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Abstract. The orientation of the heliospheric magnetic field (HMF) in near-Earth space is generally a good indicator of the polarity of HMF foot points at the photosphere. There are times, however, when the HMF folds back on itself (is inverted), as indicated by suprathermal electrons moving sunward while carrying the heat flux away from the Sun. Analysis of the near-Earth solar wind during the period 1998-2011 reveals that inverted HMF is present approximately . Inverted HMF is mapped to the coronal source surface, where a new method is used to estimate coronal structure from the potential-field source-surface model. We find a strong association with bipolar streamers containing the heliospheric current sheet, as expected, but also with unipolar or pseudostreamers, which contain no current sheet. Because large-scale inverted HMF is a widely-accepted signature of interchange reconnection at the Sun, this finding provides strong evidence for models of the slow solar wind which involve coronal loop opening by reconnection within pseudostreamer belts as well as the bipolar streamer belt. Occurrence rates of bipolar- and pseudostreamers suggest that they are equally likely to result in inverted HMF and, therefore, presumably undergo interchange reconnection at approximately the same rate. Given the different magnetic topologies involved, this suggests the rate of reconnection is set externally, possibly by the differential rotation rate which governs the circulation of open solar flux.

1. Introduction

large-scale heliospheric magnetic field (HMF) is generally well described by the Parker spiral. 135°/315° for outward/inward polarity HMF [e.g., *Borovsky*, 2010]. The heliospheric current sheet (HCS) separates sectors of inward and outward magnetic flux and projects back to a coronal source-surface as a neutral line marking the heliomagnetic equator. Crossings of the near-Earth HCS can be identified by rapid changes in the HMF direction from 135° to 315°, or vice versa. This is shown schematically in Figure 1a.

HMF connectivity to the Sun can usually be inferred by suprathermal electron (STE) observations. Open HMF, which has one end connected to the Sun, exhibits an adiabtically focussed STE beam, or "strahl," that originates in the solar corona [*Feldman et al.*, 1975; *Rosenbauer et al.*, 1977]. Thus outward (inward) magnetic sectors should contain a strahl which is parallel (antiparallel) to the HMF, as shown in Figure 1a. , when both parallel and antiparallel strahls are present, reveal "closed" HMF, with both ends of the field line connected to the Sun (times 2 and 3 in Figure 1b). They are strongly associated with interplanetary coronal mass ejections [*Gosling et al.*, 1987; *Wimmer-Schweingruber et al.*, 2006], which in turn are frequently encountered at magnetic sector boundaries [*Crooker et al.*, 1998, see also Figure 1b].

There also exist periods with a single strahl in the opposite sense to that expected from the magnetic field direction [*Kahler and Lin*, 1994, 1995; *Kahler et al.*, 1996; *Crooker et al.*, 1996; *Crooker et al.*, 2004b], as shown in Figures 1c-e. These intervals imply that the magnetic field is folded back upon itself, or inverted. Inverted HMF intervals can be bounded by a change in the magnetic field direction with no change in the strahl direction and vice versa. Pairs of the former are common and can be found both near the HCS, as in Figure 1c, and in unipolar regions [e.g., *Balogh et al.*, 1999], as in Figure 1d These pairs of field changes bound inversions that are usually of short duration, on the order of an hour or two. In contrast, inversions bounded on at least one side by a change in the strahl direction with no change in the magnetic field direction are less common but can be of long duration, on the order of a day or more [*Crooker et al.*, 2004b]. Moreover, they can only be understood in terms of a three-dimensional structure. In cases involving the HCS, as in Figure 1e, where the dashed field lines lie out of the plane of the Figure, the inversion results in a mismatch between the magnetic and electron signatures of the sector boundary [*Crooker et al.*, 2004b].

While some of the smaller inversions may be the product of large-scale turbulent processes, the larger inversions appear to be robust signatures of near-Sun magnetic interchange reconnection, as sketched in Figures 1c-e, where a green X marks a reconnection site. The legs of large loops expanding into the heliosphere reconnect with adjacent open field lines. *Crooker et al.* [2004b] suggest that the expanding loops are at the quiet end of a spectrum of large-scale transient outflows, with coronal mass ejections (CMEs) at the active end. This interpretation is supported by the observation of coronal inflows and collapsing loops at locations where the HCS is inclined to the solar rotation direction [*Sheeley and Wang*, 2001], taken to be signatures of magnetic reconnection. The association of inverted HMF with the HCS suggests the solar origin of the expanding loops can be bipolar helmet streamers which surround the coronal source-surface neutral line and separate magnetic flux from coronal holes of opposite magnetic polarity, e.g., the two polar coronal holes at solar minimum. This paper also considers unipolar streamers, called "pseudostreamers," as an additional source.

Pseudostreamers are very similar to bipolar streamers in coronagraph observations. They are also formed at the boundary between coronal magnetic flux from two different coronal holes, but unlike bipolar streamers, the flux at both foot points is of the same polarity and, thus, they do not contain current sheets [e.g., *Eselevich*, 1998; *Eselevich et al.*, 1999; *Zhao and Webb*, 2003; *Wang et al.*, 2007]. There has recently been much interest in pseudostreamers as a possible source of the slow solar wind [*Crooker et al.*, 2012; *Riley and Luhmann*, 2012], either through the expansion of coronal magnetic flux tubes [*Wang et al.*, 2012], or through the intermittent release of plasma by the opening of coronal loops via magnetic reconnection [*Antiochos et al.*, 2011]. *Crooker et al.* [2012] demonstrate that pseudostreamers occur in belts which are topologically connected to the bipolar streamer belt, thus forming a network of slow solar wind sources.

In this study we investigate the properties and solar origin of inverted heliospheric magnetic flux during the period 1998 to 2011, for which almost continuous HMF and STE data are available from the Advanced Composition Explorer (ACE) spacecraft. In particular, comparisons are made with the locations of bipolar and pseudostreamers estimated using the potential-field source-surface (PFSS) model of the corona.

2. Detection of HMF inversions

The 272eV energy channel is used, as it is well within the suprathermal range, showing little contribution from the core electron population, but still providing high count rates [e.g., *Anderson et al.*, 2012]. The SWEPAM PAD data are available from January 1998 to August 2011, which determines the interval used in this study.

discriminate between closed HMF and 90° pitch-angle depletions owing to mirroring from large-scale, downstream structures [*Gosling et al.*, 2001], so closed flux occurrence is likely overestimated. Furthermore, while counterstreaming electron intervals are separated out from inverted and uninverted flux, no attempt is made to explicitly exclude ICMEs. Indeed, if ICMEs contain "open" inverted field lines, they must result from reconnection in the corona in the same way as ambient solar wind intervals [*Owens and Crooker*, 2006, 2007]. By including all solar wind data in the study, no assumptions are made about the source and processes involved in the creation of inverted HMF.

There are

3. Properties of HMF inversions

Figure 3 shows the probability distribution functions (PDFs) of solar wind parameters. . The solar wind properties of

4. Association with bipolar and pseudostreamers

Thus to aid in the interpretation of these data, we use a potential-field source-surface (PFSS) model of the corona [*Schatten et al.*, 1969] based on WSO magnetograms to identify the locations of the HCS and, hence, bipolar streamers as well as pseudostreamers.

4.1. Case studies

The pink and light grey regions show, respectively, outward and inward polarity coronal holes, i.e., the photospheric foot points of magnetic field lines reach the source surface at 2.5 solar radii. Red (white) lines show the . Overlaid on the ecliptic plane is the observed magnetic polarity in near-Earth space, ballistically mapped back to the source surface using the observed solar wind speed, with red/white dots indicating , as determined in

Section 2. For this particular Carrington rotation, there is agreement between the magnetic polarity predicted by the PFSS model and that observed near-Earth. Green crosses show the coronal source-surface locations of observed HMF inversions at the heliographic latitude of Earth.

The two intervals of inverted HMF at Carrington longitude of . The remaining HMF inversions are also associated with a change in magnetic connectivity, with the photospheric foot points along Earth orbit shifting between different coronal holes, but without an associated change in foot point polarity, indicative of pseudostreamers. These HMF inversions are thus associated with pseudostreamers rather than bipolar streamers.

define a parameter dS, the distance between photospheric foot points of neighbouring points on the source surface. In practice, the magnitude of dS will depend on the spatial resolution at which field lines are traced, making units somewhat arbitrary. In this study, we calculate dS by moving along the ecliptic plane in $1°$ steps. When adjacent points on the source surface map to the same coronal hole, dS will be small, for example as seen between $0°$ and $60°$ Carrington longitude for CR1990. When neighbouring source-surface points map to different coronal holes, however, such as the HCS crossing at $310°$ Carrington longitude, dS will be very large. The middle panel of Figure 4 shows $\log_e(dS)$ as a function of Carrington longitude along the ecliptic plane. Vertical yellow lines mark HCS crossings, where $\log_e(dS)$ spikes correspond to bipolar streamers. The dashed horizontal line at $\log_e(dS) = 3$ marks the threshold selected to define a streamer. It is the value which $\log_e(dS)$ reaches or exceeds at all HCS crossings in the 1998 to 2011 period and corresponds to source surface points with a $1°$ separation having a photospheric footpoint separation of $\geq 5°$. It thus selects all bipolar streamers and appears to select most significant pseudostreamers while suppressing smaller structures. Blue vertical lines mark $\log_e(dS)$ spikes without polarity reversals, our definition of a pseudostreamer. The 17 1-hour intervals of inverted HMF not associated with the HCS in CR1990 all map close to the longitudes of pseudostreamers.

The bottom panel of Figure 4 is a contour plot of dS at all latitudes. It demonstrates in another way the finding reported by [*Crooker et al.*, 2012] that pseudostreamer belts , but connect to the bipolar streamer belt to form a network of slow solar wind sources that expands to cover the source surface during solar maximum. As is the case for bipolar streamers, HMF inversions are not associated with all pseudostreamers; however, Figure 4 demonstrates that streamer-associated inverted HMF is likely to be common at all latitudes near solar maximum.

4.2. Statistical analysis

In order to systematically analyse the entire 1998-2011 interval, and define strict thresholds for association between inverted HMF and streamers. We begin by including only Carrington rotations in which the PFSS model provides a reasonable representation of the observed magnetic structure of the corona and solar wind. By assigning +1 (-1) to outward (inward) Parker spiral polarity, and ignoring undetermined, counterstreaming and inverted intervals, we compute the mean-square error (MSE) between the PFSS and observed sector structure mapped to the source surface. Thus MSE is a combination of errors in the PFSS solution and errors in the simple ballistic mapping of near-Earth solar wind to the coronal source surface.

of ecliptic longitudes are covered by pseudostreamers (bipolar streamers). Note that the association scheme allows a single inverted HMF interval to map to both a bipolar and pseudostreamer if they are located close in longitude. Table 2 summarises these results.

In general, there are insufficient inverted HMF events to detect significant differences in the of solar wind properties of bipolar- and pseudostreamer-associated inversions. Probability distributions of density, however (not shown), suggest that HMF inversions from bipolar streamers contain denser solar wind than inverted HMF from pseudostreamers, consistent with general properties of pseudostreamer-associated solar wind [*Wang et al.*, 2012].

5. Conclusions and Discussion

The polarity of the photospheric foot point of heliospheric magnetic flux (HMF) can be independently estimated from both the local HMF orientation, as measured using in situ magnetometer observations, and the direction of the suprathermal electron beam, or "strahl." For the bulk of the solar wind, these two methods show agreement. There are intervals, however, in which the strahl is directed towards the Sun, implying that the magnetic field line is inverted, or folded back on itself. This is an expected signature of near-Sun magnetic reconnection by which the Sun can open previously closed heliospheric loops [*Owens et al.*, 2011; *Owens and Lockwood*, 2012]. Using an automated data analysis method, we find inverted flux in approximately 5.5% of the solar wind data between 1998 and 2011, though this is likely an underestimate due to strict selection criteria. We do not find a strong solar cycle variation in the occurrence rate of inverted HMF, but this finding is confined to the ecliptic plane . Inverted HMF is associated with dense, slow, cool solar wind, with lower than average magnetic field intensity. In order to determine the solar origin of these structures, we used a potential-field source-surface model to infer the global structure of the coronal magnetic field and a new automated detection method for bipolar and pseudostreamers. Of the 2263 1-hour inverted HMF intervals identified in the solar wind and mapped back to the coronal source surface, 1310 (58%) are associated with streamers. Given that the probability of a solar wind interval being associated with a streamer by chance is 52%, the association between inverted HMF and streamers is significant at the 99.9% level. Of the 1310 streamer-associated inverted HMF intervals, 949 (504) map to pseudostreamers (bipolar streamers). This ratio is in reasonable agreement with the occurrence rates of pseudostreamers and bipolar streamers in the ecliptic plane, 39% and 20%, respectively,

If we assume that inverted HMF is primarily a signature of reconnection in the corona [e.g., *Titov et al.*, 2011], our results suggest that the rate of reconnection is similar within bipolar and pseudostreamers. This seems reasonable in view of their magnetic structure. For the bipolar streamer case, a three-dimensional magnetic configuration for interchange reconnection that can create the inversion is illustrated in 1e and has already been discussed in section 1. For the pseudostreamer case, an appropriate magnetic configuration can be drawn in just two dimensions, as illustrated in Figure 6. Closed loops within one of the two arcades that form pseudostreamers are shown to rise as a result of photospheric flux emergence, but could equally be the result of loop foot point shearing, etc. In the top panel, the rising loop undergoes interchange reconnection before it reaches the solar wind acceleration height and therefore doesn't result in the generation of inverted HMF. This configuration is common from the solar perspective [e.g., *Wang et al.*, 2007; *Crooker et al.*, 2012]. In contrast, from the heliospheric perspective, the rising loops are dragged out by the solar wind before interchange reconnection takes place, which does generate inverted HMF, as illustrated in the bottom panels. Thus pseudostreamer loop expansion and opening via interchange reconnection would transport pre-existing open solar flux in much the same way as the CME-driven transport proposed by *Owens et al.* [2007]. Indeed, as proposed by *Crooker et al.* [2004b] for loops expanding from the helmet arcade in the case of bipolar streamers, loops that create inversions from pseudostreamers can also be considered as the quiet end of a spectrum of loops, where the active end is CMEs. This analogy holds because pseudostreamers are well-documented sources of CMEs [*Fainshtein*, 1997; *Eselevich et al.*, 1999; *Zhao and Webb*, 2003; *Liu and Hayashi*, 2006].

In addition, similar levels of association between inverted HMF with bipolar and pseudostreamers, despite the differing magnetic topologies, suggest that the reconnection rate is externally controlled. One possibility is the stress between the differential rotation of the photosphere and the rigid corotation of the corona [*Nash et al.*, 1988; *Wang and Sheeley*, 2004] and the consequent circulation of open solar flux [*Fisk et al.*, 1999; *Fisk and Schwadron*, 2001]. We note that inverted HMF is the expected heliospheric signature of large coronal loop opening, one of the proposed mechanisms for slow solar wind formation [e.g., *Fisk*, 2003]). Thus our results provide support for the idea of pseudostreamers being a source of slow solar wind through intermittent release from previously closed coronal loops [*Antiochos et al.*, 2011], though the effect of magnetic flux tube expansion [*Wang et al.*, 2012] may still be important.

Inverted HMF has direct implications for in situ spacecraft estimates of the total magnetic flux threading the solar source surface, often referred to as the unsigned open solar flux, OSF [e.g., *Owens et al.*, 2008a]. Figures 1c and 1d clearly illustrate the issue: Inverted HMF provides magnetic flux which threads the heliocentric sphere at 1 AU, but does not map back to the source surface, resulting in an overestimate in OSF from in situ observations. , decomposing the HMF along the Parker spiral direction, which can successfully remove the effects of waves and turbulence [*Erdős and Balogh*, 2012], may not address this particular issue. Both the occurrence rate and magnetic field strength associated with inverted HMF are small, suggesting this may not have a large effect on OSF estimates. Even if inverted HMF has an average magnetic flux density as high as the rest of the solar wind, the decrease in the unsigned OSF would only be $2 \times 5\% = 10\%$. The factor 2 arises as follows: if inverted HMF intervals contain ϕ_I of magnetic flux, the unsigned OSF will be overestimated by $2\phi_I$, since both the inverted and "return" flux thread the heliocentric surface but not the coronal source surface. We note that, in general, inverted HMF intervals are less than a day long, though this may be partly due to the strict criteria used and the time interval considered [c.f. *Crooker et al.*, 2004b]. Thus taking 1-day averages of the radial magnetic field for the purposes of estimating OSF may indirectly negate the effect of inverted HMF [c.f. *Wang and Sheeley*, 1995], though it does not directly address the issue of physical origin [see also *Lockwood et al.*, 2009, for discussion of correction of 1-AU measurements to the coronal source surface].

In summary, we have developed a new method for identifying bipolar streamers and pseudostreamers in PFSS synoptic maps. The results confirm that together these structures form a network of slow solar wind sources which expands over the source surface at solar maximum. Moreover, we have analyzed suprathermal electron data from the solar wind and find that, like bipolar streamers, pseudostreamers are sources of HMF inversions. These are understood to be signatures of coronal loops that expand into the heliosphere and subsequently become open through reconnection in the corona. Loop-opening is a key process in one of two competing models for the source of the slow wind.

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References

Anderson, B. R., R. M. Skoug, J. T. Steinberg, and D. J. McComas, Variability of the solar wind suprathermal electron strahl, *J. Geophys. Res.*, *117*, A04107, doi: 10.1029/2011JA017269, 2012.

Antiochos, S. K., Z. Mikić, V. S. Titov, R. Lionello, and J. A. Linker, A Model for the Sources of the Slow Solar Wind, *Astrophys. J.*, *731*, 112, doi:10.1088/0004-637X/731/2/112, 2011.

Balogh, A., R. J. Forsyth, E. A. Lucek, T. S. Horbury, and E. J. Smith, Heliospheric magnetic field polarity inversions at high heliographic latitudes, *Geophys. Res. Lett.*, *26*, 631–634, doi:10.1029/1999GL900061, 1999.

Borovsky, J. E., On the variations of the solar wind magnetic field about the Parker spiral direction, *J. Geophys. Res.*, *115*, A09101, doi:10.1029/2009JA015040, 2010.

Crooker, N. U., M. E. Burton, G. L. Siscoe, S. W. Kahler, J. T. Gosling, and E. J.

Smith, Solar wind streamer belt structure, *J. Geophys. Res.*, *101*, 24,331–24,342, doi: 10.1029/96JA02412, 1996.

Crooker, N. U., J. T. Gosling, and S. W. Kahler, Magnetic clouds at sector boundaries, *J. Geophys. Res.*, *103*, 301, 1998.

Crooker, N. U., C.-L. Huang, S. M. Lamassa, D. E. Larson, S. W. Kahler, and H. E. Spence, Heliospheric plasma sheets, *J. Geophys. Res.*, *109*, A03107, doi: 10.1029/2003JA010170, 2004a.

Crooker, N. U., S. W. Kahler, D. E. Larson, and R. P. Lin, Large-scale magnetic field inversions at sector boundaries, *J. Geophys. Res.*, *109*, doi:10.1029/2003JA010278, 2004b.

Crooker, N. U., S. K. Antiochos, X. Zhao, and M. Neugebauer, Global network of slow solar wind, *J. Geophys. Res.*, *117*, A04104, doi:10.1029/2011JA017236, 2012.

Erdős, G., and A. Balogh, Magnetic Flux Density Measured in Fast and Slow Solar Wind Streams, *Astrophys. J.*, *753*, 130, doi:10.1088/0004-637X/753/2/130, 2012.

Eselevich, V. G., On the structure of coronal streamer belts, *J. Geophys. Res.*, *103*, 2021, doi:10.1029/97JA02365, 1998.

Eselevich, V. G., V. G. Fainshtein, and G. V. Rudenko, Study of the structure of streamer belts and chains in the solar corona, *188*, 277–297, 1999.

Fainshtein, V. G., An Investigation of Solar Factors Governing Coronal Mass Ejection Characteristics, *174*, 413–435, 1997.

Feldman, W. C., J. R. Asbridge, S. J. Bame, M. D. Montgomery, and S. P. Gary, Solar wind electrons, *J. Geophys. Res.*, *80*, 4181–4196, 1975.

Fisk, L. A., Acceleration of the solar wind as a result of the reconnection of open magnetic flux with coronal loops, *J. Geophys. Res.*, *108*, 1157, doi:10.1029/2002JA009284, 2003.

Fisk, L. A., and N. A. Schwadron, The behaviour of the open magnetic field of the Sun, *Astrophys. J.*, *560*, 425–438, 2001.

Fisk, L. A., T. H. Zurbuchen, and N. A. Schwadron, Coronal hole boundaries and their interaction with adjacent regions, *Space Sci. Rev.*, *87*, 43–54, 1999.

Garrard, T. L., A. J. Davis, J. S. Hammond, and S. R. Sears, The ACE Science Center, *Space Sci. Rev.*, *86*, 649–663, doi:10.1023/A:1005096317576, 1998.

Gosling, J. T., D. N. Baker, S. J. Bame, W. C. Feldman, and R. D. Zwickl, Bidirectional solar wind electron heat flux events, *J. Geophys. Res.*, *92*, 8519–8535, 1987.

Gosling, J. T., S. J. Bame, W. C. Feldman, D. J. McComas, J. L. Phillips, and B. E. Goldstein, Counterstreaming suprathermal electron events upstream of corotating shocks in the solar wind beyond approximately 2 AU: ULYSSES, *Geophys. Res. Lett.*, *20*, 2335–2338, doi:10.1029/93GL02489, 1993.

Gosling, J. T., R. M. Skoug, and W. C. Feldman, Solar wind electron halo depleeeetions at 90-degree pitch angle, *Geophys. Res. Lett.*, *28*, 4155–4158, doi:10.1029/2001GL013758, 2001.

Gosling, J. T., R. M. Skoug, D. J. McComas, and C. W. Smith, Magnetic disconnection from the sun: Observations of a reconnection exhaust in the solar wind at the heliospheric current sheet, *Geophys. Res. Lett.*, *32*, L05,105, doi:10.1029/2005GL022406, 2005.

Gosling, J. T., S. Eriksson, D. J. McComas, T. D. Phan, and R. M. Skoug, Multiple magnetic reconnection sites associated with a coronal mass ejection in the solar wind, *J. Geophys. Res.*, *112*, 8106–+, doi:10.1029/2007JA012418, 2007.

Haggerty, D. K., E. C. Roelof, C. W. Smith, N. F. Ness, R. L. Tokar, and R. M. Skoug, Interplanetary magnetic field connection to the L1 Lagrangian orbit during upstream energetic ion events, *J. Geophys. Res.*, *105*, 25,123–25,132, doi:10.1029/1999JA000346, 2000.

Hammond, C. M., W. C. Feldman, D. J. McComas, J. L. Phillips, and R. J. Forsyth, Variation of electron-strahl width in the high-speed solar wind: ULYSSES observations, *Astron. Astrophys.*, *316*, 350–354, 1996.

Hapgood, M. A., G. Bowe, M. Lockwood, D. M. Willis, and Y. Tulunay, Variability of the interplanetary magnetic field at 1 A.U. over 24 years: 1963-1986, *Planet. Space Sci.*, *39*, 411–423, doi:10.1016/0032-0633(91)90003-S, 1991.

Kahler, S., and R. P. Lin, The determination of interplanetary magnetic field polarities around sector boundaries using E greater than 2 keV electrons, *Geophys. Res. Lett.*, *21*, 1575–1578, doi:10.1029/94GL01362, 1994.

Kahler, S., N. U. Crooker, and J. T. Gosling, Properties of interplanetary magnetic sector boundaries based on electron heat-flux flow directions, *J. Geophys. Res.*, *103*, 20,603–20,612, doi:10.1029/98JA01745, 1998.

Kahler, S. W., and R. P. Lin, An Examination of Directional Discontinuities and Magnetic Polarity Changes around Interplanetary Sector Boundaries Using E > 2 keV Electrons, *Sol. Phys.*, *161*, 183–195, doi:10.1007/BF00732092, 1995.

Kahler, S. W., N. U. Crooker, and J. T. Gosling, The topology of intrasector reversals of the interplanetary magnetic field, *J. Geophys. Res.*, *101*, 24,373–24,382, doi:10.1029/96JA02232, 1996.

Liu, Y., and K. Hayashi, The 2003 October-November Fast Halo Coronal Mass Ejections and the Large-Scale Magnetic Field Structures, *Astrophys. J.*, *640*, 1135–1141, doi: 10.1086/500290, 2006.

Lockwood, M., M. Owens, and A. P. Rouillard, Excess open solar magnetic flux from satellite data: 2. A survey of kinematic effects, *J. Geophys. Res.*, *114*, A11104, doi: 10.1029/2009JA014450, 2009.

McComas, D. J., J. T. Gosling, D. Winterhalter, and E. J. Smith, Interplanetary magnetic field draping about fast coronal mass ejecta in the outer heliosphere, *J. Geophys. Res.*, *93*, 2519–2526, doi:10.1029/JA093iA04p02519, 1988.

McComas, D. J., S. J. Bame, B. S. J., W. C. Feldman, J. L. Phillips, P. Riley, and J. W. Griffee, Solar wind electron proton alpha monitor (SWEPAM) for the Advanced Composition Explorer, *Space Sci. Rev.*, *86*, 563, 1998.

Nash, A. G., N. R. Sheeley, Jr., and Y.-M. Wang, Mechanisms for the rigid rotation of coronal holes, *Sol. Phys.*, *117*, 359–389, 1988.

Owens, M. J., and P. J. Cargill, Non-radial solar wind flows induced by the motion of interplanetary coronal mass ejections, *Ann. Geophys.*, *22*, 4397–4395, 2004.

Owens, M. J., and N. U. Crooker, Coronal mass ejections and magnetic flux buildup in the heliosphere, *J. Geophys. Res.*, *111*, A10104, doi:10.1029/2006JA011641, 2006.

Owens, M. J., and N. U. Crooker, Reconciling the electron counterstreaming and dropout occurrence rates with the heliospheric flux budget, *J. Geophys. Res.*, *112*, A06106, doi: 10.1029/2006JA012159, 2007.

Owens, M. J., and M. Lockwood, Cyclic loss of open solar flux since 1868: The link to heliospheric current sheet tilt and implications for the Maunder Minimum, *J. Geo-*

phys. Res., *117*, A04102, doi:10.1029/2011JA017193, 2012.

Owens, M. J., N. A. Schwadron, N. U. Crooker, W. J. Hughes, and H. E. Spence, Role of coronal mass ejections in the heliospheric Hale cycle, *Geophys. Res. Lett.*, *34*, L06104, doi:10.1029/2006GL028795, 2007.

Owens, M. J., C. N. Arge, N. U. Crooker, N. A. Schwadron, and T. S. Horbury, Estimating total heliospheric magnetic flux from single-point in situ measurements, *J. Geophys. Res.*, *113*, A12103, doi:10.1029/2008JA013677, 2008a.

Owens, M. J., N. U. Crooker, N. A. Schwadron, T. S. Horbury, S. Yashiro, H. Xie, O. C. St Cyr, and N. Gopalswamy, Conservation of open solar magnetic flux and the floor in the heliospheric magnetic field, *Geophys. Res. Lett.*, L20108, doi:10.1029/2008GL035813, 2008b.

Owens, M. J., N. U. Crooker, and M. Lockwood, How is open solar magnetic flux lost over the solar cycle?, *J. Geophys. Res.*, *116*, A04111, doi:10.1029/2010JA016039, 2011.

Phan, T. D., et al., A magnetic reconnection X-line extending more than 390 Earth radii in the solar wind, *Nature*, *439*, 175–178, doi:10.1038/nature04393, 2006.

Richardson, I. G., and H. V. Cane, Near-earth solar wind flows and related geomagnetic activity during more than four solar cycles (1963-2011), *J. Geophys. Res.*, *2*(26), A02, doi:10.1051/swsc/2012003, 2012.

Riley, P., and J. G. Luhmann, Interplanetary Signatures of Unipolar Streamers and the Origin of the Slow Solar Wind, *Sol. Phys.*, *277*, 355–373, doi:10.1007/s11207-011-9909-0, 2012.

Rosenbauer, H., et al., A survey on initial results of the HELIOS plasma experiment, *Journal of Geophysics Zeitschrift Geophysik*, *42*, 561–580, 1977.

Schatten, K. H., J. M. Wilcox, and N. F. Ness, A model of interplanetary and coronal magnetic fields, *Sol. Phys.*, *9*, 442–455, 1969.

Sheeley, N. R., Jr., and Y.-M. Wang, Coronal Inflows and Sector Magnetism, *Astrophys. J. Lett.*, *562*, L107–L110, doi:10.1086/338104, 2001.

Smith, C. W., J. L'Heureux, N. F. Ness, M. H. Acuna, L. F. Burlaga, and J. Scheifele, The ACE magnetic fields experiment, *Space Sci. Rev.*, *86*, 613, 1998.

Steinberg, J. T., J. T. Gosling, R. M. Skoug, and R. C. Wiens, Suprathermal electrons in high-speed streams from coronal holes: Counterstreaming on open field lines at 1 AU, *J. Geophys. Res.*, *110*, A06103, doi:10.1029/2005JA011027, 2005.

Titov, V. S., Z. Mikić, J. A. Linker, R. Lionello, and S. K. Antiochos, Magnetic Topology of Coronal Hole Linkages, *Astrophys. J.*, *731*, 111, doi:10.1088/0004-637X/731/2/111, 2011.

Wang, Y., and N. R. Sheeley, Jr., Footpoint Switching and the Evolution of Coronal Holes, *Astrophys. J.*, *612*, 1196–1205, doi:10.1086/422711, 2004.

Wang, Y.-M., and N. R. Sheeley, Jr., Solar Implications of ULYSSES Interplanetary Field Measurements, *Astrophys. J. Lett.*, *447*, L143–L146, doi:10.1086/309578, 1995.

Wang, Y.-M., N. R. Sheeley, Jr., and N. B. Rich, Coronal Pseudostreamers, *Astrophys. J.*, *658*, 1340–1348, doi:10.1086/511416, 2007.

Wang, Y.-M., R. Grappin, E. Robbrecht, and N. R. Sheeley, Jr., On the Nature of the Solar Wind from Coronal Pseudostreamers, *Astrophys. J.*, *749*, 182, doi:10.1088/0004-637X/749/2/182, 2012.

Wimmer-Schweingruber, R. F., et al., Understanding interplanetary coronal mass ejection signatures, *Space Sci. Rev.*, *123*, 177–216, doi:10.1007/s11214-006-9017-x, 2006.

Zhao, X. P., and D. F. Webb, Source regions and storm effectiveness of frontside full halo coronal mass ejections, *J. Geophys. Res.*, *108*, 1234, doi:10.1029/2002JA009606, 2003.

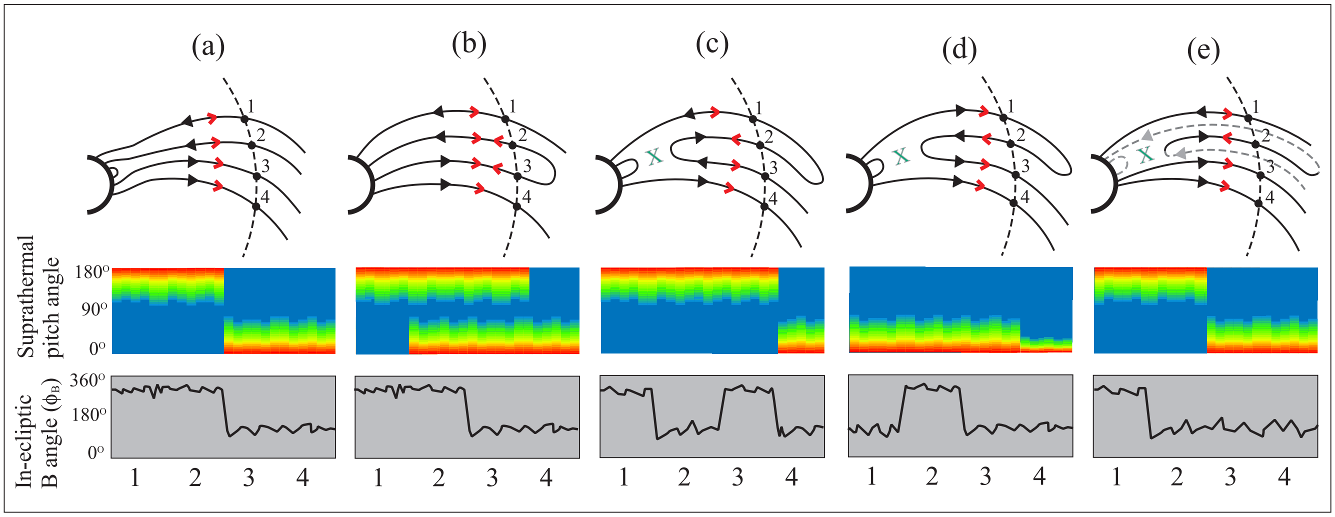

Figure 1. Sketches of possible HMF configurations and the resulting magnetic field and suprathermal electron signatures in near-Earth space. Red (black) arrows show the supratherthermal electron strahl (magnetic field polarity), while green crosses show the position of magnetic reconnection. (a) A typical sector boundary/HCS crossing. (b) A sector boundary accompanied by closed HMF loops, likely part of an ICME. (c) A sector boundary/HCS crossing containing an inverted HMF interval at time 2. (d) An inverted HMF interval at time 2 embedded within a unipolar region. (e) A sector boundary with mismatched electron and magnetic signatures. The dashed lines show portions of the inverted HMF structure which are out of the ecliptic plane and not encountered by the observing spacecraft [after *Crooker et al.*, 2004b].

		# 1-hour intervals	% of available data
Magnetometer Data	Sunward HMF	53714	44.9%
	Antisunward HMF	56684	47.3%
	Undetermined	9366	7.83%
	Inward sector	60252	50.4%
	Outward sector	59041	49.3%
	Undetermined	371	0.31%
Suprathermal electron data	Parallel strahl	37961	31.7%
	Antiparallel strahl	37774	31.6%
	Counterstreaming	17023	14.2%
	Undetermined	26906	22.5%
Combined datasets	Uninverted	57345	48.0%
	Inverted	6608	5.53%
	Counterstreaming	19388	16.2%
	Undetermined	36139	30.2%

Table 1. The number of 1-hour observation periods of different HMF populations obtained using the magnetic field and suprathermal electron selection criteria.

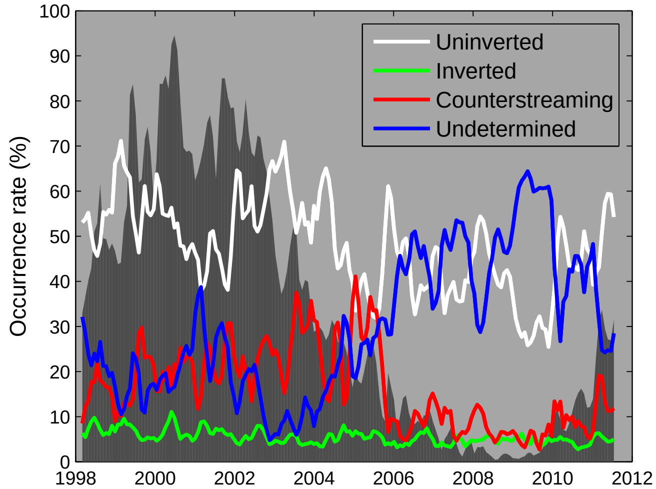

Figure 2. Three-Carrington rotation averages of the occurrence rates of various HMF topologies as a function of time. Sunspot number, scaled to fit the axis, is shown as the dark shaded region. Although some changes in the various HMF populations are likely to be due to changes in the electron detector, what this figure makes clear is that inverted flux is detected throughout the solar cycle.

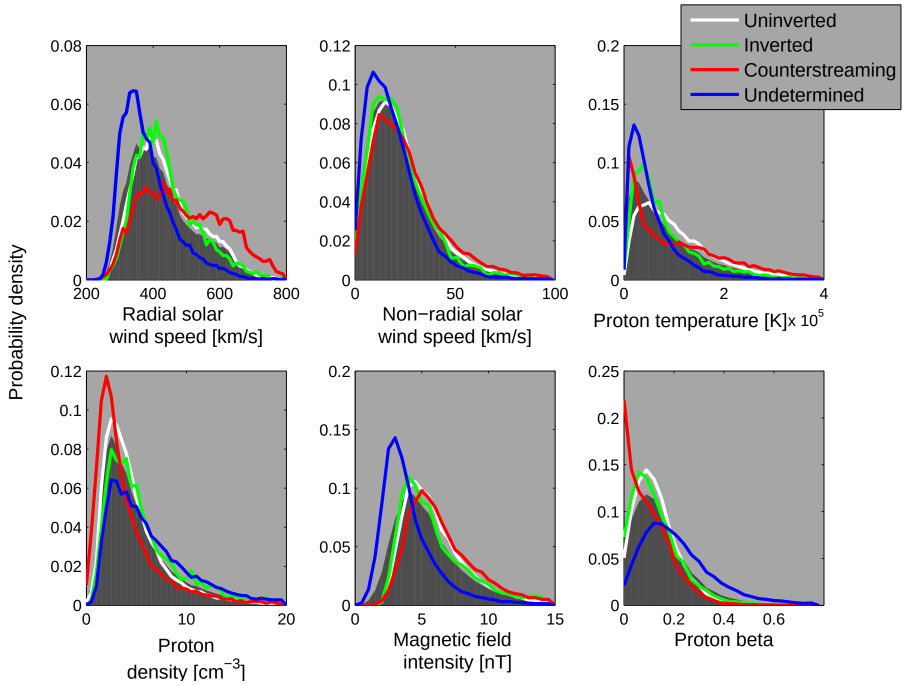

Figure 3. Probability distribution functions for various near-Earth solar wind populations. The grey shaded region shows all solar wind in the interval 1998-2011. Coloured lines show subsets of these data: White, green, red and blue lines show uninverted, inverted, counterstreaming and undetermined HMF intervals, respectively.

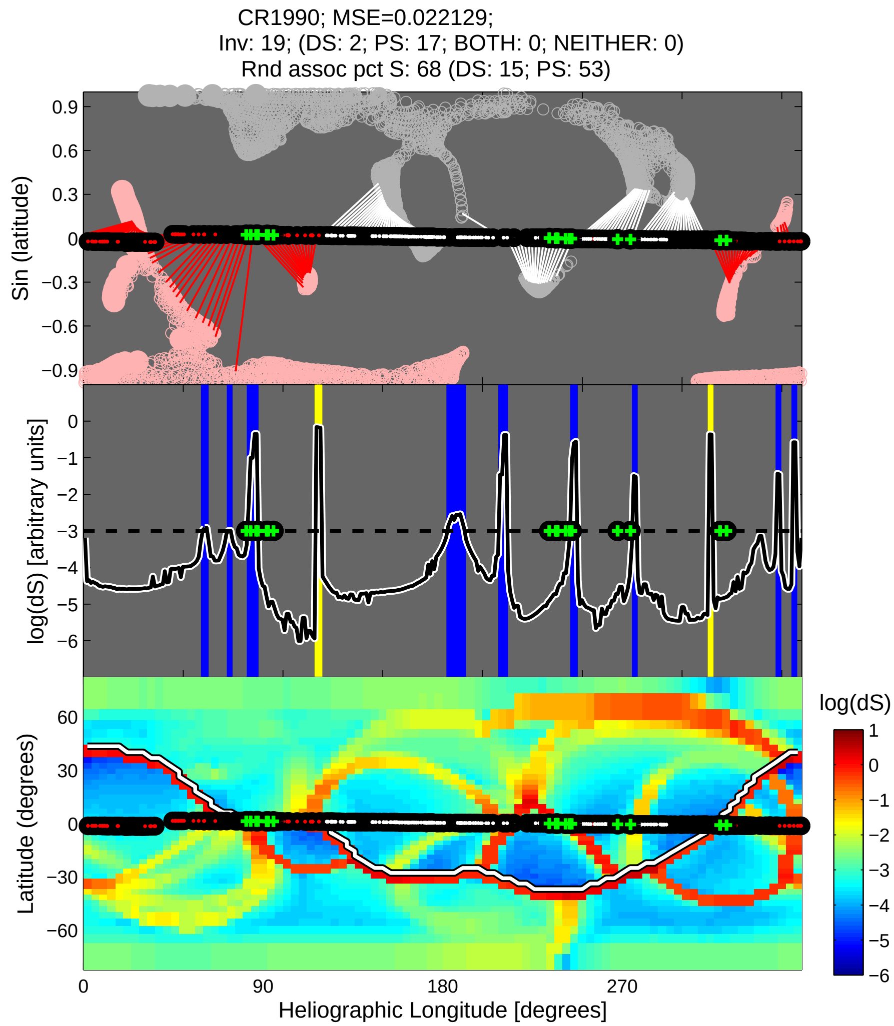

Figure 4. Top: A latitude-longitude map of the PFSS solution for Carrington rotation 1990. Pink/dark grey regions are the PFSS inward/outward coronal holes, with red/white lines showing the connection between the Earth's orbit across the source surface and photosphere. Overlaid on the black strip are red/white dots showing the observed outward/inward sectors mapped to the source surface. Green crosses are inverted flux intervals. Middle: dS, photospheric foot point separation for adjacent points on the source surface, along the ecliptic plane (shown on a $\log_e$ scale). This parameter serves as a means of identifying coronal streamers: Bipolar (pseudo) streamers are shown as vertical yellow (blue) lines. Bottom: contour plot of dS over all latitudes of the source surface. The HCS is the white curve.

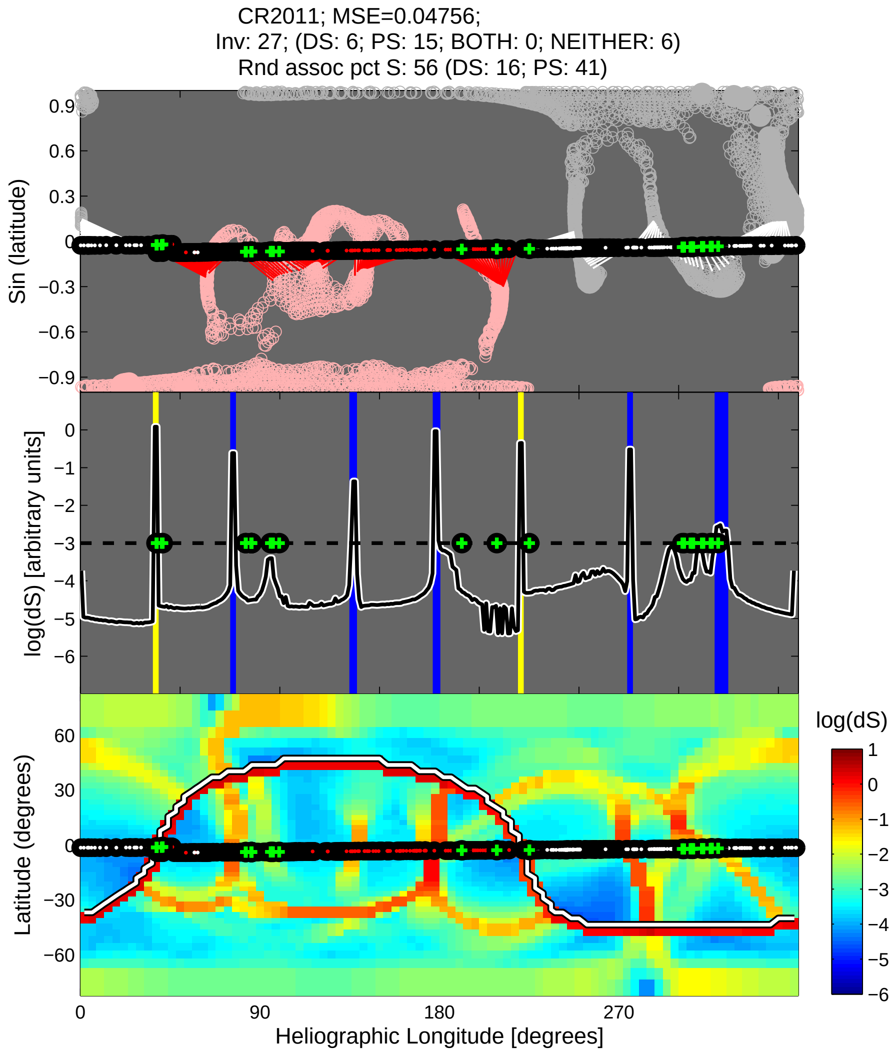

Figure 5. Parameters for Carrington rotation 2011, in the same format as Figure 4.

	Total	Any streamer	Pseudo (PS)	Bipolar (DS)	Both PS and DS	No streamer association
Inverted HMF	2263	1310	949	504	143	953
(% of total)	-	(57.9%)	(41.9%)	(22.3%)	(6.3%)	(42.1%)
Random interval	-	52.4%	39.0%	20.5%	5.1%	47.6%

Table 2. Solar origins of the inverted HMF intervals. Also shown is the probability that a random solar wind interval would be associated with the given type of streamer, *i.e.*, the percentage of ecliptic longitudes which are associated with different coronal structures.

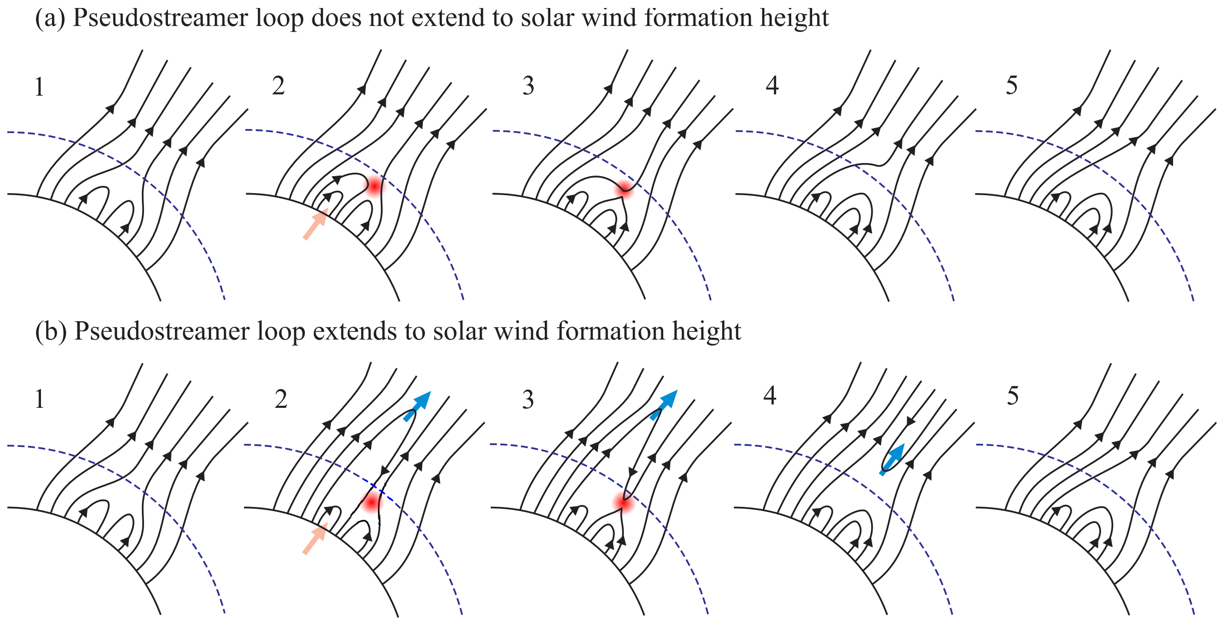

Figure 6. A sketch of of interchange reconnection within a pseudostreamer. In the top panel, a closed loop rises due to photospheric flux emergence (red arrow), but does not the reach the solar wind acceleration height (blue dashed line) before it undergoes reconnection with an open magnetic field line. This creates an Alfven wave on the open magnetic field line which propagates out into the heliosphere, but does not create inverted HMF. The bottom panels show a loop which is dragged out by the solar wind (blue arrow) before interchange reconnection occurs. It does result in the creation of inverted HMF.