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PULSED ALFVÉN WAVES IN THE SOLAR WIND

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ABSTRACT

Using 3 s plasma and magnetic field data from the *Wind* spacecraft located in the solar wind well upstream from Earth, we report observations of isolated, pulse-like Alfvénic disturbances in the solar wind. These isolated events are characterized by roughly plane-polarized rotations in the solar wind magnetic field and velocity vectors away from the directions of the underlying field and velocity and then back again. They pass over *Wind* on timescales ranging from seconds to several minutes. These isolated, pulsed Alfvén waves are pervasive; we have identified 175 such events over the full range of solar wind speeds (320–550 km s^{-1}) observed in a randomly chosen 10 day interval. The large majority of these events are propagating away from the Sun in the solar wind rest frame. Maximum field rotations in the interval studied ranged from 6° to 109°. Similar to most Alfvénic fluctuations in the solar wind at 1 AU, the observed changes in velocity are typically less than that predicted for pure Alfvén waves (Alfvénicity ranged from 0.28 to 0.93). Most of the events are associated with small enhancements or depressions in magnetic field strength and small changes in proton number density and/or temperature. The pulse-like and roughly symmetric nature of the magnetic field and velocity rotations in these events suggests that these Alfvénic disturbances are not evolving when observed. They thus appear to be, and probably are, solitary waves. It is presently uncertain how these waves originate, although they may evolve out of Alfvénic turbulence.

Key words: magnetic fields – plasmas – solar wind – turbulence – waves

Online-only material: machine-readable table

1. INTRODUCTION

Turbulence is ubiquitous in fluids and plasmas and has been extensively studied in the solar wind (e.g., Smith 2009; Bruno & Carbone 2005; Tu & Marsch 1995), the largest natural plasma accessible to direct in situ measurement. Turbulence in the solar wind often takes the form of Alfvénic fluctuations, characterized by coupled changes in magnetic field, **B**, and velocity, **V** (e.g., Belcher & Davis 1971). The fluctuations propagate predominantly away from the Sun along **B** in the solar wind rest frame; this indicates that they are largely the evolved remnants of fluctuations that originate inside the point where the solar wind flow becomes super-Alfvénic. Being largely associated with turbulence, the Alfvénic fluctuations commonly appear to be intermittent and stochastic in nature with the tip of the magnetic field vector wandering randomly about a surface of nearly constant radius (e.g., Barnes 1981).

Despite the generally turbulent nature of most Alfvénic fluctuations in the solar wind, discrete types of Alfvénic waves have been identified there. These include (1) arc-polarized waves in which the magnetic field vector rotates slowly along an arc transverse to the direction of minimum variance in **B** followed by a rapid return to the original field direction (e.g., Riley et al. 1996), (2) torsional Alfvén waves embedded within small magnetic flux ropes (Gosling et al. 2010), and possibly (3) the limited set (33 events in 14 years) of candidate solitary waves identified in *Ulysses* 1 s and 2 s solar wind magnetic field data (Rees et al. 2006). Finally, Alfvénic disturbances that propagate in opposite directions along magnetic field lines bound the plasma jets produced by magnetic reconnection in the solar wind (e.g., Gosling et al. 2005).

Our purpose here is to report observations of isolated, pulse-like Alfvénic events in the solar wind that are characterized by spatially limited, roughly plane-polarized rotations in the solar wind magnetic field and velocity vectors. These pulsed Alfvénic events are pervasive in the solar wind, are distinct from all of the above-noted types of discrete Alfvénic waves in the wind, and are clearly not merely random fluctuations. The high cadence (3 s) and accuracy of the plasma (Lin et al. 1995) and magnetic field (Lepping et al. 1995) measurements obtained from the *Wind* spacecraft, located in the solar wind well upstream from Earth at the time of the observations reported here, optimally reveals their character and pervasiveness. These isolated, pulsed Alfvénic events have the appearance of, and probably are, solitary waves, which are isolated disturbances that propagate through a fluid or plasma without changing their shape (e.g., Miles 1980; Petviashvili & Pokhotelov 1992).

2. OBSERVATIONS

Figure 1 shows four examples of Alfvénic disturbances in the solar wind within a 1 hr interval that are characterized by pulse-like, correlated changes in the components of **V** and **B** and short-lived rotations in the field azimuthal and/or polar angles. Since the underlying magnetic field was sunward-directed, the positive correlation between the changes in the components of **V** and **B** indicates that all four events were propagating anti-sunward in the solar wind rest frame. The first event was associated with a small depression in field magnitude and in proton density (not shown); the other three events were associated with small enhancements in field magnitude and proton density.

Figure 2(a) shows how the angle (α) between the instantaneous **B** and the 21 s average **B** prior to the event changed during the 2007 June 10 12:20 UT event. The rotation away from the direction of the underlying field and then back again was roughly symmetric, the maximum away rotation being 21°.3. In

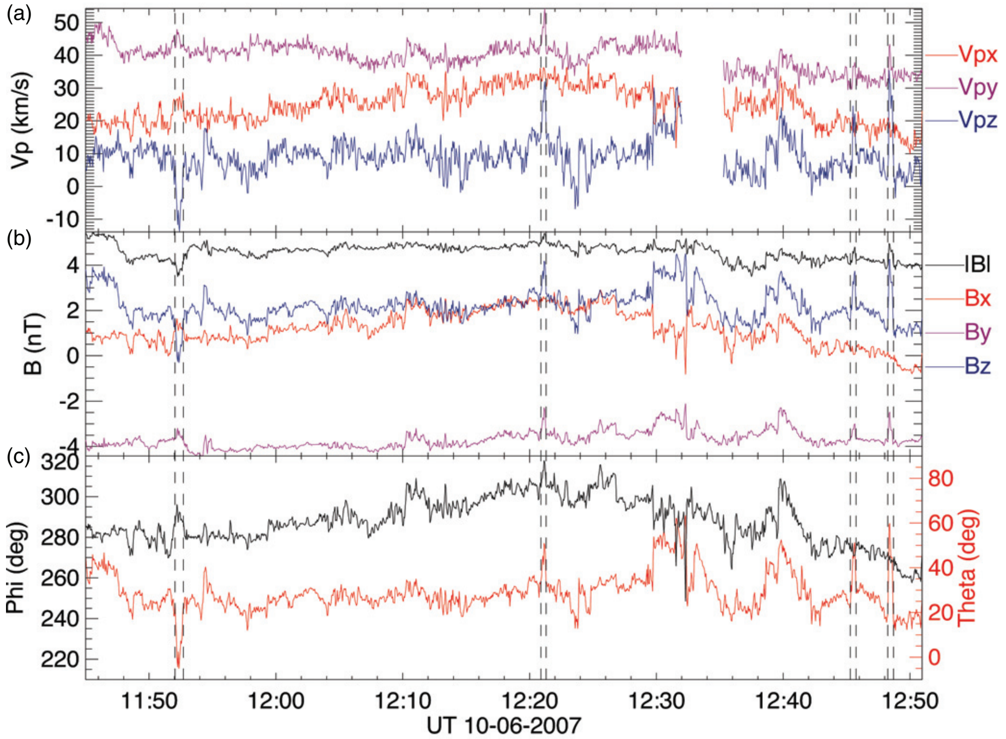

Figure 1. Examples of isolated pulsed Alfvénic fluctuations in the solar wind on 2007 June 10. (a) Solar wind velocity components (red, violet, and blue identifying, respectively, the Geocentric Solar Ecliptic, GSE, *x*, *y*, and *z* components). V_x was shifted by $+437$ km s^{-1} and V_y was left uncorrected for aberration associated with Earth's and *Wind*'s motion (~ -29.8 km s^{-1}) about the Sun. (b) Solar wind magnetic field GSE components similarly color-coded as well as the field magnitude (black). (c) Azimuthal (black) and polar (red) angles of the magnetic field vector. Dashed vertical lines bracket four isolated, pulsed Alfvénic events identified in this 65 minute interval when *Wind* was located $(1.652, 0.292, 0.147) \times 10^6$ km in GSE coordinates upstream from Earth.

order to examine the nature of the field rotation, we performed a minimum variance analysis (Sonnerup & Cahill 1967) of the magnetic field data during the event. We found that the analysis did not provide a well-determined direction of minimum variance, although it did provide a well-determined direction of maximum variance. Panels (b)–(d) of Figure 2 show the strong positive correlation between the changes in the maximum variance (L) components of **V** and **B** during the event as well as the small overall variance in both the calculated intermediate (M) and minimum (N) variance components. The minimum variance direction is not well defined because the magnetic field shows little variance throughout the *MN* plane. Both the magnetic field *LM* and *LN* hodograms, which are time traces of one field component plotted against another field component (e.g., Sonnerup & Scheible 1998), follow nearly straight horizontal lines and reverse direction as B_{L} reverses direction (panels (e) and (f) of Figure 2). Those nearly straight horizontal lines indicate that the wave was nearly plane polarized.

In order to demonstrate the degree of Alfvénicity of the 2007 June 10 12:20 UT event, we used the measured values of **B** and **V** to find the frame velocity (the de Hoffman–Teller, HT, velocity, $\mathbf{V_{HT}}$) that minimized the residual point-by-point electric field in the least-squares sense (Khrabrov & Sonnerup 1998). In the HT frame the flow velocity should be aligned parallel or antiparallel to **B** (de Hoffman & Teller 1950). The small angle, Ψ, between $\mathbf{V}$–$\mathbf{V_{HT}}$ and **B**, shown in Figure 2(a), demonstrates that we determined a good HT frame. Similarly, the high correlation (>0.99) between components of $\mathbf{V}$–$\mathbf{V_{HT}}$ and that of the Alfvén velocity, $\mathbf{V_A}$, shown in Figure 2(g) demonstrates the Alfvénic nature of the event. However, as is often the case for Alfvénic fluctuations in the solar wind at Earth's orbit (e.g., Roberts et al. 1987; Marsch 1991), the slope of the best-fit line (0.70) was somewhat less than the value (1.00) that would indicate perfect Alfvénicity ($\Delta\mathbf{V} = \pm\Delta\mathbf{B}/\sqrt{}[4\pi\rho]$, where ρ is the proton mass density).

A cursory examination of *Wind* 3 s data reveals that isolated, pulsed Alfvénic events of the nature shown in Figure 1 are quite common. Accordingly, we scrutinized the combined *Wind* 3 s plasma and magnetic field data in a randomly selected 10 day interval (2007 June 1–10) for such events. In some cases we included events superimposed on gradual changes in field orientation like the event at 12:48 UT in Figure 1. We identified 175 isolated, pulsed Alfvénic events, or an average of 17.5 events/day, over the full range (320–550 km s^{-1}) of solar wind speeds sampled during this 10 day interval. We then performed analyses of those events similar to that done for the 2007 June 10 12:20 UT event. Some of the results of our analyses are summarized in Figure 3. Table 1 in the online material provides some information on each pulsed Alfvénic event identified.

Figure 3(a) shows that the large majority of identified pulsed Alfvénic events passed over *Wind* in less than 60 s, the most probable duration being $\sim$25 s. Only two of the events had durations exceeding 110 s. A few had the minimum duration (6 s) that can be resolved by a 3 s measurement. A temporal width of 25 s in a 400 km s^{-1} wind corresponds to a distance of 1×10^4 km, which is of the order of 100 ion inertial lengths. This clearly indicates the fluid (as opposed to kinetic) nature of the events identified.

Most of the pulsed Alfvénic events, like those shown in Figure 1, were associated with small changes in field magnitude. Figure 3(b) reveals that many (65%) of the events were associated with quite small ($<10\%$) changes in field strength, with small enhancements in field strength being more probable

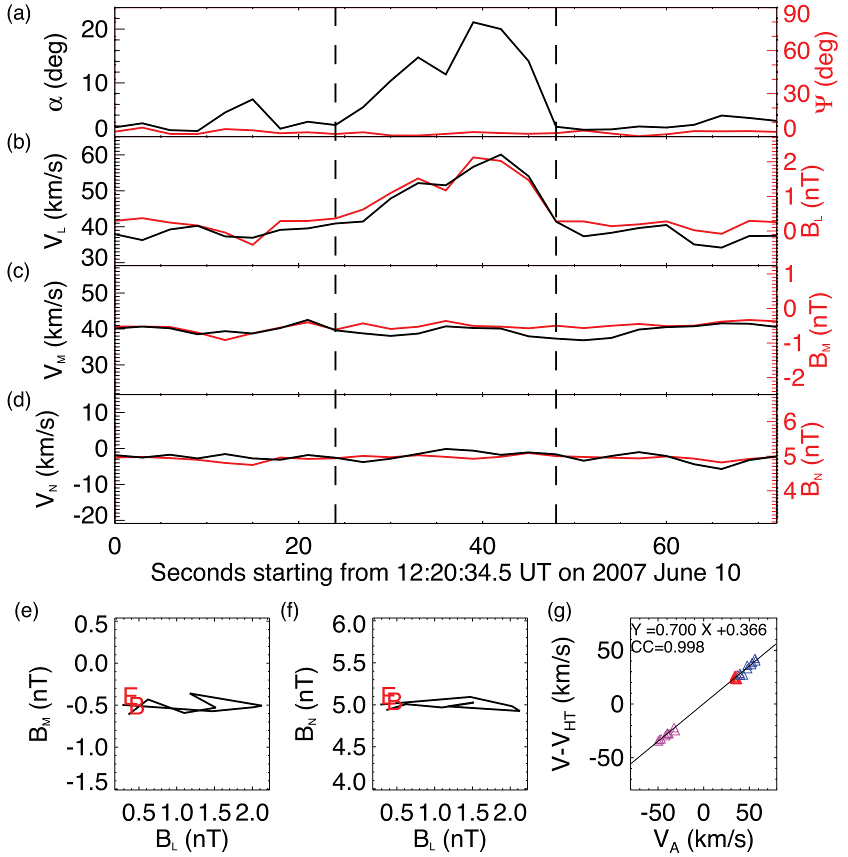

Figure 2. Analysis of the 12:20 UT pulsed Alfvénic event on 2007 June 10. (a) Ψ, the angle (red) between $\mathbf{B}$ and $\mathbf{V}$ in the calculated de Hoffman–Teller frame, and α, the angle (black) between $\mathbf{B}$ and the 21 s average value of $\mathbf{B}$ immediately prior to the event, as functions of time. (b)–(d) The components of $\mathbf{V}$ (black) and $\mathbf{B}$ (red) as functions of time in *LMN* coordinates, where *L*, *M*, *N* are the directions of maximum, intermediate, and minimum variance, respectively. Dashed vertical lines in panels (a)–(d) bracket the pulsed Alfvénic event. (e)–(f) Magnetic hodograms of the event in *LMN* coordinates. B and E in these panels indicate respectively the beginning and end points of the event. (g) Correlation, CC, on a point-by-point basis between the components of $\mathbf{V}$ in the de Hoffman–Teller frame and the components of the Alfvén velocity, $\mathbf{V_A}$. Red, violet, and blue points correspond to the GSE *x*, *y*, and *z* components, respectively.

Table 1

Pulsed Alfvén Wave Characteristics and Analysis Results

Day	Begin	D (s)	V (km s^{-1})	$\Delta B/B_0$	Alpha (deg)	$\Delta N/N_0$	$\Delta T/T_0$	Slope	DWP
01	2:53:10.5	48	346	−0.053	28.2	−0.093	0.090	0.56	A
01	3:20:07.5	27	341	0.069	15.7	0.12	−0.064	0.62	A
01	3:29:07.5	51	333	0.021	16.0	0.096	−0.099	0.55	A
01	3:57:31.5	21	332	−0.032	12.1	0.073	0.066	0.58	A
01	7:11:43.5	207	364	0.20	59.9	0.15	0.11	0.37	A
01	7:25:31.5	15	366	−0.058	12.0	−0.048	−0.035	0.71	A

Notes. Day: day of 2007 June; Begin: wave start time; D: duration of wave; V: solar wind speed at wave onset; $\Delta B/B_0$: maximum fractional change in field magnitude relative to average orientation prior to wave; Alpha: maximum field rotation angle away from the average initial field orientation; $\Delta N/N_0$: maximum fractional change in proton density relative to average proton density prior to wave; $\Delta T/T_0$: maximum fractional change in proton temperature relative to average proton temperature prior to wave; Slope: the degree of Alfvénicity of the wave; DWP: direction of wave propagation away from (*A*) or toward (*T*) the Sun in the solar wind rest frame.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

than small depressions. There were roughly equal numbers of events with negative and positive changes in field strength, but about twice as many events with large (>20%) depressions in field strength than with large enhancements in field strength. Many of the events were also associated with small changes in proton density and/or temperature (see the complete form of Table 1 available in the online version of the journal). However, in general the events did not appear to be pressure-balanced or slow-mode structures.

Maximum magnetic field rotations for the pulsed Alfvénic events ranged from 6° to 109°. Figure 3(c) reveals that the most probable rotation was ∼15°, but a substantial number of events were associated with considerably larger field rotations. The median and mean rotation angles were 21° and 25°, respectively.

In all of the events, minimum variance analysis provided a well-determined direction of maximum variance. On the other hand, in many cases the analysis failed to provide a well-determined direction of minimum variance. In most such events,

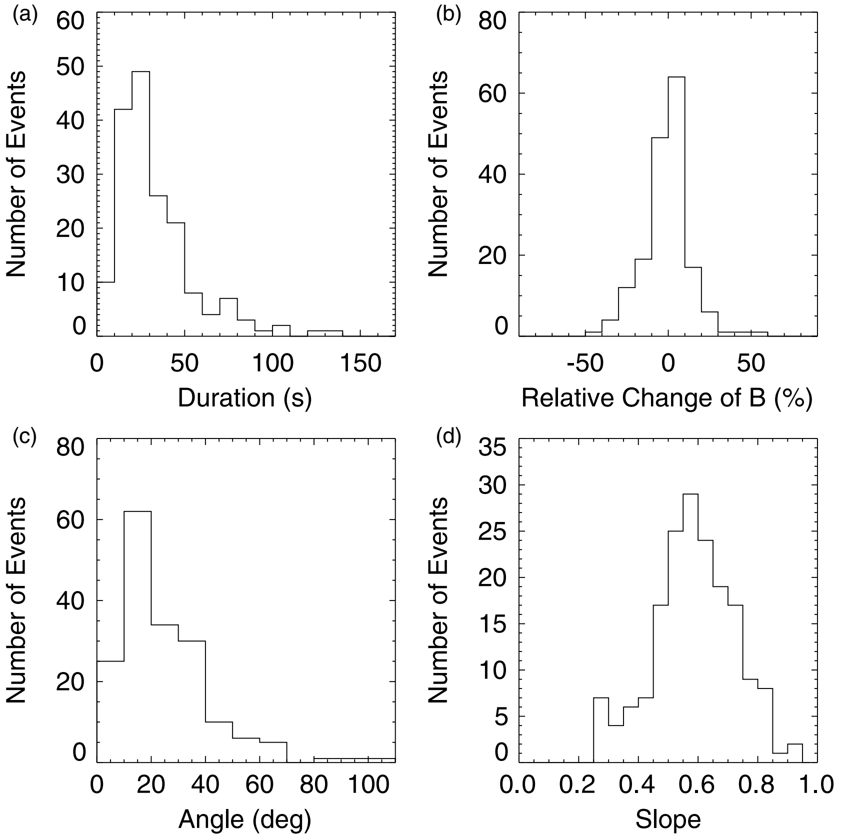

Figure 3. Histograms illustrating some basic characteristics of 175 pulsed Alfvénic events identified in the interval 2007 June 1–10. (a) Event durations. (b) Maximum percentage changes in field magnitude from outside to inside the events. (c) Maximum field rotations away from the initial field direction. (d) Absolute values of the slopes (Alfvénicities) of the events.

the magnetic field *LM* and *LN* hodograms followed nearly straight lines and reversed direction as B_L reversed direction, indicating that the rotations were nearly plane polarized, as shown in the Figure 2 event. Many of the events for which we did obtain a well-determined minimum variance direction had associated changes in the underlying magnetic field orientation. In such cases the magnetic field *LM* hodograms usually traced out separate, roughly straight, lines in the opposite *L*-directions with beginning and end points separated in the *M*-direction. Finally, some of the events with reasonably well-determined minimum variance directions had sizable, but usually random, fluctuations in the intermediate variance component.

We obtained good de Hoffman–Teller frames for all 175 pulsed Alfvénic events; the flow in those frames were, with but a few exceptions, aligned within 5° of the field direction. We also obtained excellent correlations between the components of **V** in the calculated de Hoffman–Teller frames and the components of the Alfvén velocity on a point-by-point basis. This indicates the strong Alfvénic nature of the events. However, as Figure 3(d) illustrates, the degree of Alfvénicity ranged from 0.28 to 0.93, with the most probable, mean, and median values all being $\sim$0.59. This range is similar to that of Alfvénic fluctuations in the solar wind in general at Earth's orbit (e.g., Marsch 1991) and indicates that the magnetic field fluctuation energy exceeds the plasma kinetic energy in these pulsed waves.

We have determined whether the changes in **V** and **B** were positively or negatively correlated on an event-by-event basis. With 14 exceptions, the correlations were positive when the underlying magnetic field was directed toward the Sun and were negative when the underlying field was directed outward from the Sun. This indicates that most of the pulse-like events were propagating anti-sunward in the solar wind rest frame, as is generally the case for Alfvénic fluctuations in the solar wind. Because the magnetic field underlying the pulse-like events often has a stochastic nature, we have verified the underlying field polarity of the events by examining the flow polarity (parallel or anti-parallel to **B**) of the solar wind suprathermal electron strahl, which carries the electron heat flux away from the Sun (e.g., Rosenbauer et al. 1977).

The 14 sunward-directed events tended to be temporally bunched and were probably generated by the solar wind's interaction with backstreaming energetic ions from Earth's bow shock. Although we cannot demonstrate that conclusively with the *Wind* data set, we have previously shown an association between backstreaming bow shock ions and pulsed Alfvénic fluctuations, albeit somewhat broader than the events included in the present study, propagating sunward in the solar wind rest frame (Gosling et al. 2009).

3. DISCUSSION

Using 3 s plasma and magnetic field observations from the *Wind* spacecraft, we have found that isolated, pulsed Alfvénic fluctuations are pervasive in the solar wind at all wind speeds examined during a randomly selected 10 day interval. These fluctuations are characterized by spatially limited, roughly symmetric and roughly plane-polarized rotations in the magnetic field and velocity vectors. They are clearly not simply random fluctuations. Like Alfvénic fluctuations in the solar wind in general, the large majority of these events propagate anti-sunward in the solar wind rest frame. The typical pulse-like and roughly symmetric nature of the magnetic field and velocity rotations in these events suggest that these Alfvénic disturbances do not evolve as they propagate. They thus appear to be, and probably are, solitary waves.

A slow-mode type solitary wave model based on the Derivative Nonlinear Schrödinger equation was developed by Baumgärtel (1999) to explain brief depressions in $|\mathbf{B}|$ in the solar wind during which the field rotates but ends up at approximately the same orientation as that prevailing prior to the depression. The model predicts coupled changes in the components of **V** and **B** and also predicts solitary events associated with small magnetic field enhancements. Baumgärtel called the field depression events "dark" solitons and the field enhancement events "bright" solitons. The model predicts that dark solitons would be far more prevalent than bright solitons. An important characteristic predicted by this slow-mode soliton wave model is a single bipolar (+ ,− or −, +) oscillation in the intermediate variance field component.

Rees et al. (2006) searched for bright soliton-like events having large, single bipolar oscillations in the intermediate variance field component using the entire 1 and 2 s solar wind magnetic field data set obtained by the *Ulysses* spacecraft covering a 14 year interval. They found 33 candidate events, but could not confirm their possible slow-mode or Alfvénic nature owing to the 4 minute cadence of the *Ulysses* plasma measurement, which was much longer than the typical temporal widths (30 s) of the observed events. Moreover, they showed that the magnetic field *LM* hodograms of their observed events were banana-shaped and were unlike the *LM* hodograms predicted by the slow-mode model. Subsequent theoretical work has focused on models that can produce bright solitary-like events having banana-shaped magnetic *LM* hodograms (Sauer et al. 2007; Baumgärtel et al. 2007; Mjolhus 2009).

The pervasive, isolated, pulsed Alfvénic events described in this Letter appear to be solitary waves but are not necessarily solitons, which are solitary waves that can pass through one another emerging unchanged except for a phase shift. Despite some agreement with predictions of the original Baumgärtel model (notably the presence of both "bright" and "dark" waves, and correlated changes in **V** and **B**), these waves do not appear to be the type of solitary structures he examined. None of the events we have identified had single bipolar oscillations in the intermediate variance field component or had magnetic *LM* hodograms of the nature predicted by the slow-mode model. Further, there was no obvious trend in these events for anti-correlation between changes in $|\mathbf{B}|$ and changes in proton density (see the complete form of Table 1 in the online version of the journal) as predicted by the slow-mode model. Nor did any of our identified events have the type of bipolar oscillations in the intermediate variance field component found in the Rees et al. (2006) study or the banana-shaped hodograms associated with those observed oscillations.

We are presently uncertain as to the origin of these apparent solitary waves, most of which propagate anti-sunward. It is difficult to understand how such waves can long survive in an inhomogeneous, turbulent medium that is expanding as the square of heliocentric distance. It has been suggested that solitary waves can evolve out of Alfvénic turbulence and that solitary waves generated in that manner might play an important role in heating and accelerating the solar wind, particularly relatively close to the Sun (e.g., Buti 1996; Ofman & Davila 1997). But it is not yet obvious to us that the observed waves are of the same physical nature as predicted by turbulence models. Measurements by the *Solar Probe*, scheduled for launch in 2018, should reveal if the number of solitary Alfvén waves increases close to the Sun and if the waves play an important role in heating and accelerating the solar wind.

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