



**HAL**  
open science

## Alfvénic Velocity Spikes and Rotational Flows in the Near-Sun Solar Wind

Justin C. Kasper, Stuart D. Bale, John W. Belcher, Matthieu Berthomier,  
Anthony W. Case, Benjamin D. G. Chandran, D.W. Curtis, D. Gallagher,  
S.P. Gary, L. Golub, et al.

► **To cite this version:**

Justin C. Kasper, Stuart D. Bale, John W. Belcher, Matthieu Berthomier, Anthony W. Case, et al..  
Alfvénic Velocity Spikes and Rotational Flows in the Near-Sun Solar Wind. *Nature*, 2019, 576 (7786),  
pp.228-231. 10.1038/s41586-019-1813-z . hal-03086221

**HAL Id: hal-03086221**

**<https://hal.science/hal-03086221>**

Submitted on 22 Dec 2020

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



# MIT Open Access Articles

## *Alfvénic velocity spikes and rotational flows in the near-Sun solar wind*

The MIT Faculty has made this article openly available. **Please share** how this access benefits you. Your story matters.

<b>Citation</b>	Kasper, J.C. et al. "Alfvénic velocity spikes and rotational flows in the near-Sun solar wind." <i>Nature</i> 576, 7786 (December 2019): 228–231 © 2019 The Author(s)
<b>As Published</b>	<a href="http://dx.doi.org/10.1038/s41586-019-1813-z">http://dx.doi.org/10.1038/s41586-019-1813-z</a>
<b>Publisher</b>	Springer Science and Business Media LLC
<b>Version</b>	Author's final manuscript
<b>Citable link</b>	<a href="https://hdl.handle.net/1721.1/127221">https://hdl.handle.net/1721.1/127221</a>
<b>Terms of Use</b>	Article is made available in accordance with the publisher's policy and may be subject to US copyright law. Please refer to the publisher's site for terms of use.

# Alfvénic Velocity Spikes and Rotational Flows in the Near-Sun Solar Wind

J. C. Kasper<sup>1,2\*</sup>, S. D. Bale<sup>3,4,5</sup>, J. W. Belcher<sup>6</sup>, M. Berthomier<sup>7</sup>, A. W. Case<sup>2</sup>, B. D. G. Chandran<sup>8,9</sup>, D. W. Curtis<sup>4</sup>, D. Gallagher<sup>10</sup>, S. P. Gary<sup>11</sup>, L. Golub<sup>2</sup>, J. S. Halekas<sup>12</sup>, G. C. Ho<sup>13</sup>, T. S. Horbury<sup>5</sup>, Q. Hu<sup>14</sup>, J. Huang<sup>1</sup>, K. G. Klein<sup>15,16</sup>, K. E. Korreck<sup>2</sup>, D. E. Larson<sup>4</sup>, R. Livi<sup>4</sup>, B. Maruca<sup>17,18</sup>, B. Lavraud<sup>19</sup>, P. Louarn<sup>19</sup>, M. Maksimovic<sup>20</sup>, M. Martinovic<sup>15</sup>, D. McGinnis<sup>12</sup>, N. V. Pogorelov<sup>14</sup>, J. D. Richardson<sup>6</sup>, R. M. Skoug<sup>11</sup>, J. T. Steinberg<sup>11</sup>, M. L. Stevens<sup>2</sup>, A. Szabo<sup>19</sup>, M. Velli<sup>21</sup>, P. L. Whittlesey<sup>4</sup>, K. H. Wright<sup>25</sup>, G. P. Zank<sup>14</sup>, R. J. MacDowall<sup>19</sup>, D. J. McComas<sup>22</sup>, R. L. McNutt, Jr.<sup>13</sup>, M. Pulupa<sup>4</sup>, N. E. Raouafi<sup>13</sup>, and N. A. Schwadron<sup>8,9</sup>

<sup>1</sup>Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI 48109, USA

<sup>2</sup>Smithsonian Astrophysical Observatory, Cambridge, MA 02138, USA

<sup>3</sup>Physics Department, University of California, Berkeley, CA 94720-7300, USA

<sup>4</sup>Space Sciences Laboratory, University of California, Berkeley, CA 94720-7450, USA

<sup>5</sup>The Blackett Laboratory, Imperial College London, London, SW7 2AZ, UK

<sup>6</sup>Kavli Center for Astrophysics and Space Sciences, Massachusetts Institute of Technology, 77 Massachusetts Avenue Cambridge, MA 02139-4307, USA

<sup>7</sup>Laboratoire de Physique des Plasmas, CNRS, Sorbonne Université, Ecole Polytechnique, Observatoire de Paris, Université Paris-Saclay, Paris, 75005, France

<sup>8</sup>Department of Physics and Astronomy, University of New Hampshire, Durham, NH 03824, USA

<sup>9</sup>Space Science Center, University of New Hampshire, Durham, NH 03824, USA

<sup>10</sup>Heliophysics and Planetary Science Branch ST13, Marshall Space Flight Center, Huntsville, AL 35812, USA

<sup>11</sup>Los Alamos National Laboratory P.O. Box 1663 Los Alamos, NM 87545, USA

<sup>12</sup>Department of Physics and Astronomy, University of Iowa, IA 52242, USA

<sup>13</sup>Johns Hopkins University Applied Physics Laboratory 11100 Johns Hopkins Road, Laurel, MD 20723-6099, USA

<sup>14</sup>Department of Space Science and Center for Space Plasma and Aeronomic Research, University of Alabama in Huntsville, Huntsville, AL 35805, USA

<sup>15</sup>Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA

<sup>16</sup>Department of Planetary Sciences, University of Arizona, Tucson, AZ 85719, USA

<sup>17</sup>Department of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA

<sup>18</sup>Bartol Research Institute, University of Delaware, Newark, DE 19716, USA

<sup>19</sup>NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA

<sup>20</sup>LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université de Paris, 5 place Jules Janssen, 92195 Meudon, France

<sup>21</sup>Department of Earth, Planetary & Space Sciences, University of California, Los Angeles CA 90095, USA

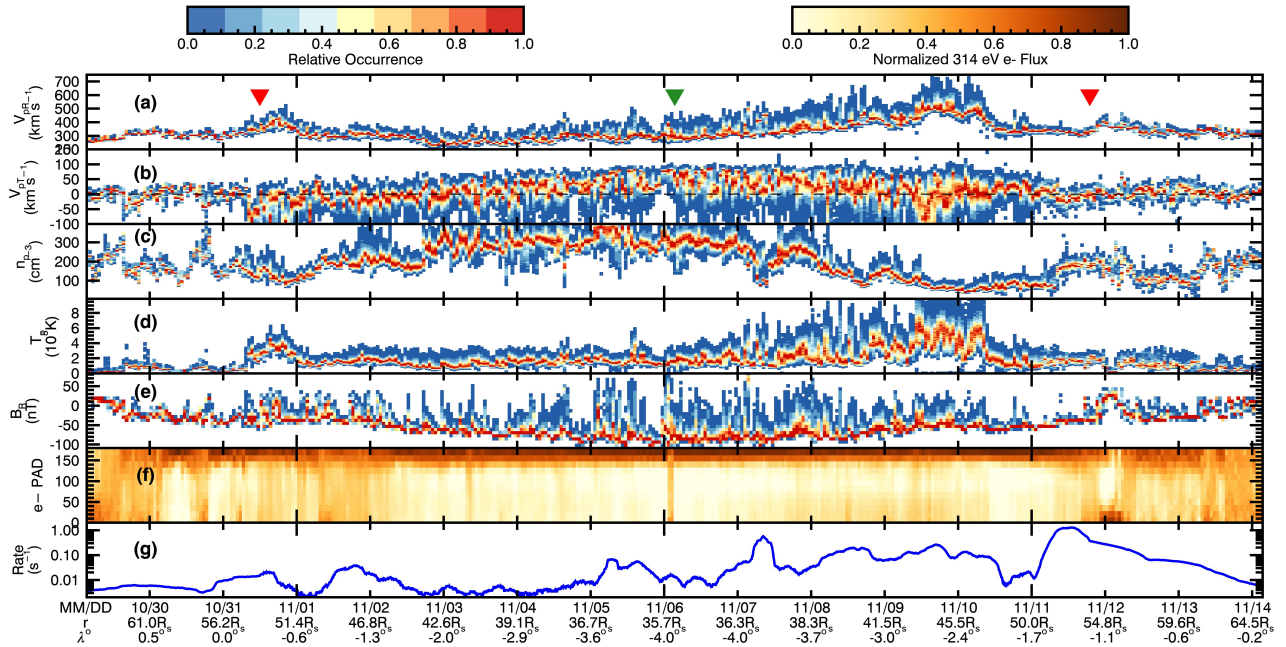
<sup>22</sup>Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA

<sup>24</sup>Institut de Recherche en Astrophysique et Planétologie, CNRS, UPS, CNES, Université de Toulouse, Toulouse, France

<sup>25</sup>Universities Space Research Association, Science and Technology Institute, Huntsville AL 35805, USA

\*jckasper@umich.edu

**ABSTRACT**

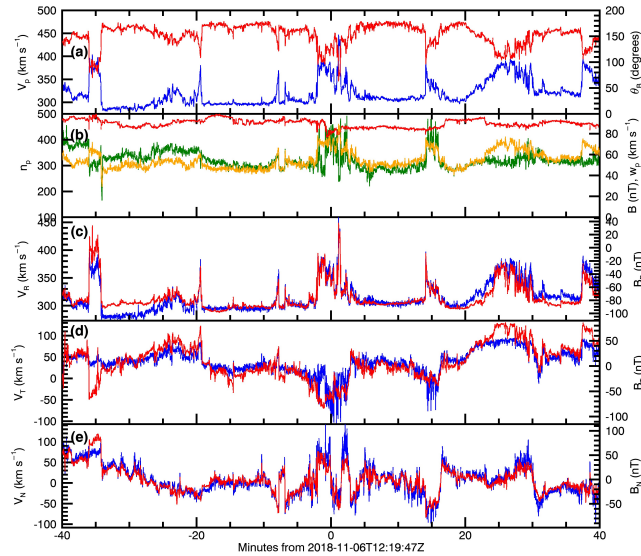


**Figure 1.** An overview of the first encounter with the Sun by Parker Solar Probe. (a) relative occurrence rate of proton radial speed  $V_{pR}$  in one hour intervals. Red triangles are the start and end of the high-rate data collection below  $54R_S$  and the green triangle indicates perihelion at  $35.7R_S$ . (b) same for transverse component  $V_{pT}$  of proton velocity in solar equatorial plane, (c) proton number density  $n_p$ , (d) proton temperature  $T_p$ , (e) radial component of magnetic field  $B_R$ , (f) electron pitch-angle distribution, and (g) 20 – 200 keV proton rate. The date, distance  $r$ , and latitude  $\lambda$  relative to the solar equator are indicated at daily intervals.

The prediction of a supersonic solar wind<sup>1</sup> was first confirmed by spacecraft near Earth<sup>2,3</sup> and later by spacecraft at heliocentric distances  $r$  as small as  $62$  solar radii ( $R_S$ )<sup>4</sup>. These missions showed that plasma accelerates as it emerges from the corona, aided by unidentified processes that transport energy outward from the Sun before depositing it in the wind. Alfvénic fluctuations are a promising candidate for such a process because they are seen in the corona and solar wind and contain significant energy<sup>5–7</sup>. Magnetic tension forces the corona to co-rotate with the Sun, but to date any residual rotation reported far from the Sun has been much smaller than the amplitude of waves and deflections from interacting wind streams<sup>8</sup>. Here we report observations of solar-wind plasma at  $r \simeq 35R_S$ <sup>9–11</sup>, well inside the radius at which stream interactions become important. We find that the Alfvén waves organize into structured velocity spikes up to minutes long that are associated with propagating S-like bends in the magnetic-field lines. We detect an increasing azimuthal flow velocity of the solar wind around the Sun, peaking at  $35 - 50 \text{ km s}^{-1}$ , significantly above the amplitude of waves. These flows exceed classical predictions of a few  $\text{km s}^{-1}$ , challenging models of circulation in the corona and calling into question our understanding of how stars lose angular momentum and spin down as they age<sup>12–14</sup>.

Parker Solar Probe (PSP) launched in August 2018 on a Delta IV Heavy rocket. The high energy of the launch combined with a gravitational assist from Venus in September 2018, placed PSP into an eccentric orbit with a period of 147 days and a perihelion at  $r = 35.7R_S$ , nearly a factor of two closer to the Sun than any previous mission<sup>4</sup>. This letter makes use of observations collected by instruments on the spacecraft during the first two encounters with the Sun in November 2018 and April 2019. While the instruments collect observations at a low rate far from the Sun, the primary science collection at high rate occurs during the encounter phase of each orbit at  $r < 54R_S$  (0.25 au). Encounter one (E1) lasted from 31 October to 12 November 2018, with the first perihelion occurring at 03:27 UT on 6 November. During these two encounters the longitude of PSP relative to the rotating surface of the Sun barely changed; PSP essentially dove down into, and then rose straight up from, a single narrow region above the Sun. E1 and E2 data thus describe a handful of specific solar-wind streams.

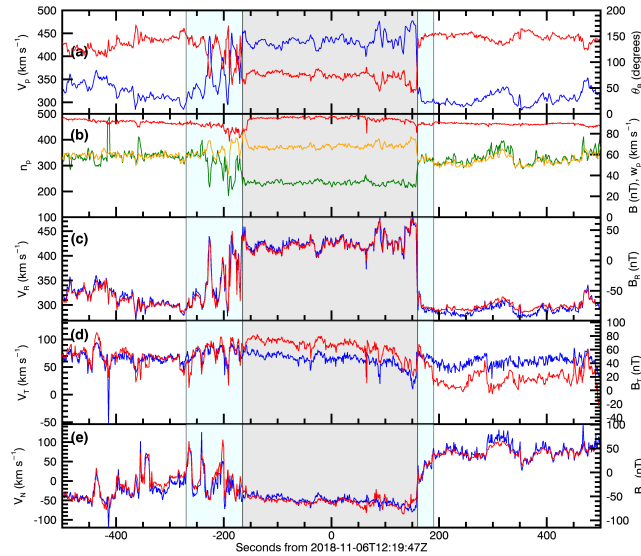
Nearly two million thermal energy distribution functions of the solar-wind protons were recorded during E1, and more than three times that during E2 (Fig. 1, Extended Data Figure 1). From these distribution functions solar wind proton bulk properties such as velocity, density, and temperature are derived. Within any hour interval, the distribution of radial solar-wind speed



**Figure 2.** Solar wind fluctuations near closest approach. Near-Sun fluctuations meet Alfvénic criteria, but are organized into structures and contain density enhancements. (a) magnitude of  $V_{pR}$  (blue) and angle  $\theta_{BR}$  of  $B$  from radial outwards, (b) magnitudes of  $n_p$  (green),  $B$  (red), and proton thermal speed  $w_p$  (yellow); (c-e) variation of each vector component of velocity (blue) and magnetic field (red) in the  $R$ ,  $T$ , and  $N$  directions. There is a baseline solar wind speed with  $\approx 300\text{km/s}$  and jets where  $V_p$  jumps by  $\approx 100\text{km/s}$ . The fluctuations are highly Alfvénic, with equal energy in field and flow, but organized into structures instead of randomly distributed, and there is evidence of compressions.

55  $V_{pR}$  was strongly peaked at a minimum value, with a one-sided tail extending to larger  $V_{pR}$ .  $V_{pR}$  reached its minimum value of  
56 200 km/s about a quarter of the way though E1 and then steadily rose to about 600 km/s. Numerical simulations and simple  
57 extrapolations of the observed photospheric magnetic field suggest that PSP spent all of E1 south of the global heliospheric  
58 current sheet (HCS), in a region with inward magnetic polarity ( $B_R < 0$ )<sup>15</sup>. Near the start and end of E1 PSP sampled slow  
59 wind from near the HCS. Closer to the Sun PSP observed first very slow wind and then fast wind, both of which are thought  
60 to emerge from a low-latitude coronal hole<sup>15</sup>. Below 40  $R_S$ ,  $V_{pT}$  has a net positive value, which peaks at closest approach.  
61 This flow may be the long-sought signature of plasma co-rotation in the corona. The density peaks in the slowest wind, at  
62 a value of approximately  $400\text{ cm}^{-3}$ , about 50 times higher than typical values at 1 au, as expected from mass conservation  
63 and spherical expansion. The proton temperature  $T_p$  and  $V_{pR}$  remain positively correlated<sup>16</sup>. At perihelion the protons are  $\approx 4$   
64 times hotter than protons with similar  $V_{pR}$  at 1 au, consistent with radial scalings reported from earlier missions<sup>4</sup>. The radial  
65 component of the magnetic field,  $B_R$ , increases in magnitude with proximity to the Sun but unexpectedly changes sign many  
66 times. The pitch-angle ( $\theta$ ) distribution (PAD) for electrons, or the number of electrons at a given energy as a function of their  
67 angle relative to  $B$ , is a valuable diagnostic of these changes in the direction of  $B$ . Here we show the PAD in a 22-eV-wide  
68 energy channel centered on 314 eV, well above the electron thermal energy. The sharp peak near  $180^\circ$  corresponds to the *strahl*,  
69 a beam of super-thermal electrons that travel away from the Sun along magnetic-field lines. Near the Sun *strahl* evolves towards  
70 small  $\sin \theta$  because of magnetic-moment conservation<sup>17</sup>. If the reversals in  $B_R$  seen by PSP result from PSP's crossing between  
71 open field lines (connected to the Sun at only one end) with different signs of  $B_R$  back at the Sun, then the *strahl* would flip  
72 between  $180^\circ$  and  $0^\circ$  each time  $B_R$  changed sign. Instead, every time  $B_R$  flips, the *strahl* maintains its  $180^\circ$  orientation, clearly  
73 indicating that the reversals in  $B_R$  are due to S-like bends in the magnetic-field lines (Extended Data Figure 2). Closed field  
74 lines with both ends connected to the Sun and *strahl* traveling both parallel and anti-parallel to  $B$  are seen during the arrival of a  
75 coronal mass ejection on 12 November, following an enhancement in energetic particles<sup>18</sup>.

76 Fig. 2 shows a timeseries of 80 minutes of observations several hours after perihelion illustrating typical velocity and  
77 magnetic-field fluctuations. About half the time  $B$  points radially inward towards the Sun and  $V$  sits at a relatively constant  
78  $300\text{km/s}$ . The remaining time includes seven distinct intervals in which  $B$  rotates away from its radial-inwards orientation



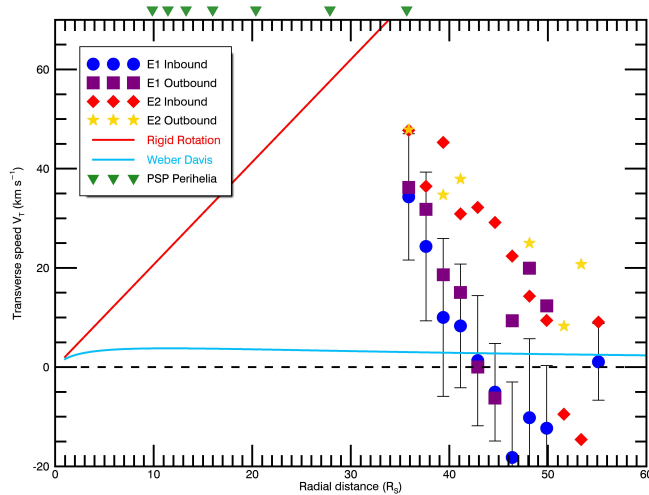
**Figure 3.** A closer look at a velocity spike. The same formatting is used as in Figure 2, but focused on a single 1,000 second interval. The left blue region indicates the 105 s period when PSP moved from the ambient plasma into the spike. The central core of the spike is indicated by the grey region and lasted for 325s, characterized by steady but disturbed flow and field with a large rotation in  $B$  to  $\theta_B \sim 70^\circ$ , a jump in flow to  $343 \text{ km s}^{-1}$ . Return from the core spike into ambient solar wind is marked by the second blue region and took 30s.

79 and  $V_{pR}$  simultaneously jumps and  $V$  also rotates, linking the one-sided tail in  $V_{pR}$  and the reversals in polarity seen in the E1  
80 overview. These jumps in flow associated with rotations in  $B$  and  $V$  are similar to one-sided Alfvénic structures first seen farther  
81 from the Sun<sup>6,7</sup>. The spikes seen by PSP are different in that they have larger amplitudes and are often associated with an  
82 increase in density,  $n_p$ , indicating that the spikes have a non-Alfvénic component. The correlated variations in the components  
83 of  $B$  and  $V$ , their relative amplitudes, and the constant value of  $|B|$  are consistent with large-amplitude, spherically polarized  
84 Alfvén waves propagating through the plasma in the anti-Sunward direction, similar to earlier observations<sup>5,19</sup>. We can classify  
85 this wind stream (and indeed much of E1) as Alfvénic slow solar wind<sup>20</sup>.

86 About 1,000 long-duration ( $> 10 \text{ s}$ ) and isolated velocity spikes with large rotations in  $B$  were identified in E1. (About half  
87 as many were seen in E2.) Often the spikes can be separated chronologically into a core region with plasma conditions that are  
88 very different from the ambient solar wind but relatively constant, a comparatively short transition region on one side of the  
89 core, and a longer transition region on the other side containing large-amplitude fluctuations (See Fig. 3). During the 105s  
90 transition at the beginning of this spike the flow underwent seven large oscillations of amplitude  $150 \text{ km s}^{-1}$ , possibly resulting  
91 from Kelvin-Helmholtz instability.

92 Equally unexpected as the spikes and  $B_R$  reversals are the large-amplitude and sustained positive rotational velocities seen  
93 below  $40R_S$  for E1 and  $50R_S$  for E2 (Fig. 4). Net rotation has been reported farther from the Sun, but it was on the same order  
94 as instrument error and much smaller than the standard deviation in flow due to fluctuations and stream interactions<sup>8,21</sup>. Here  
95  $V_{pT}$  rises to  $35 \text{ km s}^{-1}$  (E1) and  $50 \text{ km s}^{-1}$  (E2). This is much greater than the variance from fluctuations including the velocity  
96 spikes, there is no evidence of stream interactions, and the values are much greater than the precision in averaged flows of less  
97 than  $0.5 \text{ km s}^{-1}$  and an absolute error in flow due to a pointing error of less than  $3 \text{ km s}^{-1}$  (See Methods). These are the first in  
98 situ observations of net rotational flow in the solar wind significantly above fluctuations and uncertainty.

99 Some level of rotational flow has always been expected in the solar wind near the Sun, as magnetic tension in the corona  
100 should force the plasma to rotate as the Sun spins. However, the large rotational velocities measured greatly exceed the value  
101 in the axisymmetric Weber-Davis model<sup>13</sup>, posing a major challenge to our understanding of the dynamics of the near-Sun  
102 solar wind. Determining the origin of these tangential flows will be essential for understanding how the Sun loses angular  
103 momentum and spins down as it ages<sup>12,14,22</sup>. Further studies of the angular momentum should include magnetic fields, waves,



**Figure 4.** Large circulation of solar wind seen near Sun. Averaged rotational flow,  $V_{pT}$ , over  $1.75R_{\odot}$  intervals during E1 (inbound in blue with error bars indicating standard deviation representative of all observations, outbound in purple) and E2 (inbound in red, outbound in yellow) as a function of radial distance. Each symbol is an average over at least 10,000 observations and the values closest to perihelion are averaged over 60,000–230,000 observations. Error bars for E1 inbound show one s.d. of the individual observations and are representative of the variation for the other 3 phases. The uncertainty in the mean of  $V_{pT}$  is much smaller than the symbols. Current and upcoming perihelia are shown with green triangles. Lines indicate no rotation (dashed), rigid co-rotation everywhere (red), and the axisymmetric Weber-Davis model (blue).

and other ions. Future PSP orbits will clarify the extent to which these large rotational flows characterize other solar-wind streams. These orbits will also provide critical additional diagnostics of the state of the plasma, including turbulence, velocity spikes, temperature anisotropy, and particle velocity-distribution functions, at heliocentric distances as small as  $9.86R_{\odot}$ .

## References

1. Parker, E. N. Dynamics of the Interplanetary Gas and Magnetic Fields. *Astrophys. J.* **128**, 664–676 (1958).
2. Gringauz, K. I., Bezrokhikh, V. V., Ozerov, V. D. & Rybchinskii, R. E. A Study of the Interplanetary Ionized Gas, High-Energy Electrons and Corpuscular Radiation from the Sun by Means of the Three-Electrode Trap for Charged Particles on the Second Soviet Cosmic Rocket. *Soviet Physics Doklady* **5**, 361–364 (1960).
3. Bonetti, A., Bridge, H. S., Lazarus, A. J., Rossi, B. & Scherb, F. Explorer 10 Plasma Measurements. *J. Geophys. Res.* **68**, 4017–4063 (1963).
4. Marsch, E. *et al.* Solar wind protons - Three-dimensional velocity distributions and derived plasma parameters measured between 0.3 and 1 AU. *J. Geophys. Res.* **87**, 52–72 (1982).
5. Belcher, J. W. & Davis, J., Leverett. Large-amplitude Alfvén waves in the interplanetary medium, 2. *J. Geophys. Res.* **76**, 3534–3563 (1971).
6. Gosling, J. T., McComas, D. J., Roberts, D. A. & Skoug, R. M. A One-Sided Aspect of Alfvénic Fluctuations in the Solar Wind. *Astrophys. J. Lett.* **695**, L213–L216 (2009).
7. Horbury, T. S., Matteini, L. & Stansby, D. Short, large-amplitude speed enhancements in the near-Sunfast solar wind. *Mon. Not. Roy. Astron. Soc.* **478**, 1980–1986 (2018).
8. Pizzo, V. *et al.* Determination of the solar wind angular momentum flux from the HELIOS data - an observational test of the Weber and Davis theory. *apj* **271**, 335–354 (1983).
9. Fox, N. J. *et al.* The Solar Probe Plus Mission: Humanity’s First Visit to Our Star. *Space Sci. Rev.* **204**, 7–48 (2016).
10. Kasper, J. C. *et al.* Solar Wind Electrons Alphas and Protons (SWEAP) Investigation: Design of the Solar Wind and Coronal Plasma Instrument Suite for Solar Probe Plus. *Space Sci. Rev.* **204**, 131–186 (2016).
11. Bale, S. D. *et al.* The FIELDS Instrument Suite for Solar Probe Plus. Measuring the Coronal Plasma and Magnetic Field, Plasma Waves and Turbulence, and Radio Signatures of Solar Transients. *Space Sci. Rev.* **204**, 49–82 (2016).

- 129 **12.** Schatzman, E. A theory of the role of magnetic activity during star formation. *Annales d'Astrophysique* **25**, 18–29 (1962).
- 130 **13.** Weber, E. J. & Davis, J., Leverett. The Angular Momentum of the Solar Wind. *Astrophys. J.* **148**, 217–227 (1967).
- 131 **14.** Finley, A. J., Matt, S. P. & See, V. The Effect of Magnetic Variability on Stellar Angular Momentum Loss. I. The Solar  
132 Wind Torque during Sunspot Cycles 23 and 24. *Astrophys. J.* **864**, 125 (2018).
- 133 **15.** Bale, S. D. *et al.* The magnetic structure and electrodynamics of the emerging solar wind. *Nature* (Submitted).
- 134 **16.** Elliott, H. A., Henney, C. J., McComas, D. J., Smith, C. W. & Vasquez, B. J. Temporal and radial variation of the solar  
135 wind temperature-speed relationship. *Journal Geophysical Research: Space Physics* **117** A09102 (2012).
- 136 **17.** Pilipp, W. G. *et al.* Characteristics of electron velocity distribution functions in the solar wind derived from the helios  
137 plasma experiment. *jgr* **92**, 1075–1092 (1987).
- 138 **18.** McComas, D. M. *et al.* Energetic Particle Environment near the Sun from Parker Solar Probe. *Nature* (Submitted).
- 139 **19.** Vasquez, B. J. & Hollweg, J. V. Formation of arc-shaped Alfvén waves and rotational discontinuities from oblique linearly  
140 polarized wave trains. *J. Geophys. Res.* **101**, 13527–13540 (1996).
- 141 **20.** Bruno, R. & Carbone, V. The Solar Wind as a Turbulence Laboratory. *Living Reviews Solar Physics* **10**, 2 (2013).
- 142 **21.** Richardson, I. G. Solar wind stream interaction regions throughout the heliosphere. *Living Reviews Solar Physics* **15**, 1  
143 (2018).
- 144 **22.** Axford, W. I. The Solar Wind. *Solar Physics* **100**, 575–586 (1985).

## 145 Figure Legends

146 **Figure 1:** An overview of the first encounter with the Sun by Parker Solar Probe.

147 (a) relative occurrence rate of proton radial speed  $V_{pR}$  in one hour intervals. Red triangles are the start and end of the  
148 high-rate data collection below  $54R_S$  and the green triangle indicates perihelion at  $35.7R_S$ . (b) same for transverse component  
149  $V_{pT}$  of proton velocity in solar equatorial plane, (c) proton number density  $n_p$ , (d) proton temperature  $T_p$ , (e) radial component  
150 of magnetic field  $B_R$ , (f) electron pitch-angle distribution, and (g) 20 – 200 keV proton rate. The date, distance  $r$ , and latitude  $\lambda$   
151 relative to the solar equator are indicated at daily intervals.

152 **Figure 2:** Solar wind fluctuations near closest approach.

153 Near-Sun fluctuations meet Alfvénic criteria, but are organized into structures and contain density enhancements. (a)  
154 magnitude of  $V_{pR}$  (blue) and angle  $\theta_{BR}$  of  $B$  from radial outwards, (b) magnitudes of  $n_p$  (green),  $B$  (red), and proton thermal  
155 speed  $w_p$  (yellow); (c-e) variation of each vector component of velocity (blue) and magnetic field (red) in the  $R$ ,  $T$ , and  $N$   
156 directions. There is a baseline solar wind speed with  $\approx 300\text{km/s}$  and jets where  $V_p$  jumps by  $\approx 100\text{km/s}$ . The fluctuations are  
157 highly Alfvénic, with equal energy in field and flow, but organized into structures instead of randomly distributed, and there is  
158 evidence of compressions.

159 **Figure 3:** A closer look at a velocity spike.

160 The same formatting is used as in Figure 2, but focused on a single 1,000 second interval. The left blue region indicates the  
161 105 s period when PSP moved from the ambient plasma into the spike. The central core of the spike is indicated by the grey  
162 region and lasted for 325s, characterized by steady but disturbed flow and field with a large rotation in  $B$  to  $\theta_B \sim 70^\circ$ , a jump in  
163 flow to  $343\text{ km s}^{-1}$ . Return from the core spike into ambient solar wind is marked by the second blue region and took 30s.

164 **Figure 4:** Large circulation of solar wind seen near Sun.

165 Averaged rotational flow,  $V_{pT}$ , over  $1.75R_S$  intervals during E1 (inbound in blue with error bars indicating standard deviation  
166 representative of all observations, outbound in purple) and E2 (inbound in red, outbound in yellow) as a function of radial  
167 distance. Each symbol is an average over at least 10,000 observations and the values closest to perihelion are averaged over  
168 60,000-230,000 observations. Error bars for E1 inbound show one s.d. of the individual observations and are representative  
169 of the variation for the other 3 phases. The uncertainty in the mean of  $V_{pT}$  is much smaller than the symbols. Current and  
170 upcoming perihelia are shown with green triangles. Lines indicate no rotation (dashed), rigid co-rotation everywhere (red), and  
171 the axisymmetric Weber-Davis model (blue).

172 **Extended Data Figure 1:** An overview of the second encounter with the Sun by Parker Solar Probe.

173 In the same format as Fig. 1. Spikes in the velocity are again seen coincident with the magnetic field reversals, but the jump  
174 in speed is smaller, likely because the Alfvén speed was slower in E2 than E1. The density at perihelion is substantially lower.



175 **Extended Data Figure 2:** Schematic of an "S-shaped" magnetic structure creating a field reversal, heat flux reversal, and  
176 spike in velocity.

177 This figure illustrates the possible geometry of an "S-shaped" propagating Alfvénic disturbance (gray box) and how it  
178 would appear to the spacecraft (black square) as it flew through the spike on the green trajectory. The light lines with arrows  
179 indicate the configuration of the magnetic field, with all field lines ultimately pointed back to the Sun. Arrows at each black  
180 square indicate the vector velocity (blue), electron strahl (orange), and magnetic field (red) seen by the spacecraft. If this was a  
181 purely Alfvénic structure then the spike would move away from the Sun anti-parallel to  $B$  at the local Alfvén speed,  $C_A$ . In the  
182 frame of the spike the shape of the structure would be static, with plasma flowing in along field lines on the upper left and  
183 through the spike, emerging at the lower right, always flowing at  $C_A$ . In the frame of the spacecraft, the constant flow along  
184 field lines in the propagating spike frame would translate into a radial increase of  $V$  by  $C_A$  when  $B$  was perpendicular to  $R$ , and  
185 a maximum jump of  $2C_A$  when  $B$  was completely inverted. Since the heat flux escapes away from the Sun, it would rotate so as  
186 to always be anti-parallel to  $B$  and appear to be flowing back to the Sun at the center of this disturbance.

## 187 Methods

188 **Data Collection and Analysis** The data presented in this letter were collected over the course of the first two encounters of  
189 the Sun by Parker Solar Probe in November 2018 and April 2019. This study makes use of all of the in situ instruments on  
190 the spacecraft. Thermal plasma properties are measured by the PSP SWEAP instrument suite<sup>10</sup>, including the Solar Probe  
191 (SPC) Cup, SPAN electron, and SPAN ion plasma data. Magnetic field data from the outboard FIELDS magnetometer was also  
192 used<sup>11,15</sup>, along with energetic particle rates as seen by  $IS \odot IS$ <sup>18</sup>. SPC measures the reduced distribution function of ionized  
193 hydrogen and helium and the two dimensional flow angles of the ions as a function of energy/charge. These measurements are  
194 performed at least once per second and typically more than four times per second throughout the encounter phase of each orbit  
195 (below  $0.25 au$  or  $54 R_s$ ). This paper uses moments of the entire SPC proton distribution function to calculate a total effective  
196 proton velocity, density, and radial component of the temperature. While the SPAN ion sensor generally did not view the peak  
197 of the proton velocity distribution, the overlapping region seen by SPAN and SPC has been compared to confirm that there are  
198 no gross offsets in calibration or derived plasma properties such as velocity, but this technique will be more accurate when the  
199 solar wind flows into SPAN closer to the Sun. Observations of electrons with a center energy of 314 eV and width of 22 eV by  
200 the two SPAN electron sensors were combined, along with the FIELDS determination of the magnetic field direction, to create  
201 the electron pitch angle distributions.

202 All underlying data are being archived and will be available for download at the NASA Space Physics Data Facility in  
203 November 2019<sup>23</sup>. Additional SWEAP data and information are available at the SWEAP web page<sup>24</sup>. Data were analyzed and  
204 graphics developed in the Interactive Data Language (IDL).

205 **Statistics** The distributions of plasma properties in Fig. 1 and Extended Data Figure 1 were produced with one hour  
206 time resolution. During the encounters the time resolution of the plasma instrument ranged from slightly more than one  
207 measurement per second to more than four measurements per second, so each column in those panels represents the distribution  
208 of approximately 3,600-14,400 measurements. All error bars indicate one standard deviation (s.d.) of the measurements from  
209 the mean. At least 10,000 and generally more than 80,000 observations are used in calculating the mean transverse flow  $V_{pT}$  in  
210 Figure 4.

211 **Estimates of Uncertainty** The absolute accuracy of the Solar Probe Cup (SPC) ion measurements are summarized here.  
212 As verified in ground testing, the absolute accuracy for  $V_{pR}$  is less than 0.01% over a measurable range of approximately 119  
213 km/s to 1065 km/s. The absolute accuracy in temperature is similarly negligible over a measurable range of approximately  
214 7.3 kK to 21.1 MK (i.e. thermal speeds of 11 km/s to 600 km/s). Speeds and temperatures at the extremes of these ranges  
215 are subject to systematic considerations, but no such measurements have been presented here. The accuracy of the density  
216 measurement is determined by comparison with the plasma frequency as observed by FIELDS<sup>11</sup>. Thus the absolute accuracy  
217 of the SPC density measurement is estimated at  $\approx 1\%$  and is no worse than 3%. The absolute accuracy for off-radial flow  
218 components are verified via spacecraft roll maneuvers about the SPC symmetry axis. For solar wind fluxes typical of the first  
219 two encounters, the uncertainty associated with this calibration corresponds to a typical absolute accuracy of  $\approx 0.5$  degrees.  
220 For  $400 km s^{-1}$  solar wind this corresponds to an expected error in  $V_{pT}$  of  $3 - 4 km s^{-1}$ , which is much smaller than the net  
221 rotational flow observed.

222 **Signatures of Alfvénic Fluctuations** In discussing Fig. 2 we stated that the correlation of fluctuations in components  
223 of  $\mathbf{B}$  and  $\mathbf{V}$  were generally indicative of outward propagating Alfvén waves. Consider vector waves or fluctuations  $\Delta\mathbf{V}$  and  
224  $\Delta\mathbf{B}$  superimposed on a steady background  $\mathbf{B}_0$  and  $\mathbf{V}_0$ . In the long wavelength fluid magnetohydrodynamic (MHD) limit  
225 Alfvén waves propagate exactly parallel or anti-parallel to  $\mathbf{B}_0$ , are dispersionless and do not compress the plasma, and there  
226 is a simple linear relationship  $\Delta\mathbf{B} = \pm D_A \Delta\mathbf{V}$ , where  $D_A = (n_p + 4n_\alpha)^{0.5} \Theta / 21.8 (nT km^{-1} s)$ , densities are in units of  $cm^{-3}$ ,  
227 and  $\Theta = (1 - \beta_{\parallel} + \beta_{\perp})^{-0.5}$ . Here  $\Theta$  is a correction for thermal pressure anisotropy where  $\beta_{\parallel}$  is the ratio of parallel plasma  
228 pressure to magnetic pressure and  $\beta_{\perp}$  is the ratio of perpendicular plasma pressure to  $\mathbf{B}$ . For this period we find that on average

229  $n_p = 220 \text{ cm}^{-3}$ ,  $\beta_{\parallel} = 0.202$ , and  $\beta_{\perp} = 0.315$ . SPC and SPAN were not configured optimally to measure the ionized helium  
230 abundance  $n_{\alpha}$ , so assuming the typical range  $0.5 < n_{\alpha}/n_p < 4.5\%$  we expect  $D_A = 0.68 - 0.74 \text{ (nT km}^{-1} \text{ s)}$ . We find  $D_A$  for  
231 each of the RTN components to be 0.71, 1.09, 0.70  $\text{(nT km}^{-1} \text{ s)}$ , so the  $R$  and  $N$  components are exactly within the expected  
232 range and the fluctuations in the  $T$  direction are about 33% higher. It is common for the  $D_A$  to be different for each component  
233 of the velocity<sup>5</sup>. We then used the calculated value of  $D_A$  to rescale the range of the vector components of  $B$  so they should  
234 overlap with  $V$  if the fluctuations were purely Alfvénic. The sign of the relation between  $\Delta B$  and  $\Delta V$  is given by the sign of  
235  $-\mathbf{k} \cdot \mathbf{B}_0$ , where  $k$  is the wavevector and gives the direction of propagation, and  $B$  is an average direction of the field over a long  
236 time scale. Since the ambient direction of the magnetic field outside the large amplitude fluctuations points towards the Sun and  
237 the correlations are overwhelmingly positive this means we are seeing outward waves.

238 **Identification of velocity spikes.** Isolated velocity spikes were identified by looking for all intervals in each encounter  
239 where the orientation of the magnetic field started in the quiet configuration pointed nearly towards the Sun, rotated more than  
240  $45^\circ$  away from the quiet configuration for at least 10 seconds, and then returned back to the original direction. Candidate events  
241 were then examined manually to identify starting and ending times.

## 242 Methods References

243 23. NASA's Space Physics Data Facility <https://spdf.gsfc.nasa.gov/>.

244  
245 24. The SWEAP Suite on Parker Solar Probe <https://www.cfa.harvard.edu/sweap>.

## 246 Acknowledgements

247 The SWEAP Investigation and this publication are supported by the PSP mission under NASA contract NNN06AA01C. The  
248 SWEAP team expresses its gratitude to the scientists, engineers, and administrators who have made this project a success,  
249 both within the SWEAP institutions and from NASA and the project team at JHU/APL. J.C.K. acknowledges support of the  
250 2019 Summer School at the Center for Computational Astrophysics, Flatiron Institute. The Flatiron Institute is supported by  
251 the Simons Foundation. S.D.B. acknowledges the support of the Leverhulme Trust Visiting Professorship program. TH was  
252 supported by UK STFC ST/S0003641/1.

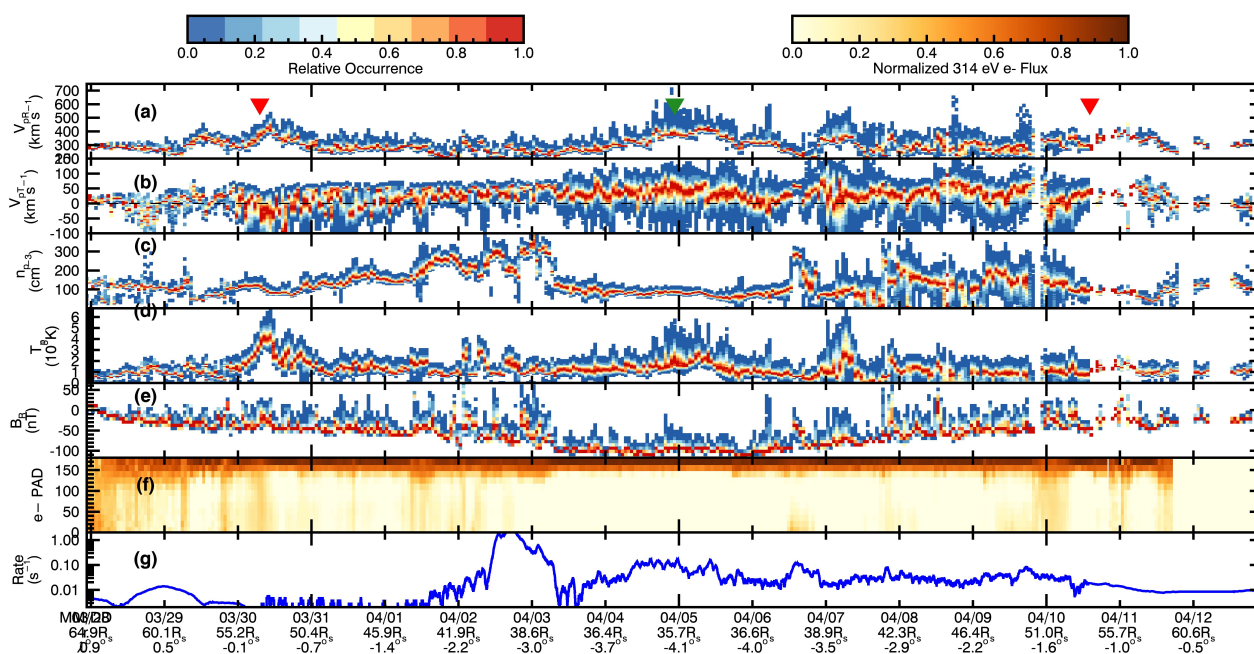
## 253 Author contributions statement

254 J.C.K. is the SWEAP Principal Investigator and led the data analysis and writing of this letter. S.D.B. is the FIELDS PI and a  
255 SWEAP Co-Investigator and provided the magnetic field observations. J.W.B. leads the US group where the solar wind Faraday  
256 cup was developed and provided guidance on identifying Alfvénic fluctuations. M.B. provided a pre-amplifier ASIC used  
257 within the SPAN electron instruments. A.W.C. is the Solar Probe Cup instrument scientist and ensured that the instrument met  
258 its performance requirements and was calibrated. B.D.G.C. contributed theoretical calculations and writing to the manuscript.  
259 D.W.C. D.G. was the institutional lead at NASA MSFC responsible for materials testing and calibration of SPC. S.P.G. provided  
260 recommendations on measurement requirements in order to detect instabilities. L.G. provided related solar observations and  
261 results. J. H. contributed to the analysis of the electron observations and to the manuscript. G.H. provided a time of flight  
262 ASIC to reduce the size and power of the SPAN ion instrument. T.H. participated in the analysis of the Alfvénic spikes.  
263 Q.H. identified magnetic flux ropes. K.G.K. contributed to writing the manuscript and provided warm plasma growth rate  
264 calculations. K.E.K. led the SWEAP Science Operations Center and coordinated observing plans between the instruments  
265 and the project. M.V. contributed to writing the manuscript and discussing the relationship between Alfvénic fluctuations and  
266 angular momentum. D.L. is the institutional lead at Berkeley responsible for the implementation of the SPAN instruments and  
267 the SWEAP Electronics Module suite-wide computer. R.L. is the SPAN ion instrument scientist. B.A.M. performed simulations  
268 of the fields of view of the SWEAP ion instruments and their probabilities of detecting the solar wind. B.L. identified flux  
269 ropes and other signatures of coronal mass ejections in the data. P.L. coordinated solar furnace testing of the Solar Probe Cup  
270 materials before launch. M.M. absolute calibration, quality of vdfs. N.P. Numerical simulations. J.D.R. FC design, radial  
271 variation. R.K.S. Electron PADs. J.T.S. field rotation causes. M.L.S. Overall data pipeline for SWEAP, SPC high level data  
272 products. A.S. estimated the location of the heliospheric current sheet. P.W. set up the SPC calibration at MSFC and then  
273 became SPAN electron instrument scientist at Berkeley. K.W. arranged the SPC calibration at MSFC. G.P.Z. leads the SWEAP  
274 theory team. R.J.M. leads the FIELDS fluxgate magnetometer. D.J.M. is the IS $\odot$ IS PI. He provided the energetic particle data.  
275 R.M. Lead for the EPI-Lo energetic particle instrument. M.P. FIELDS SOC lead. N.R. PSP Project Scientist and reviewed  
276 jets and similar coronal transients. N.A.S. runs the IS $\odot$ IS Science Operations Center. All authors participated in planning  
277 the observations and data collection, reviewed and discussed the observations, and read, provided feedback, and accepted the  
278 contents of the manuscript.

279 **Author Information**

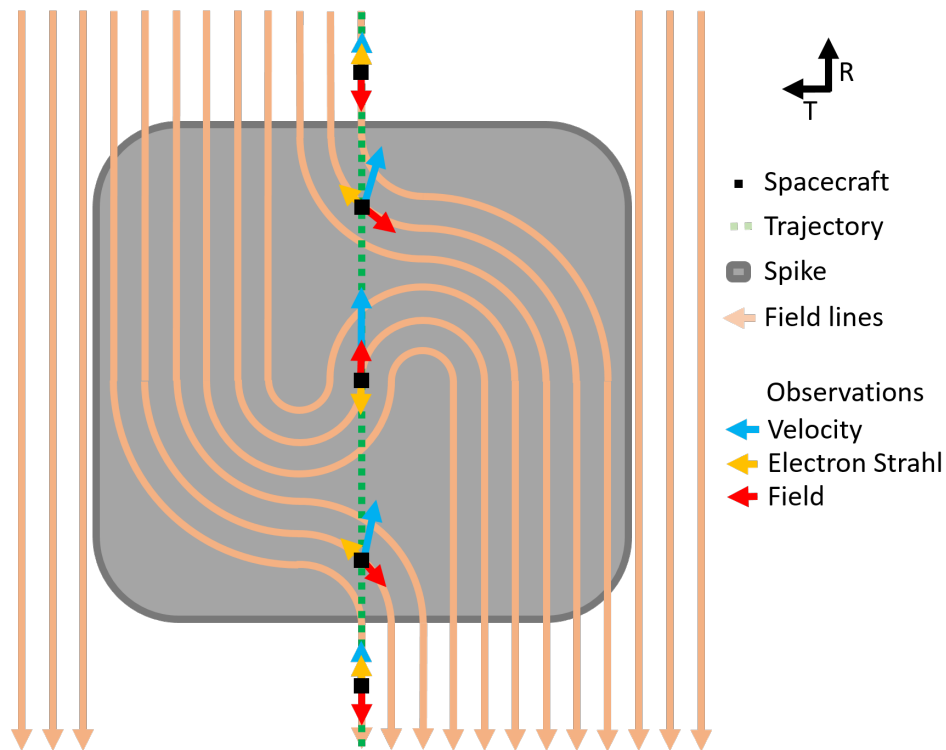
280 Correspondence and requests for materials should be addressed to Justin Kasper (jckasper@umich.edu). Reprints and  
 281 permissions information is available at [www.nature.com/reprints](http://www.nature.com/reprints). The authors declare no competing financial interests. Readers  
 282 are welcome to comment on the online version of the paper. Publisher’s note: Springer Nature remains neutral with regard to  
 283 jurisdictional claims in published maps and institutional affiliations. None of the authors has a competing financial interest in  
 284 this work.

285 **Extended Data – Online Supporting Materials**



286  
 287 **Extended Data Figure 1:** An overview of the second encounter with the Sun by Parker Solar Probe.

288 In the same format as Fig. 1. Spikes in the velocity are again seen coincident with the magnetic field reversals. A net  
 289 positive  $V_{PT}$  is seen at the second perihelion.



290 **Extended Data Figure 2:** Schematic of an “S-shaped” magnetic structure creating a field reversal, heat flux reversal, and  
 291 spike in velocity.  
 292

293 This figure illustrates the possible geometry of an “S-shaped” propagating Alfvénic disturbance (gray box) and how it  
 294 would appear to the spacecraft (black square) as it flew through the spike on the green trajectory. The light lines with arrows  
 295 indicate the configuration of the magnetic field, with all field lines ultimately pointed back to the Sun. Arrows at each black  
 296 square indicate the vector velocity (blue), electron strahl (orange), and magnetic field (red) seen by the spacecraft. If this was a  
 297 purely Alfvénic structure then the spike would move away from the Sun anti-parallel to  $B$  at the local Alfvén speed,  $C_A$ . In the  
 298 frame of the spike the shape of the structure would be static, with plasma flowing in along field lines on the upper left and  
 299 through the spike, emerging at the lower right, always flowing at  $C_A$ . In the frame of the spacecraft, the constant flow along  
 300 field lines in the propagating spike frame would translate into a radial increase of  $V$  by  $C_A$  when  $B$  was perpendicular to  $R$ , and  
 301 a maximum jump of  $2C_A$  when  $B$  was completely inverted. Since the heat flux flows away from the Sun, it would rotate so as to  
 302 always be anti-parallel to  $B$  and appear to be flowing back to the Sun at the center of this disturbance.