The heavy lines mark the quartiles of the distributions. The 50% quartile running between the blue and green bands traces the median values.

slow wind preceding the interface must have come from the preceding streamer on days 207–208, which reached central meridian 10 days earlier. This long period of time implies oblique passage through the streamer.

The interplanetary data in Figure 3b support the idea of oblique passage. The slow wind preceding the first interface extends all the way back to the polarity reversal on day 212, corresponding to the streamer on the Sun spanning days 207–208. One might ask why ln dS in Figure 3a does not show a pattern of extended elevated values corresponding to the extended slow speed in Figure 3b. A look at Figure 1 helps explain this lack. There, dS has essentially two values—small and large. There are no boundary effects like the ones that are assumed to give rise to slow wind [e.g., *Riley and Luhmann*, 2012]. The ln dS plot in Figure 3a does

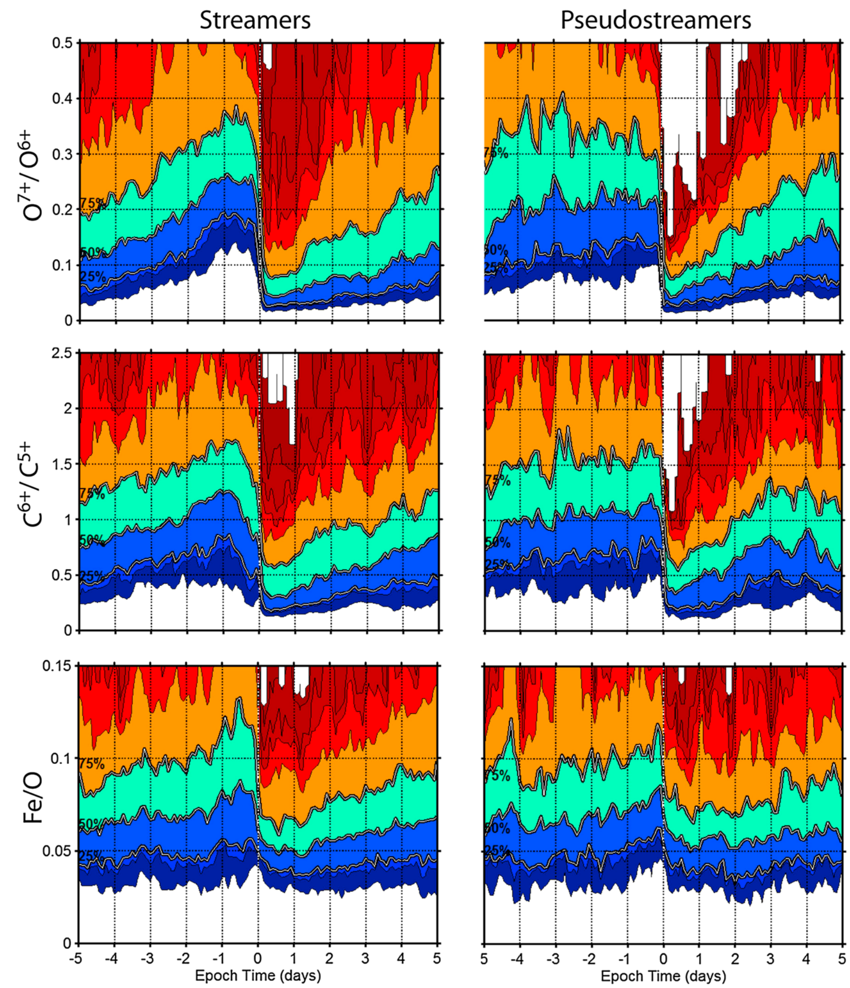

Figure 5. Cumulative distribution functions for ionic and elemental composition parameters across stream interfaces in the format of Figure 4.

hint at oblique passage, however, in the form of the flat-topped peaks. These successive high values indicate skimming near the heart of the streamer belt.

The long gap between the polarity reversal and the first interface in Figure 3 would preclude identification of this event as a streamer case in any automated scheme trained to test whether an interface has an associated polarity reversal using only interplanetary data, since the gap between most interfaces and their associated polarity reversals is usually shorter than a day [*Gosling et al.*, 1978]. The second interface in Figure 3 more nearly fits the usual streamer pattern. Although the gap between the mapped interface and the polarity reversal in Figure 3a is over 2 days long, in Figure 3b, at 1 AU, the gap is roughly 1 day long. Thus, both interfaces in Figure 3 are classified as streamer cases. Consistent with this view is the fact that Figure 3b displays only one stream per sector, in contrast to the two per sector in Figure 2b, where a pseudostreamer brought slow wind mid-sector to create those two streams.

Examining the streamer identification parameter and the interplanetary data for each of the selected 128 stream interface cases, as illustrated in Figures 2 and 3, we found that 84 met the criteria of a streamer case and 44 met the criteria of a pseudostreamer case. Superposed epoch analysis was then performed separately on the two different kinds of cases. Figures 4 and 5 present the results in the form of cumulative distribution functions (cdfs).

Figure 4 displays cdfs of the variations of plasma parameters across the stream interfaces, from 5 days before to 5 days after the crossing at zero epoch. The slow-wind side of the interfaces lies in the negative epoch range, as is clear from the speed cdfs in the top row. They indicate that the slowest winds occurred during the

2 days preceding the interface (−2 to 0 epoch time), where the median (50%) speed contour dips down to about 350 km/s in streamer flow compared to about 375 km/s in pseudostreamer flow, consistent with the comparison in *Crooker and McPherron* [2012]. Also, apparent from −2 to 0 epoch is the larger spread of speed values for pseudostreamer flow, indicating greater variability compared to streamer flow. Comparison of the density and proton temperature cdfs in the middle panels shows similar findings from −2 to 0 epoch time. The expected elevated density and depressed temperatures [e.g., *Gosling et al.*, 1978] are slightly more pronounced for streamer flow compared to pseudostreamer flow, consistent with the limited findings of *Neugebauer et al.* [2004], and the variability for pseudostreamer flow is slightly higher. The cdfs for magnetic field magnitude in the bottom panel show a stronger peak at the interface for streamers compared to pseudostreamers, consistent with the stronger speed gradient across the interface bounding streamers, which results in stronger compression.

Similar to Figure 4, Figure 5 displays cdfs of the variations of composition parameters across the interfaces. From −2 to 0 epoch time, both the ionic composition ratios of O^{7+}/O^{6+} and C^{6+}/C^{5+} and the elemental composition ratio of Fe/O are elevated, as expected [e.g., *Wimmer-Schweingruber et al.*, 1997; *Crooker and McPherron*, 2012], with slightly higher ratios for streamer flow compared to pseudostreamer flow, consistent with the case studies of *Wang et al.* [2012]. Moreover, the broad width of the regions of characteristic slow flow in both streamers and pseudostreamers in Figures 4 and 5 suggests that the source mechanism proposed by *Wang et al.* [2012], that is, a large expansion factor within coronal hole boundaries [e.g., *Wang and Sheeley*, 1990], may contribute to the slow flows in addition to the competing source mechanism of opening large flux loops through interchange reconnection [e.g., *Fisk et al.*, 1998; *Antiochos et al.*, 2011].

3. Discussion and Conclusions

The results in Figures 4 and 5 clearly show that pseudostreamer flows have the same characteristics as streamer flow, that is, low speed and proton temperature and high density and composition ratio, but that these characteristics are slightly less pronounced in pseudostreamers. These findings raise two related issues, discussed below, regarding the speed of pseudostreamer flows and the concept of two kinds of solar wind—slow and fast.

One might argue that the slow speeds of pseudostreamer flows identified in this study were essentially guaranteed by the selection process, since the wind speed downstream of the impinging fast flow behind the interface is always slow. By definition, interfaces are boundaries between fast and slow flow. It may well be that some pseudostreamer flows not included in this study are fast, as first predicted by *Wang et al.* [2007]. Occasionally, one can see high-speed segments in what otherwise is a slow-wind web on synoptic maps of solar wind speed predicted by the Wang-Sheeley-Arge model [*Arge et al.*, 2004], but these appear to be uncommon. We conclude that the slow flows analyzed in this paper are typical of pseudostreamer flows.

On the other hand, the finding that in every way the pseudostreamer flow has less pronounced characteristics than streamer flow supports the idea that the solar wind comprises a continuum of dynamic states, as proposed by *Zurbuchen et al.* [2002] and inherent in the correlation between solar wind speed and O^{7+}/O^{6+} [*Fisk*, 2003; *Gloeckler et al.*, 2003]. The continuum stretches from the fastest winds from coronal holes to the slowest winds from streamers. Pseudostreamer flow can be said to represent the first step up from streamer flow in this continuum. The concept that solar wind is either slow or fast comes from the fact that much of the time spacecraft are sampling wind near the extremes of the continuum. Only since the beginning of the declining phase of solar cycle 23, in 2003, were pseudostreamer flows prevalent enough to be identified as solar wind at a different position on the continuum.

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