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No evidence for the localized heating of solar wind protons at intense velocity shear zones

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Key Points:

- No proton heating is observed at the sites of intense velocity shear
- Temperature-density signatures are consistent with adiabatic compressions
- The compressions could be associated with the large Mach numbers of the shears

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Abstract Using measurements from the Wind spacecraft at 1 AU, the heating of protons in the solar wind at locations of intense velocity shear is examined. The 4321 sites of intense shear in fast coronal hole origin plasma are analyzed. The proton temperature, the proton specific entropy, and the proton number density at the locations of the shears are compared with the same quantities in the plasmas adjacent to the shears. A very slight but statistically significant enhancement of the proton temperature is seen at the sites of the shears, but it is accompanied by a larger enhancement of the proton number density at the sites of the shears. Consequently, there is no enhancement of the proton specific entropy at the shear sites, indicating no production of entropy; hence, no evidence for plasma heating is found at the sites of the velocity shears. Since the shearing velocities have appreciable Mach numbers, the authors suggest that there can be a slight adiabatic compression of the plasma at the shear zones.

1. Introduction

Abrupt velocity shears (vorticity layers) are ubiquitous in the solar wind plasma [*Burlaga*, 1968; *Neugebauer et al.*, 1984; *Borovsky*, 2008], particularly in the fast wind of coronal hole origin [*Borovsky*, 2012]. As it passes a spacecraft, a velocity shear layer appears as a large sudden jump $\Delta \underline{v}$ in the vector flow velocity $\underline{v}$ of the solar wind plasma. The strength of the velocity shear is measured by the magnitude of the jump $\Delta v \equiv |\Delta \underline{v}|$ in the vector flow velocity. A statistical analysis of flow shear in the solar wind found two populations with a transition in the vicinity of Δv~30 km/s [cf. *Borovsky*, 2012, Figure 1]: a population of weak shears that may be owed to MHD turbulence in the solar wind plasma and a population of strong shear events. In Figure 1 of *Borovsky* [2012], shears with $\Delta v \geq 60$ km/s are clearly in the population of strong shear events. For those shears with $\Delta v > 60$ km/s, the statistical analysis of *Borovsky* [2012] found that the mean value of the velocity jump over the local Alfven speed $\Delta v/v_A$ is 1.03, and the mean value of the velocity jump over the local magnetosonic speed $\Delta v/C_s$ is 0.77.

In general, the sudden large vector velocity changes are colocated with sudden large changes in the direction of the interplanetary magnetic field (directional discontinuities): multispacecraft analysis confirms that those directional discontinuities are planar current sheets with normals to the plane that are perpendicular to the magnetic field [*Horbury et al.*, 2001; *Knetter et al.*, 2004]. The velocity change vector is parallel or antiparallel to the magnetic field change vector, which is perpendicular or normal to the plane. Hence, the velocity changes across these directional discontinuities are shears [*Denskat and Burlaga*, 1977; *Neugebauer*, 1985; *De Keyser et al.*, 1998; *Borovsky*, 2012]. It has been argued [*Neugebauer et al.*, 1986] that the magnetic shear of these layers may stabilize the velocity shears to Kelvin-Helmholtz disruption.

The origin of these velocity shears remains a controversy [*Bruno et al.*, 2001; *Neugebauer and Giacalone*, 2010; *Owens et al.*, 2011; *Malaspina and Gosling*, 2012]: among the possibilities are (1) steepened Alfvén waves [*Vasquez and Hollweg*, 1999; *Tsurutani and Ho*, 1999], (2) fossil shears from plumes and jets in the chromosphere [*Feldman et al.*, 1993; *Yamauchi et al.*, 2003; *Neugebauer*, 2012], (3) high Mach number vorticity sheets generated by MHD turbulence [*Greco et al.*, 2009; *Zhdankin et al.*, 2012], and (4) the Alfvénic wiggling of fossil flux tubes [*Borovsky*, 2008; *Bruno and Carbone*, 2013] excited by reconnections in the chromosphere [*Shibata et al.*, 2007; *Pariat et al.*, 2009] or by flow-driven instabilities [*Mann et al.*, 1992; *Parhi et al.*, 1999]. Often the velocity shears occur in matching pairs of adjacent shear and antishear separated by tens of seconds [*Gosling et al.*, 2011; *Arnold et al.*, 2013]; most of these paired shears are undetectable in a data set that is not of high resolution. The solar wind velocity shears have been visualized in the kinking of comet plasma tails [*Buffington et al.*, 2008; *Jackson et al.*, 2013].

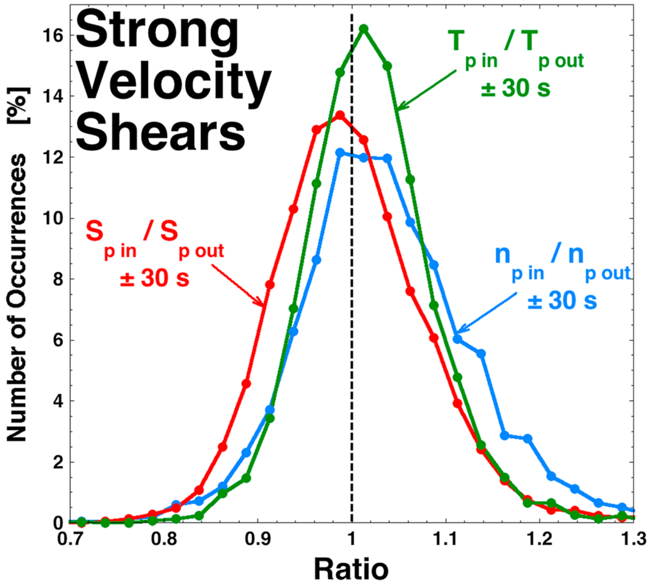

Figure 1. The strong shear occurrence distributions of T_{in}/T_{out}, S_{in}/S_{out}, and n_{in}/n_{out} for protons are plotted from the ACE and Wind data sets.

Adiabatic expansion of the solar wind would conserve the proton specific entropy $S_p = T_p/n^{4/3}$ [*Schindler and Birn*, 1978; *Goertz and Baumjohann*, 1991]; with a density falling off with distance r from the Sun as $n \propto r^{-2}$, specific entropy conservation would have the proton temperature decreasing with distance as $T_p \propto r^{-4/3}$. The protons of the solar wind undergo nonadiabatic heating in the inner heliosphere as seen by a proton temperature that decreases with distance slower than $r^{-4/3}$ [*Eyni and Steinitz*, 1981; *Freeman and Lopez*, 1985; *Freeman*, 1988; *Hellinger et al.*, 2011]. Hence, the specific entropy of the protons increases with distance from the Sun [*Marsch et al.*, 1983; *Schwartz and Marsch*, 1983; *Whang et al.*, 1989]. This nonadiabatic heating of the solar wind protons is particularly prevalent in the fast solar wind [*Eyni and Steinitz*, 1981; *Freeman*, 1988]; the fast wind is also where velocity shears are prevalent [*Borovsky*, 2012]. The kinetic energy associated with differential flows has been suspected as a possible energy source for the observed in situ heating of the solar wind [*Coleman*, 1968; *Parker*, 1969]. Potential mechanisms for solar wind heating associated with velocity shears are the phase mixing of Alfvén waves [*Ruderman et al.*, 1999; *Kaghashvili*, 1999], damping of MHD surface waves [*Hollweg et al.*, 1990; *Yang and Hollweg*, 1991], damping of shear-driven plasma waves [*Migliuolo*, 1984; *Markovskii et al.*, 2006], the excitation and dissipation of MHD turbulence [*Roberts et al.*, 1992; *Ghosh et al.*, 1998], excitation and dissipation of Kelvin-Helmholtz waves [*Korzhov et al.*, 1985; *Neugebauer et al.*, 1986], and Landau damping of the shear structure itself [*Borovsky and Gary*, 2009, 2011]. A second possible source for the proton heating of the solar wind is the kinetic energy of the field-aligned differential drift between protons and alpha particles in the solar wind plasma [cf. *Safranknova et al.*, 2013]. A third possible source for the proton heating is the electron heat flux from the Sun. These nonshear sources of heating will not be considered in the present study.

Borovsky and Denton [2010] looked for evidence of the production of MHD turbulence at the long-lived strong velocity shears at 27 corotating interaction region (CIR) stream interfaces and found no evidence of localized turbulence production. Using 64 s ACE data binned into 30 min intervals, they also found no evidence for plasma heating at those stream interface velocity shears. *Borovsky and Denton* [2011] looked for proton and electron heating at 194,070 strong current sheets in the solar wind, which are often the sites of strong velocity shear; using ACE 64 s measurements, they found proton temperatures elevated by 1–2% at the sites of the current sheets, but the proton specific entropies were elevated by 1% or less at the sites of the current sheets [cf. *Borovsky and Denton*, 2011, Table 1]. They concluded that there is no significant localized heating of the solar wind protons or electrons at strong current sheets. *Osman et al.* [2012], using ACE 64 s measurements, compared the proton temperature at the sites of intermittent magnetic structures in the solar wind with the proton temperature of the plasma surrounding the structures; for the strongest intermittent structures, they found the proton temperature to be 2–3% higher at the sites of intermittency [cf. *Osman et al.*, 2012, top trace of Figure 1a].

In Appendix A, an estimate is made of the expected specific entropy signature at the sites of velocity shears. If the well-established bulk heating of the solar wind protons with distance from the Sun is occurring at shear sites, the increase of the proton specific entropy at the shear sites will be large and easily detected.

In this report, we examine strong velocity shears in the fast solar wind for evidence of localized heating of the solar wind protons.

Table 1. Properties of the Occurrence Distributions of Inside-To-Outside Ratios for the Wind Collection of $\Delta \underline{v} > 60$ km/s Shears in Fast Solar Wind

Ratio	Number of Values	Mean Value Standard Deviation (±)	Median Value	Logarithmic Mean Value
$T_{p\ \text{in}}/T_{p\ \text{out}} \pm 3$ s	4321	1.002 ± 0.058	1.001	1.000
$T_{p\ \text{in}}/T_{p\ \text{out}} \pm 6$ s	4223	1.008 ± 0.062	1.006	1.006
$T_{p\ \text{in}}/T_{p\ \text{out}} \pm 30$ s	4200	1.021 ± 0.070	1.016	1.018
$T_{p\ \text{in}}/T_{p\ \text{out}} \pm 60$ s	4175	1.025 ± 0.075	1.018	1.022
$S_{p\ \text{in}}/S_{p\ \text{out}} \pm 3$ s	4321	0.986 ± 0.075	0.989	0.983
$S_{p\ \text{in}}/S_{p\ \text{out}} \pm 6$ s	4223	0.983 ± 0.077	0.986	0.986
$S_{p\ \text{in}}/S_{p\ \text{out}} \pm 30$ s	4200	0.999 ± 0.083	0.994	0.996
$S_{p\ \text{in}}/S_{p\ \text{out}} \pm 60$ s	4175	1.004 ± 0.086	0.997	0.997
$n_{p\ \text{in}}/n_{p\ \text{out}} \pm 3$ s	4321	1.029 ± 0.090	1.022	1.025
$n_{p\ \text{in}}/n_{p\ \text{out}} \pm 6$ s	4223	1.034 ± 0.092	1.031	1.030
$n_{p\ \text{in}}/n_{p\ \text{out}} \pm 30$ s	4200	1.036 ± 0.091	1.029	1.032
$n_{p\ \text{in}}/n_{p\ \text{out}} \pm 60$ s	4175	1.037 ± 0.091	1.031	1.033

2. The Data Analysis

From a collection of long (multiday) intervals of fast solar wind occurring in January–July 2003, 35 days of fast coronal hole origin wind is analyzed using Wind 3DP 3 s solar wind proton measurements [*Lin et al.*, 1995].

Following *Borovsky* [2012] [cf. *Borovsky*, 2008, Figure 1], for the present study, we define a shear event in the 3 s Wind data set to be $|\Delta \underline{v}| > 60$ km/s in 6 s. With this definition, 4321 abrupt shear events are collected. Strong velocity shear layers, like many other boundaries in the solar wind plasma (i.e., proton density jumps, magnetic field strength jumps, specific entropy jumps, and plasma beta jumps), are about 10 s wide in the Wind data set. (An exception is the alpha particle density jumps, which are sometimes narrower than the 3 s resolution of the data set; abrupt transitions in the helium density are being reported with higher-resolution measurements [*Zastenker et al.*, 2013; *Safranknova et al.*, 2013].) At 3 s time resolution, the strong velocity shears are typically 2 or 3 data points wide. If the condition $|\Delta \underline{v}| > 60$ km/s is met for two adjacent data points within a single shear zone (as it is 33% of the time for the 4321 events), the location of the shear is taken to be the data point with the larger value of $|\Delta \underline{v}|$.

To measure the localized heating of the solar wind plasma at sites of strong shear, the plasma temperature at the site of the shear is compared to the temperature in the two plasmas adjacent to the shear. If the time at which the shear is observed is t_{shear}, to make a comparison of the temperature at the shear to the temperatures ±3 s before and after the shear, the ratio $T_{\text{in}}/T_{\text{out}}$ is defined as $2\,T(t_{\text{shear}})/[T(t_{\text{shear}} + 3\text{ s}) + T(t_{\text{shear}} - 3\text{ s})]$. Likewise, for a ±6 s comparison, the ratio $T_{\text{in}}/T_{\text{out}}$ is defined as $2\,T(t_{\text{shear}})/[(T(t_{\text{shear}} + 6\text{ s}) + T(t_{\text{shear}} - 6\text{ s})]$. Similarly, the ratios are calculated for ±30 s and ± 60 s.

For detecting the signatures of heating (entropy production), the specific entropy $S = T/n^{2/3}$ [cf. *Marsch et al.*, 1983; *Schwartz and Marsch*, 1983; *Whang et al.*, 1989; *Borovsky and Cayton*, 2011] is superior to the temperature since it does not respond to adiabatic fluctuations (i.e., compressions and rarefactions), which produce temporary temperature perturbations. Similar to the temperature ratios, the ratios $S_{\text{in}}/S_{\text{out}}$ are defined for ±3 s, ±6 s, ±30 s, and ±60 s.

In the 35 day, the Wind data set, the mean speed of the solar wind at the velocity shear sites, is $v = 739$ km/s: at that speed, ±3 s corresponds to about ±2200 km along the solar wind flow streamline away from the center of the shear zone, and ±60 s corresponds to about ±44,000 km away from the shear zone. With the thickness of velocity shears being typically ~8 s (see Appendix A), the denominator measurements for the ratios taken at ±3 s and ±6 s are often not fully outside of the abrupt shear zone. For the ratios taken at ±30 s and ±60 s, the measurements in the denominators are truly outside of the shear zone.

In Figure 1, the distributions of the proton temperature ratios $T_{p\ \text{in}}/T_{p\ \text{out}}$ (green) and the proton specific entropy ratios $S_{p\ \text{in}}/S_{p\ \text{out}}$ (red) for ±30 s are binned for the 4321 strong velocity shears in the Wind data set. The distribution of temperature ratios are centered close to unity, indicating no strong localized enhancement of the temperature at the location of the shears. The distribution of specific entropy ratios is also centered close to unity, indicating no strong heating of the solar wind protons at the locations of the strong shears.

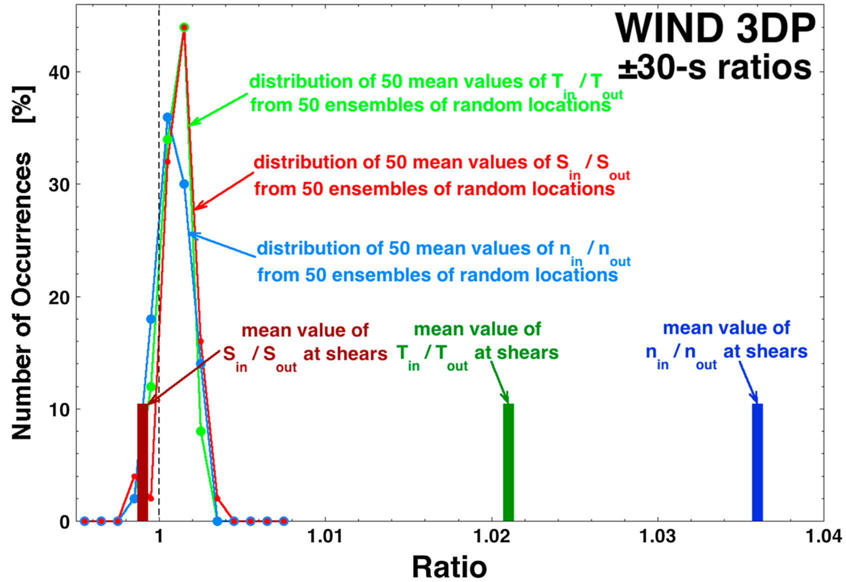

Figure 2. The mean values of T_{in}/T_{out} (green), S_{in}/S_{out} (red), and n_{in}/n_{out} (blue) for protons at strong shears are indicated as vertical bars. For the 50 sets of 4200 random locations in the solar wind, the 50 mean values of T_{in}/T_{out}, S_{in}/S_{out}, and n_{in}/n_{out} for protons at the random locations are binned as the green, red, and blue curves, respectively.

For ±3 s, ±6 s, ±30 s, and ± 60 s, the mean value, median value, and logarithmic mean value for each set of the ratios are collected in Table 1. (The logarithmic mean, which is 10 to the power of the mean of the base-10 logarithms of the ratios $10^{<\text{Log}(x)>}$, is pertinent to ratioed quantities since it prevents greater-than-unity values from dominating less-than-unity values in the averaging.) In Table 1, the mean value of temperature ratios $T_{p\ in}/T_{p\ out}$ for ±30 s and ±60 s are about 2% above unity. There is no such offset from unity for the specific entropy ratios $S_{p\ in}/S_{p\ out}$. Hence, we see an ~2% enhancement of the proton temperature T_p at the shear sites, but not an enhancement of the proton specific entropy $S_p = T_p/n_p^{2/3}$.

Figure 2 demonstrates that this ~2% enhancement of the temperature at the shear sites is statistically significant. When the temperature ratio T_{in}/T_{out} for ±30 s is calculated at the locations of 4200 strong shears in the Wind data set, the mean value of the 4200 ratios is 1.021. This value of 1.021 is indicated as the dark green vertical bar in Figure 2. If the 4200 locations in the solar wind where the ratios are calculated are randomly relocated, the mean value of the 4200 calculated T_{in}/T_{out} ratios comes out very close to 1.000. To demonstrate this, 50 sets of 4200 random locations in the solar wind are created, and for each of the 50 sets, the 4200 T_{in}/T_{out} ratios are calculated, and for each set, the mean of the 4200 ratios is calculated. The 50 mean values that result as the light green distribution in Figure 2 are binned. Note that the mean values in the random distributions are typically slightly above unity. (That is, because ratios above 1.0 dominate over ratios below 1.0 in the averaging: i.e., the average of 9/10 and 10/9 is 1.0056.) The green T_{in}/T_{out} distribution is narrow near unity, and the value 1.021 is not consistent with a random occurrence of the mean owed to noise in the data set, etc. Hence, the value obtained of 1.021 is statistically significant: there is about a 2.1% enhancement of the proton temperature of the solar wind plasma at the sites of the strong shears relative to the plasmas on either side of the shears.

In Figure 1, the distributions of the proton number-density ratios n_{in}/n_{out} (blue) are also binned for the strong velocity shears in the Wind data set. The distribution of density ratios are centered close to unity, indicating no strong localized enhancement of the density at the location of the shears. For ±3 s, ±6 s, ±30 s, and ±60 s, the mean value, median value, and logarithmic mean value of the density ratios n_{in}/n_{out} for the strong shears are listed in Table 1. Here it is seen that the mean value of the density ratio is about 3–4% above unity.

Looking again at Figure 2, the mean value of the density ratio n_{in}/n_{out} for ±30 s calculated at the locations of 4200 strong shears in the Wind data set is 1.036, which is marked as the dark blue vertical bar. For an ensemble of 50 sets of 4200 random locations in the solar wind, the 50 mean values of n_{in}/n_{out} (for ±30 s) calculated for each set of the 4200 locations are binned as the blue curve in Figure 2. Again, the value of 1.036 for n_{in}/n_{out} is not consistent with a random occurrence. The value of 1.036 is statistically significant: there is about a 3.6% enhancement of the solar wind proton number density at the locations of the strong shears relative to the density in the plasmas on either side of the shears.

The slight temperature enhancement and the slightly larger-density enhancement are consistent with entropy conservation. This can be seen with the ±30 s mean values of Figure 2. If the specific entropy outside the shear is $S_{out} = T_{out}/n_{out}^{2/3}$, and the specific entropy inside the shear is $S_{in} = T_{in}/n_{in}^{2/3}$, where $T_{in} = 1.021T_{out}$ and $n_{in} = 1.036n_{out}$, then $S_{in} = (T_{out}/n_{out}^{2/3})(1.021/1.036^{2/3}) = 0.9972S_{out} = S_{out}/1.0028$. The measured fractional change S is an order of magnitude less than the measured fractional changes in T and n.

3. Summary

At the sites of intense velocity shear in the solar wind, a slight enhancement (~2%) of the proton temperature is seen, and a slight enhancement (~3.6%) of the proton number density is seen. The locally enhanced proton temperature T_p and the locally enhanced proton number density n_p are consistent with an adiabatic behavior of the protons in the plasma that conserves the proton specific entropy $S_p = T_p/n_p^{2/3}$, with no evidence for localized proton heating at the shear, i.e., no evidence for localized entropy production.

In summary, no statistical evidence is found for localized heating of the solar wind protons at abrupt velocity shears.

There is a well-established bulk heating of the protons of the solar wind with distance from the Sun. If that bulk heating was occurring at the sites of velocity shear, the calculations in Appendix A indicate that the increase of the proton specific entropy at the shear sites would have to be much larger than the values obtained in the Wind spacecraft analysis of section 2.

The results of the present study are in agreement with the results of *Borovsky and Denton* [2010], which found no heating at CIR stream interfaces and are in agreement with the results of *Borovsky and Denton* [2011], which found no localized heating at the sites of strong current sheets in the solar wind. The present study is performed at much higher time resolution than those two previous studies. Using Wind 3 s measurements, *Wang et al*. [2013] examined 20,578 discontinuities in the fast solar wind at 1 AU. In general, they found slight (~1%) increases in the temperature and densities of the protons inside the discontinuities relative to the plasma outside the discontinuities. *Wang et al*. [2013] identified a class of discontinuities with larger temperature and density increases: this class is composed of 1.8% of the 20578 discontinuities and were classified as tangential discontinuities in the fast wind. On average, one of these tangential discontinuities passes the spacecraft every 1.5 h. The present study of velocity shears is in basic agreement with the *Wang et al*'s [2013] discontinuity examination: no strong heating at discontinuities.

Finding no localized heating at the sites of the velocity shears does not mean that the kinetic energy of differential flows in the solar wind is not the energy source for solar wind heating in the inner heliosphere. However, the heating does not occur at the sites of intense velocity shear and the velocity shear mechanisms discussed above (e.g., phase mixing of Alfvén waves, damping of MHD surface waves, damping of shear-driven plasma waves, the excitation and dissipation of MHD turbulence, excitation and dissipation of Kelvin-Helmholtz waves, and Landau damping of the shear structure itself) are not producing nonadiabatic heating of the protons at the sites of the shears.

We suggest that the origin of the density and temperature enhancements at the sites of the strong velocity shears might be associated with the order unity Mach numbers of the shearing flow. If the shear layer is not strictly planar, one can imagine some compressional effects in the plasma flow with n and T increasing in concert.

Appendix A: How Much Heating is Needed

If the observed proton heating of the solar wind from 0.29 to 1 AU occurs in the small-scale velocity shears in the solar wind plasma, we can estimate the amount of specific entropy change that should be seen at the locations of the shears. This estimate will depend on the thicknesses of the shear zones and on the amount of time that plasma spends in the shear zones getting heated.

There is a systematic increase in the proton specific entropy S_p with increasing distance from the Sun. This is seen in the Helios data set from 0.29–1 AU [*Marsch et al*., 1983; *Schwartz and Marsch*, 1983; *Whang et al*., 1989],

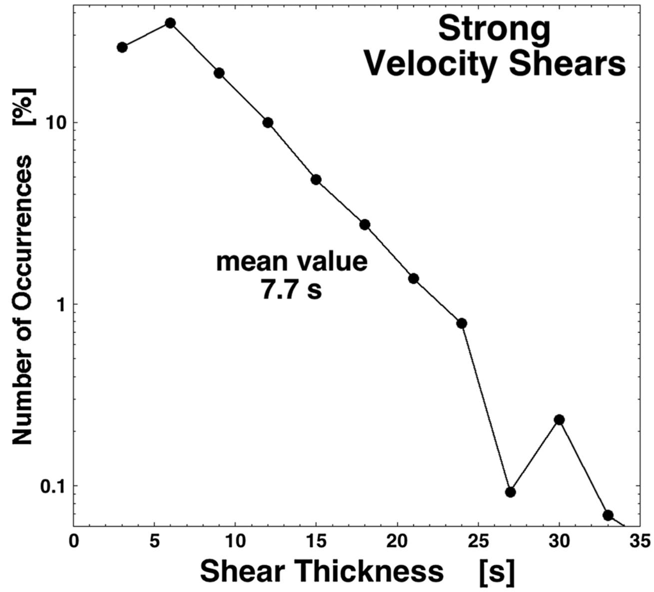

Figure A1. The distribution of temporal widths of the strong shear zones in the high-speed solar wind. When a shear zone is found (with $\Delta v > 60$ km/s over 6 s), the duration of the zone is measured as the region, wherein the 3 s changes in the velocity vector have magnitudes >20 km/s.

and it is seen beyond 1 AU in the Ulysses data set [*Liu et al*., 1995; *Goldstein et al*., 1996]. Using the data set of hourly averages of the measurements from the plasma instruments on Helios 1 + 2 [*Rosenbauer et al*., 1977], the change in the proton specific entropy is quantified for the fast solar wind plasma. For fast solar wind (600 km/s $< v <$ 850 km/s), the mean proton specific entropy in the distance range 0.3–0.4 AU is $<S_p> = 4.76$ eV cm^2; in the distance range 0.9–1 AU, it is $<S_p> = 8.13$ eV cm^2. The ratio of these two values is 1.71. Hence, in going from 0.35 AU to 0.95 AU, the proton specific entropy of the fast solar wind increases by 71%.

In the Wind data set analyzed in section 2 above, 4231 abrupt velocity shear events were found in 35 days of data. The distribution of temporal thicknesses of the shear zones is plotted in Figure A1. The mean thickness is 7.7 s. With each shear zone lasting on average 7.7 s, that is 3.26×10^4 s of shear zones in 3.02×10^6 s of data. Hence, the shear zones have a filling factor of $3.26 \times 10^{4/3}.02 \times 10^6 = 1.08 \times 10^{-2} = 1/93$ in the solar wind plasma. The average speed of the solar wind in the 35 day Wind data set is 739 km/s; at that speed, the distance from 0.35 AU to 0.95 AU is traversed in 1.2×10^5 s (33.8 h). If the fast solar wind has an proton specific entropy increase of 71% going from 0.35 AU to 0.95 AU, then that is a temporal rate of increase of 5.9×10^{-4}%/s for the proton specific entropy of the bulk plasma. If that heating is occurring inside of the small-scale shear zones with a filling factor of 1/93, then the rate of increase of the proton specific entropy in the shear zones is 5.5×10^{-2}%/s. Hence, in 7.7 s of time, the proton specific entropy needs to increase by 0.55% in the shear zone.

It is relevant to ask how long a time an element of plasma remains inside of a shear zone. At an advection speed of 739 km/s, the shear zone takes about 7.7 s to cross the Wind spacecraft; hence, a shear zone is about 5.7×10^3 km wide along the path of the spacecraft through the shear zone. The planes of the shear zones tend to be aligned with the Parker spiral direction [cf. *Borovsky*, 2012, Figure 4], so they are inclined at about 45° to the path of the spacecraft. Hence, their thicknesses are about $0.707 \times 5.7 \times 10^3$ km, which is 4.0×10^3 km. Indications are that these shear planes are aligned with the magnetic field of the solar wind [cf. *Horbury et al*., 2001; *Knetter et al*., 2004]; i.e., the normals to the planes are oriented at 90° to the magnetic field. In that case, they are like a plasma boundary, not propagating through the solar wind plasma, and the plasma that is in the shear zone spends a long time there. In that case, if the proton heating of the solar wind was occurring in the shear zones, the shear zones with an entropy increase rate of 5.5×10^{-2}%/s would have much higher entropy than the surrounding plasma.

Even if the shears were to propagate through the plasma at the Alfvén speed v_A, for $n = 3.3$ cm^{-3} and $B = 5$ nT, $v_A = 60$ km/s and an element of plasma spend 4.0×10^3 km/60 km/s = 67 s inside of the shear layer. At a heating rate of 5.5×10^{-2}%/s for 67 s, the proton specific entropy of each element of plasma would need to increase by 3.7% as the shear zone crossed in order to account for the observed bulk heating of the solar wind plasma. (And with filling factors of 1/93, shear zone propagating at the Alfvén speed would propagate over a given element of solar wind plasma every 104 min, which is 19.3 passovers in the 33.8 h advection time from 0.35 AU to 0.95 AU; in each passover heating, the plasma would need to increases by 3.7% to give a total heating of 71% for the 19.3 passes.)

Increases in the proton specific entropy of 0.55% and 3.7% would be easily detectable, but are not seen.

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