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Using the WSA Model to Test the Parker Spiral Approximation for SEP Event Magnetic Connections

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ABSTRACT

In studies of solar energetic ($E > 10$ MeV) particle (SEP) events the Parker spiral (PS) field approximation, based only on the measured 1 AU solar wind (SW) speed V_{sw} , is nearly always used to determine the coronal or photospheric source locations of the 1 AU magnetic fields. There is no objective way to validate that approximation, but here we seek guidelines for optimizing its application. We first review recent SEP studies showing the extensive use of the PS approximation with various assumptions about coronal and photospheric source fields. We then run the Wang-Sheeley-Arge (WSA) model over selected Carrington rotations (CRs) to track both the photospheric and 5 Rs source locations of the forecasted 1 AU SW, allowing us to compare those WSA sources with the PS sources inferred from the WSA V_{sw} forecast. We compile statistics of the longitude differences (WSA-PS) for all the CRs and discuss the limitations of using the WSA model to validate the PS approximation. Over nearly all of each CR the PS and WSA source longitudes agree to within several degrees. The agreement is poor only in the slow-fast SW interaction regions characterized by high-speed events (HSEs), where the longitude differences can reach several tens of degrees. This result implies that SEP studies should limit use of the PS approximation around HSEs and use magnetic field polarities as an additional check of solar source connections.

Subject headings: Energetic Particles - Acceleration, Magnetic fields - Models, Coronal Mass Ejections - Low Coronal Signatures

1. Introduction

1.1. Magnetic Solar Source Connections of SEP Events

Studies of solar energetic ($E > 1$ MeV) particle (SEP) events have been limited by two factors. First, the events themselves are observed remotely from their solar sources and in situ, usually at 1 AU at the Lagrangian L1 point. Second, unlike

photons or neutral particles, their propagation to 1 AU is governed by magnetic field lines convected out from the Sun by the solar wind (SW) and characterized by turbulence and spreading (Ragot, 2011; Laitinen et al., 2013) in the interplanetary medium. The SEP primary acceleration sites are only broadly understood (Reames, 2013) as compact coronal regions of magnetic reconnection or shocks driven by coronal mass ejections (CMEs).

A primary requirement in many SEP studies is to trace the in situ magnetic field of an observed SEP event back to its solar source through an estimate of its topology and geometry. This requirement is complicated by the complexity of closed and open coronal magnetic fields, which are typically represented with potential field source surface (PFSS) models that connect observed photospheric fields to a source surface at 2.5 Rs at which the fields are all radial from the Sun (Owens and Forsyth, 2013).

1.2. The PS Model in SEP Studies

The simplest assumption for the magnetic field source location is that it lies at the base of a Parker spiral (PS) field (Owens and Forsyth, 2013) defined by a constant radial flow of the SW to L1 with some average SW speed V_{sw} . This assumption restricts the solar source latitude to lie in the ecliptic plane, with a resulting heliographic latitude range of $\pm 7.25^\circ$, depending on the solar B_0 angle. Fixed V_{sw} values were invoked in recent statistical studies of coronal holes (CHs) and SEP events (W60°, Shen et al., 2006; 2010) and of longitudinal distributions of SEP events ($V_{sw} = 450 \text{ km s}^{-1}$, Lario et al., 2006; $V_{sw} = 400 \text{ km s}^{-1}$, Lario et al., 2013).

In general, however, most work to relate SEP events to their solar sources begins with the PS approximation using the local in situ V_{sw} . For some recent SEP studies, that inferred source location was taken as the magnetic footpoint, with no further qualification, and then compared to the location of a solar event, usually a flare. This approach was used in STEREO A and B (STA, STB) observations of the 17 January 2010 (Dresing et al., 2012), 3 November 2011 (Prise et al., 2014) and 11 April 2013 (Cohen et al., 2014) SEP events, ^3He -rich events (Wiedenbeck et al., 2013), and in statistical studies of $E > 50 \text{ keV}$ electron events (Dresing et al., 2014; Agueda et al., 2014). Similarly, Rouillard et al. (2012) accounted for the 21 March 2011 SEP onset times at STA and L1 by matching PS footpoints with an EUV wave and the edges of CME-driven streamer deflections. In their comparisons of SEP events first with flares and CMEs and then with EIT waves, Miteva et al. (2013, 2014, respectively) acknowledged that their PS extrapolations were valid only to a 2.5 Rs source surface, but used those locations as the 1

AU footpoints in their work. Klassen et al. (2015) found that the PS magnetic separation of the footpoints of STA and STB on the PFSS source surface was 47° for a spike electron event observed at both spacecraft.

1.3. The PS+PFSS Model in SEP Studies

1.3.1. Photospheric Sources

Other recent SEP event analyses have combined the PS approximation with the PFSS model (PS+PFSS) to determine the photospheric source footpoints. In the PFSS model the open photospheric fields diverge to the overlying source surface at 2.5 Rs, or at 5 Rs in the coupled PFSS+SCS (SCS, Schatten (1972) current sheet) model approach of this work, as shown in the three Carrington rotations (CRs) of Figure 1. The limitations of the PFSS model due to appropriate photospheric field maps have been addressed by various authors (Luhmann et al., 2008; Nitta and DeRosa, 2008; Linker et al., 2013). Wiedenbeck et al. (2013) surveyed clusters of field lines that expand from small photospheric sources of angular radii R to the overlying longitudinal extents on the 2.5 Rs source surface. They selected the largest longitudinal extents of field clusters for each day from ~ 5100 PFSS daily maps as a function of R . Their plot, reproduced as Figure 2, shows that these largest extents are several tens of degrees. Thus, if the PS extrapolation lands in the appropriate cluster, the photospheric location is correct to within the size of R , but for an incorrect cluster, the inferred photospheric location is incorrect by tens of degrees.

The PS+PFSS approximation is used to make photospheric field connections to SEP events. Klein et al. (2008) used PS+PFSS to connect L1 footpoints to open fields in active regions for seven simple SEP events. Ko et al. (2013) similarly correlated SEP Fe/O abundances with the footpoint field strengths for 24 gradual SEP events. In various STA/STB SEP event comparisons with EUV waves, Nitta (2012), Park et al. (2013, 2015), and Gómez-Herrero et al. (2015) also followed this approach.

The question of how accurately the PS or the PS+PFSS approximation selects the source longitude is rarely considered, but Klein et al. (2008) cited two basic uncertainties to infer an error range

of less than $\pm 10^\circ$. First, Nolte & Roelof (1973) in their introduction of the PS method (called the EQRH approximation) argued that the transition from quasi-rigid rotation to radial flow at heights above the source surface and the acceleration of solar wind with distance were offsetting factors which combined to produce an uncertainty of $< 10^\circ$. The second uncertainty was that of cross-field displacement of flux tubes resulting from interplanetary magnetic fluctuations. Klein et al. (2008) cited a value of $\pm 6^\circ$ – 10° , but recent calculations (Ragot, 2011; 2012) show flux tube displacements from the nominal PS field may be as high as several tens of degrees in very turbulent fields. In addition, Kahler et al. (2014) did a direct comparison of PS and WSA (Sec. 2.1) models for 33 SEP events and found average differences of $\sim 20^\circ$ for both photospheric source latitudes and longitudes. While the resulting longitudinal uncertainty ΔL of the PS method is difficult to estimate, the claim of $\pm 10^\circ$ may be a low estimate.

1.3.2. ^3He -rich SEP Events as PS Tests

Impulsive ^3He -rich events provide opportunities for testing the calculated PS+PFSS connections to assumed known compact solar SEP sources. MacNeice et al. (2011) used a stringently selected list of 15 impulsive SEP events with well determined solar source regions for a comparison of the PS model, with and without the PFSS model, against the WSA and WSA-ENLIL (Odstrcil and Pizzo, 2009) models were $\simeq 20^\circ$ and comparable to the PS and PS+PFSS averages of 23° and 25° .

Data from the Atmospheric Imaging Assembly (AIA; Lemen et al., 2012) on the Solar Dynamics Observatory (SDO) have allowed observers to determine ^3He -rich event source regions with a certainty not previously available (MacNeice et al., 2011). Bučík et al. (2014) examined four ^3He -rich events observed in July 2011 at STA, STB and L1, using the PS+PFSS model to determine the footpoints. The two candidate source regions AR 11244 and AR 11246 were separated by about 50° in longitude, with a similar width for each of their field line extensions to the $2.5 R_s$ source surface. The PS+PFSS model source fields matched the presumed source ARs in all four cases, but in two cases the PS field line lay near the boundaries

of the two broad source surface extensions of the ARs. Chen et al. (2015) did a similar analysis of two pairs of ^3He -rich events observed at L1 and also found PS footpoints within extended magnetic connections to the source ARs of each pair. A recent unusual series of ^3He -rich events observed on STA and STB with a longitudinal separation of 38° in May 2014 was due to a source region with a 95° width on the source surface (Wiedenbeck et al., 2015). These results support the concern of MacNeice et al. (2011) that impulsive SEPs may escape the Sun along field lines extending well away from the compact acceleration sites, undermining the validity of ^3He event sources as compact targets for tracing field lines.

A recent survey of 26 ^3He -rich event periods at L1 by Nitta et al. (2015) produced less favorable results. They found a large longitudinal spread of SEP source regions extending well beyond both the simple PS and the PS+PFSS source regions. In addition, they determined whether the PS+PFSS SEP source ARs had any open field regions matching the L1 field polarities. In 10 cases, including 3 of the 4 events of the Chen et al. (2015) study, there were no matching open field polarities to account for source connections. Their results confirmed the conclusion of Wiedenbeck et al. (2013) that within the PFSS model the longitudinal extents of field lines along the heliographic equator can not account for the large angular ranges of some ^3He -rich events.

1.4. Beyond PS+PFSS

Several SEP event studies have moved beyond the straightforward PS or PS+PFSS approach to solar connections. Luhmann et al. (2012) studied the series of SEP events in August 2010 observed at L1 and STB by combining a PFSS and ENLIL/cone model to describe the time-dependent perturbations of the CMEs on the interplanetary fields. In their SEPMOD model, SEPs were injected at the $\sim 20 R_s$ inner boundary of ENLIL over regions of open fields extending from flaring regions. Injection rates were based on assumed flare-related parameters and reproduced the major features of the observed SEP events. Examining the EUV wave locations in the 11 April 2013 SEP event, Lario et al. (2014) compared source locations for L1, STA, and STB derived from three methods: PS only; PS with the

Magnetohydrodynamics Outside a Sphere (MAS) model (Riley and Lionello, 2011) to 30 Rs; and PS+PFSS. The PS latitudes, restricted to $\pm 7^\circ$, disagreed with the MAS and PS+PFSS latitudes by up to 19° . The three methods were in good agreement in longitude for L1 (186° - 187°) and STA (295° - 302°), but ranged from 35° to 55° for STB. Note that the three methods all depend on the initial PS assumption.

Rouillard et al. (2011) determined the times when L1 and STB were first magnetically connected to a CME-driven shock on 3 April 2010. They used an ENLIL model of the CME observations and in situ shock observations at 1 AU to validate the model. They also modified the model upstream Vsw values to match the observed in situ values at STB and L1 over the five-day period preceding shock arrival at 1 AU to get optimum PS connections to the shock. The 12-hour delay between CME eruption and L1 SEP onset was consistent with the time for L1 connection to the western edge of the shock.

These works indicate a trend toward increasingly spatially and temporally resolved properties of coronal shocks and particle acceleration that can only be tested at L1 with accurate determinations of solar magnetic connections. **The PS approximation widely used in SEP studies assumes a completely ballistic Vsw with no stream-stream interactions which could distort the PS configuration to result in foot-point longitude displacements. The WSA model includes these interactions in an ad-hoc manner to produce a forecast Vsw at L1. In the next section we describe the model and its validation and apply the model to a number of CRs. The model is expanded to include the solar source longitudes and latitudes of the calculated L1 SW. The goal is to compare the WSA source longitudes with their corresponding PS longitudes deduced from the L1 values of the WSA forecasted Vsw. This procedure will test the limits of the PS method, using only results of the WSA model. Alternative comparisons between (1) PS source locations calculated with L1 spacecraft observations of Vsw and (2) the WSA model outputs for the same L1 solar sources will be done elsewhere.**

2. Data Selection and Analysis

2.1. The WSA Model for SEP Event Solar Sources

Here we use the Wang–Sheeley–Arge (WSA) model (Arge et al., 2004, MacNeice, 2009; Norquist and Meeks, 2010) to compare the coronal and photospheric source regions of the model with those of the PS approximation. WSA is a combined empirical and physics-based representation of the corona and quasi-steady global SW flow. Briefly, a standard PFSS model is used **here** with a National Solar Observatory (NSO) magnetogram from the Global Oscillation Network Group (GONG) to generate an open radial magnetic field on the PFSS surface at 2.5 Rs, which in turn serves as an inner boundary for the **SCS** model (MacNeice, 2009) that provides a nearly radial field at 5 Rs with a thin current sheet. Then a 1D kinematic model with an ad-hoc model to account for stream interactions is used to forecast Vsw and the IMF polarity at L1. **When the coronal portion of WSA is used to drive an advanced MHD model like ENLIL, the SCS model within WSA is extended out to 21.5 Rs (Lee et al., 2013).**

For each CR since 2009, magnetograms served as input to the Air Force Data Assimilative Flux Transport (ADAPT) model, which makes use of rigorous data assimilation methodologies (Hickmann et al., 2015). That model generates for a given day a flux-evolved synchronic map, or set of maps based on several realizations of the flux transport parameters (Arge et al., 2013). The WSA model was run on synchronic ADAPT maps for a given day of a CR. The maps are available at <ftp://gong2.nso.edu/adapt/maps/public/gong/>.

WSA forecasts are generated by letting the SW packets leave the Sun from the 5 Rs outer boundary with a fixed speed for each packet and a uniform cadence of one packet every 2.5° of solar longitude. The SW portion of the model is a simple 1D modified kinematic model in which the wind packets interact every $1/8$ AU to allow interaction between faster and slower packets (MacNeice et al. 2011). The model propagates SW parcels out to L1 (or any other desired point in space), keeping track of their source longitudes back at the Sun along with other parameters such as the magnetic field strengths and polarities of the footpoints.

The interactions result in nonuniform packet arrival times at L1, but each packet is tagged with a WSA forecast value of V_{sw} and B and a direct mapping of its magnetic field line back to its source region. We compared the WSA sources with the PS sources calculated for each forecast value of V_{sw} .

Kahler et al. (2014) used the WSA model in this mode to look for angular separations between L1 magnetic footpoints and sources of CMEs associated with SEP events. They used synoptic maps from Mount Wilson Observatory (MWO) and the NSO and compared WSA forecasts with L1 observations of V_{sw} and B . Here we use ADAPT maps derived from NSO full disk magnetograms, and we are not concerned with their forecast accuracy, but rather with how the 1 and 5 Rs source footpoints compare with those deduced from the PS approximation.

2.2. Selection of CRs

To compare the 5 Rs solar source longitudes of the WSA ADAPT (hereafter WSA) model (Hickman et al., 2015) with those derived from the PS approximation, we first sought WSA model prediction runs for full CRs, including some periods of high solar activity. To include SEP events, we used the Richardson et al. (2014) list of $E > 25$ MeV SEP events observed at L1 and STEREO A/B. Those active periods of SEP events are also characterized by interplanetary CMEs (ICMEs) for which the WSA model is not appropriate, so we further selected only CRs with no more than four ICMEs on the list of Near-Earth ICMEs compiled by Richardson and Cane (2012) at <http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm>. For each CR we selected three ADAPT maps corresponding to times near the beginning, middle and end of that CR and compared the WSA model forecast V_{sw} based on that day with the V_{sw} observed at the ACE satellite to look for qualitative agreement between the two V_{sw} profiles.

ADAPT is a data assimilative ensemble model providing 12 different realizations for any given moment in time. Each set of 12 ADAPT realizations was comprised of three subsets of four maps having fixed meridional flow rates but randomly varying super granule patterns. From the 36 available WSA runs (12 realizations $\times$ 3 different days)

the one judged to have the best qualitative match to the observed V_{sw} profile for a given CR was used in our analysis. Figure 3 shows superposed WSA and ACE V_{sw} plots for three sample CRs. The plots are similar to those illustrated in Arge et al. (2004) and in MacNeice (2009). For forecasting and validation studies the irregular time sequence of the WSA forecasts is converted to a uniform sequence of ~ 5.3 data points per day by interpolating values of the original WSA forecasts. The resulting plots of Figure 3 belie the original nonuniform sequences of the WSA model at L1.

The 21 selected CRs are listed in Table 1, along with their start dates and the numbers of SEP events and ICMEs (column 3). Note that the first WSA forecast values of V_{sw} occur several days after the start of each CR due to the time for SW propagation time to L1. The portions of the WSA profiles extending beyond the ends of the CRs into the subsequent CRs are not shown and were not used in the analysis. The V_{sw} profiles are characterized by rapid increases to high speeds followed by the longer gradual declines due to the decreasing slower wind inputs to lower speeds. The rapid V_{sw} increases have been termed high-speed events (HSEs), defined by Owens et al. (2008) as increases of $\Delta V_{sw} \geq 100 \text{ km s}^{-1}$ in 2 days or less. The WSA forecasts of HSEs have been validated by Owens et al. (2008), by MacNeice (2009) with a more complex HSE definition, and with both definitions by Norquist (2013), who concluded that the WSA generally overpredicts the occurrence of HSEs, but often underpredicts because of the occurrence of ICMEs. We note that the only ICME occurrence among the three CRs of Figure 3 occurred on 16-17 May 2012 of CR 2123. We did not attempt to separate ICMEs from HSEs in our analysis. The goal was to compare the WSA source longitudes with the PS longitudes on the assumption that the WSA model provides a realistic calculation of both source longitude and V_{sw} . The question then was to determine the differences between the WSA and the inferred PS longitudes.

2.3. Overview and Declining V_{sw} Regions

For each CR we calculated and compared the 5 Rs running values of the source Carrington longitudes (CLs) of the WSA and of the PS approximation based on the WSA forecast of V_{sw} . Figure 4 shows PS and WSA CL connections for three CRs,

each beginning with 360° for the earliest CR date and progressing monotonically down to near 0° , where we have cut off the V_{sw} values before the beginning of the subsequent CR. The WSA model generates $360^\circ/2.5^\circ = 144$ data points per CR, but the variable V_{sw} at 5 Rs produces an irregular cadence of those WSA model data points at L1 that contrasts with the replotted regular cadence of the Figure 3 plots, as discussed above.

The PS and WSA CL connections agree so well over nearly all the CL ranges that only the overplotted WSA data points are visible. The agreement is best in the periods of declining high V_{sw} , as expected for solar source regions of progressively slower speeds characterized by ballistic flows in rarefaction regions with no stream-stream interactions, indicated in the middle region of Figure 5, the iconic cartoon of Richardson (2004). However, if V_{sw} declines sufficiently rapidly, one encounters PS periods discussed by Nolte et al. (1977) and referred to as “dwells”, in which the PS CLs are nearly constant for one to three days. Their interpretation of those periods, assuming the PS approximation, was that the SW was emitted from constant CLs, but from varying coronal heights. Examples of dwells in Figure 4 are seen at rotation days 19-20 and 26-27 of CR 2100, 9-11 of CR 2126, and 26-27 of CR 2154.

The WSA model assumes radial flows at 5 Rs and no crossing of stream flows in the 2-D plane of the ecliptic. The latter condition sets a basic limit on the WSA modeled values of dV_{sw}/dt . When V_{sw} is decreasing (the rarefaction region of Figure 5), the PS footpoint longitude relative to central meridian, ϕ , moves westward at a rate that depends on dV_{sw}/dt . With a sufficiently large $-dV_{sw}/dt$, we may find that $d\phi/dt$ matches the solar rotation rate and the CL will appear to be fixed over an extended time period. Taking

$$d\phi/dt = D\Omega((V_{sw})^{-2}(dV_{sw})/dt) > \Omega,$$

where Ω is the solar rotation rate and D is 1 AU, then if

$$-d(V_{sw})/dt > (V_{sw})^2/D,$$

we encounter the unphysical situation that earlier arriving faster SW has left the Sun after the

later arriving slower solar wind, requiring the fast and slow streams to cross each other in the ecliptic plane (Riley and Lionello, 2011), contrary to the WSA model. We do not encounter this situation either in the L1 observations or in the WSA V_{sw} profiles. Note that the WSA L1 data points are widely spaced in time, indicating long intervals between plasma arriving from sources uniformly spaced 2.5° apart. However, the agreement of the PS with the output of the WSA model, with its assumed radial SW flows at 5 Rs, tells us that the dwells encountered in the PS approximation may not be so much artifacts as real source regions of limited CL ranges.

2.4. The Compression Regions of V_{sw}

The only times of significant disagreement between WSA and PS CLs occur at the relatively low values of V_{sw} preceding HSEs. These periods are characterized by WSA plasmas from multiple solar source regions separated by 2.5° but with closely bunched arrival times at L1 produced by the WSA model. They correspond to the slow SW regions at the leading edges of the compression or corotating interaction regions (CIRs) of Figure 5. The slowly varying V_{sw} yields a relatively fixed PS CL during the bunched times, but as the WSA CLs move eastward in these time bunches, the CL difference $\Delta L = \text{WSA} - \text{PS}$ becomes significantly negative. These negative ΔL excursions are not so obvious on the time plots of Figure 4, but they are clear in the CR scatter plots of ΔL versus V_{sw} in Figure 6 for the data points of the same three CRs of Figure 4. Most WSA points lie along the line $\Delta L \sim 0^\circ$, but the several columns of points are the large deviations corresponding to the slow V_{sw} values at bunches preceding the HSEs. We use these plots to define our version of HSEs and select those cases in which the lowest $\Delta L \leq -15^\circ$. There are then 9 HSEs for the three CRs of Figure 6 and a total of 57 such HSEs in our 21 CRs. We give the ΔV_{sw} of each HSE and the preceding ΔL in columns 4 and 5 of Table 1.

In the top left panel of Figure 7 we mark the four CR 2126 HSEs of Table 1 and show in the other three panels how ΔL decreases through the sequence of WSA model data points. Note that the sequence of WSA data points, rather than time, constitutes the independent variable. In each sequence the negative ΔL values accumulate

only through the constant V_{sw} ($\Delta V_{sw} = 0$) values in a data point bunch. ΔL resets to 0° with a subsequent increase or decrease of V_{sw} . The largest ΔL values of all but one of the 59 HSEs of Table 1 occurred just before a large increase of V_{sw} , similar to the HSE plots for the other CRs.

The 57 cases of $\Delta L \leq -15^\circ$ of Table 1 are plotted against their corresponding preceding speeds V_{sw} and ΔV_{sw} values in Figure 8. The maximum ΔL values are weighted strongly toward both low V_{sw} and large ΔV_{sw} , as seen in the example of Figure 7. All values of ΔV_{sw} exceed the 100 km s^{-1} threshold for the original HSE definition of Owens et al. (2008). Nearly all the largest ΔL excursions lie in the -30° to -40° range, which we take as the maximum range of difference resulting from the use of the PS approximation. ΔL is strongly correlated ($P < 0.001$) with ΔV_{sw} (C.C. = -0.49) and V_{sw} (C.C. = 0.53), but the large scatter suggests that the extreme ΔL values can be reached for almost any HSEs if we assume the $\Delta V_{sw} > 100 \text{ km s}^{-1}$ criterion. In no case in our comparison did we find positive values of ΔL exceeding 1° , so the PS approximation CL was never significantly west of the WSA CL for the assumed 5 Rs sources.

2.5. The HSE Magnetic Polarities

The WSA program tracks the source magnetic polarities as well as the CLs. The generally close agreement between the WSA and PS CLs evident for most of each CR (Figure 4) ensures that both source regions will have the same magnetic polarity. However, for the periods preceding the HSEs the large ΔL values (Figure 8) suggest that the PS CLs displaced westward of the WSA CLs may lie in opposite polarity photospheric source regions, as can be seen in Figure 1. We examined the magnetic polarities across the $\Delta V_{sw} = 0$ data bunches preceding the HSEs and list them in the last column of Table 1. Those polarities changed in 11 of the 57 HSEs throughout the constant V_{sw} periods, and in each case the polarity change occurred at the start of a series of non-zero ΔV_{sw} , as shown in the Figure 9 examples.

Polarity changes can also occur for ΔL excursions smaller than the $\leq 15^\circ$ associated with HSEs. Figure 9 shows that the selected ΔL excursions also occurred during low values of ΔV_{sw} . WSA sources of the long data-point sequences of ΔV_{sw}

$= 0$ correspond to slow wind regions (Figure 7) that map back to the western edges of coronal hole extensions to 5 Rs. The subsequent HSEs then map back to the high-speed regions of the coronal hole interiors, as expected in the WSA model.

2.6. Photospheric Footpoint Connections

Our WSA-PS footpoint analysis thus far has been restricted to comparisons at the 5 Rs source surface. This may be appropriate for some SEP event analyses, but we can extend the comparison to the photospheric footpoint longitudes CLp using the basic PFSS+SCS approximation with the NSO magnetograms shown in Figure 1. The magnetic field line sources at the 5 Rs source surface generally converge to smaller coronal hole (CH) sources at 1 Rs, which is most evident in the CRs 2135 and 2142. We expect that if the WSA and PS CLs share the same CH source, then the photospheric WSA-PS ΔL_p should be less than the corresponding ΔL at 5 Rs. On the other hand, when the WSA and PS 1 Rs sources lie in different CHs, the resulting ΔL_p values will usually be much larger.

In Figures 10 and 11 we show the CLp values for two CRs, plotted as functions both of WSA data points (top) and of time (bottom). Similar to the plots of the 5 Rs CLs in Figure 4, the data point sequence of Lp begins several days after the CR start and extends to the end of the CR. We saw earlier that at the bunches of WSA data points the PS CL remains nearly constant while the WSA CLs move eastward, and those cases are seen in the flat extensions of the fixed PS CLp after the WSA longitudes progress to lower CLps in the top panels. The WSA bunches occur at the sharp drops in CL corresponding to the boundaries of the source CHs, where the source magnetic polarities may or may not change. For our purpose of diagnosing the probability that the PS CLp approximation matches the WSA CLp model at 1 Rs, the time sequences in the bottom figure panels are the definitive comparisons. As we saw with the 5 Rs comparisons of Figure 4, the significant ΔL_p differences are a minor aspect of the CRs and occur just preceding the HSEs evident in the V_{sw} profiles. However, the top panels of Figures 10 and 11 show that when they occur, those CLp differences can reach several tens of degrees.

We further find that there is little correlation

between the ΔL and ΔL_p values, again as expected from the extensions to 5 Rs of the 1 Rs field sources shown in Figure 1. Large ΔL values may be associated with small ΔL_p values when the WSA and PS sources originate from the same CH, but with different CH sources small ΔL can be associated with large ΔL_p . In Figure 12 we compare histograms of logs of the numbers of ΔL and ΔL_p for all 21 CRs and find that ΔL_p extends to about twice the angular range of ΔL , but is more concentrated at $\Delta L_p \sim 0$ than is ΔL . Qualitatively this means that if both the WSA and PS footpoints are within several 10s of degrees at 5 Rs, they will be close together at the source CH CLs.

3. Summary of Results

In this work we started with the WSA SW model incorporating solar magnetic field evolution into a coupled PFSS+SCS model with an outer boundary set at 5 Rs combined with simple interplanetary dynamics. WSA yields L1 values of V_{sw} and magnetic field polarity along with the 1 Rs and 5 Rs CLs of each arriving SW packet. We use those V_{sw} values to track the ΔL between the WSA and PS CLs as the basis for a comparison with the PS model. WSA should match the actual SW better than the PS approximation, since it takes into account stream interactions. In contrast to previous studies, this comparison is done completely within the context of the WSA model and uses no in situ spacecraft observations. The goal is to determine when and how well the PS approximation agrees with WSA. We then apply to spacecraft observations of V_{sw} the lessons learned from the WSA model comparisons to determine the validity of the PS approximation.

To first order, the results shown in Figure 4 indicate that the PS approximation yields excellent agreement with the WSA CLs. The very nonuniform cadence of the bunches of SW parcels at L1 shown in Figures 7 and 9 is obviously an artifact of the limited spatial and temporal resolution of the WSA model, but it has allowed us to examine the physics leading to the largest ΔL and ΔL_p values. The SW of the declining V_{sw} profiles of the WSA seems to propagate nearly ballistically from the eastern and central regions of CHs and undergoes minimal stream-stream interactions, so that the PS assumption works very well in that

situation. The times of poor PS agreement with WSA appear only when the slow SW on the leading edges and the fast SW of the trailing edges of the stream interaction regions results in WSA CLs displaced eastward from the inferred PS CLs. The ΔL immediately resets to 0 at the onset of HSEs (Figures 7 and 9), but this again is likely a misleading artifact of the WSA. The periods of poor PS approximation should probably be taken as those of both the slow and fast V_{sw} around the HSEs. Although these significant displacements constitute a large fraction of the WSA SW packets, they are only a small fraction of the duration of each CR for both 5 Rs and 1 Rs, as evident in Figures 4, 10 and 11.

The ΔL differences statistically increase with lower pre-HSE SW speeds and larger ΔV_{sw} speeds, as shown in Figure 8. We suggest therefore that the periods around the larger increases in V_{sw} at L1 spacecraft data will be the times when the PS approximation is poorest, and that the inferred PS CL will be improperly displaced to the west because stream interactions are not taken into account. We also sought to establish upper limits to the magnitudes of ΔL and ΔL_p , and statistically these are $\sim -35^\circ$ and -80° , respectively, as shown in Figure 12, the log plots of those distributions. The more peaked distribution near 0° of the bottom photospheric plot shows qualitatively that one is more likely to get a good approximation to the photospheric footpoint, useful for comparisons of SEP events with EIT waves, than to the 5 Rs source surface footpoint, more applicable to CME shock studies. Although a direct quantitative comparison is not possible, the ΔL_p distribution of the lower panel of Figure 12 appears at least consistent with the Figure 2 (Wiedenbeck et al. 2013) broad angular distributions of the photospheric source fields on the PFSS source surface.

4. Further Considerations of the PS Approximation

We have seen in Section 1 that the determination of solar CLs of magnetic fields is an essential step to relate SEP events at L1 to their solar injection sources. The PS approximation has been extensively used, but it has not previously been critically examined except for studies with

impulsive SEP events. Those event comparisons were not encouraging, but the simplicity of the PS approximation using SW observations at L1 ensures its continued use to determine SEP source regions. The basic problem, especially for gradual SEP events associated with CMEs, is that we have no absolute knowledge of the solar source regions of L1 field lines to use as tests of the PS approximation. A further complication is that the coronal fields observed at the times of SEP events have evolved from the fields of 3–4 days earlier from which the observed L1 SW originated. The problem for the investigator is to determine when and how well the PS approximation might provide a credible SEP source region.

The uncertainty of the source surface foot-point locations inferred from the PS approximation alone is difficult to determine, but the requirement of matching source and in situ magnetic field polarities provides a valuable check on PS approximations. The in situ field polarities are usually unambiguous at L1 when determined from both field orientations and heat-flux flow directions (Owens and Forsyth, 2013). We reported in Section 2.5 that the WSA source magnetic polarities were reversed in 11 of the 57 HSEs (Table 1) when the PS approximation was used. Since our HSEs were defined in terms of the largest ΔL values we encountered in the 21 CRs of the study, they constitute a worst case situation for polarity mismatches from the PS approximation. The relative numbers of mismatches encountered may be small, but they still should provide a necessary tool to be used with the PS approximation.

Riley and Lionello (2011) considered the errors resulting from “ballistic” (equivalent to the PS) SW mappings between 30 Rs to 1 AU. They anticipated qualitatively that the rarefaction regions would map reasonably well, and the compression, or interaction, regions would be distorted as the preceding slow SW is accelerated and the trailing fast SW is decelerated. This implies that the PS approximation in the interaction regions would place the slow SW CLs too far to the west and the fast SW CLs too far to the east. In the WSA model, however, the ad hoc interaction of slow and fast SW produces the periods of slow SW bunching of L1 data points that precede HSEs (Figure 7). Throughout these bunches Vsw is nearly constant as the WSA CLs track progressively east-

ward and away from the fixed PS CLs, as indicated in Figures 7 and 9. The bunching regions therefore appear to be predominately fast SW regions considerably decelerated by the preceding slow SW regions, resulting in WSA CLs displaced eastward of the PS CLs. The sharp HSEs characteristic of the WSA Vsw profiles contrast with the smoothed boundaries of the Vsw stream profiles produced by a more realistic heliospheric MHD model (Riley and Lionello, 2011) that reduces SW gradients. Thus the ΔL excursions shown in Figure 12 should be considered upper limits to those produced by more realistic models.

We must keep in mind the limitations of the WSA model as we compare the PS approximation with the model outputs. The SW parcels are projected radially with fixed speeds and no SW acceleration term. The nonlinear dynamic interactions of different SW streams near the Sun are different from those near L1 (Riley and Lionello, 2011), providing another limitation on models of kinematic evolution, such as the WSA model used here. We anticipate that a similar comparison of PS against the more advanced WSA-ENLIL model (MacNeice et al., 2011), which includes solar wind dynamics, could yield CL results inconsistent with those presented here. Another big factor is the presence of ICMEs, which are not part of the WSA model, and can considerably distort the magnetic geometry of the evolutionary SW.

Thus far we have limited our consideration of determining field line sources to the use of 1 AU observations of Vsw, perhaps supplemented with B field polarities, to use in the PS approximation. Several alternative techniques using additional 1 AU SW observations have been proposed, which could also be useful for determining solar source fields in SEP events. Schulte in den Bäumen et al. (2012) and Li et al. (2016) add to the 1 AU Vsw values averages of the 1 AU radial and azimuthal B field components to map the interplanetary B field lines throughout the heliospheric ecliptic plane. Their model allows field lines to cross SW streams of different Vsw values, can detect loops, and permits azimuthal field components at the solar source region of choice. They supplement the B field and Vsw observations with accompanying suprathermal pitch angle distributions to confirm the field topologies.

Jackson et al. (2015) combine latitudinal field

components at the 1.6 Rs cusp surface of the current-sheet source surface (CSSS) model and global velocities inferred from interplanetary scintillation (IPS) observations to model the 1 AU Bn components. They had in mind closed loops as the sources of cusp-surface latitudinal fields, but open nonradial fields are a more likely alternative. A related idea (Manoharan et al., 2014) is to use velocities from IPS observations to set values of V_{sw} at the outer boundary of the Schatten Current Sheet (SCS) model, which is the outer portion of the WSA model. The common theme of these works is an attempt to use more than only the 1 AU V_{sw} observations to trace heliospheric magnetic field lines. The use of this additional observational information could serve as the next advance over the simple PS approximation to determine the solar sources of 1 AU magnetic fields.

5. Conclusion

Because the solar source regions of SEP events are becoming better defined, it is important to understand and improve on the PS approximation to determine more accurately the coronal or photospheric magnetic footpoints of the SEP observations at L1. We have run the WSA model on 21 selected CRs to compare the WSA CLs with those deduced from the PS approximation using the model V_{sw} values. The goal is to use results of these model comparisons as a guide for the applicability of the PS approximation with spacecraft data. The comparisons here have shown that the PS approximation agrees well, to within several degrees at the 5 Rs source, with the WSA model for the great majority of the CRs. The PS approximation fails in the SW interaction regions characterized by minimum V_{sw} values in slow SW regions and subsequent rapid V_{sw} increases, the HSE events, marking the onsets of high speed streams. The WSA model results for the interaction regions show that the WSA CLs lie east of the inferred PS CLs by as much as tens of degrees and often in regions of opposite magnetic polarity. We hope that other SW models can confirm or improve on the WSA model results presented here

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Table 1: CRs and High Speed Events with $-(\text{WSA-PS}) \geq \Delta 15^\circ$.

CR #	Start Date	SEP/ICME ^a	ΔV_{sw}^b	ΔL^c	Polarity
2094	27 Feb 2010	0/0	162	30°	P
			140	17°	P
			200	25°	P
2096	22 Apr 2010	0/0	043	15°	N
			212	20°	P
			237	25°	P
2098	16 Jun 2010	0/0	115	20°	N
			288	30°	N
			118	21°	N
2100	9 Aug 2010	4/0	121	25°	N
			188	33°	N/P
			165	20°	N
2102	3 Oct 2010	0/0	153	35°	P
			109	20°	P
			164	25°	P
2104	26 Nov 2010	0/0	257	25°	N
			−18	22°	P
			214	25°	P
2105	24 Dec 2010	1/0	318	37°	P
			294	32°	P
2106	20 Jan 2011	6/0	194	37°	P
			185	20°	N
			269	27°	N/P
2115	22 Sep 2011	2/1	...	...	...
2118	13 Dec 2011	5/0	152	27°	N
			112	25°	P
			340	27°	P
			283	25°	N
2119	9 Jan 2012	4/2	077	25°	P
			296	35°	P
			247	27°	P/N
2121	4 Mar 2012	3/3	245	32°	P
			084	25°	P
			106	22°	P
2123	28 Apr 2012	3/1	105	27°	P/N
			253	30°	N
			218	28°	N/P
2125	21 Jun 2012	6/3	227	18°	N
			259	35°	N/P
			031	18°	P/N
			089	16°	N
2126	18 Jul 2012	3/1	147	15°	P
			148	20°	N
			127	20°	N
			074	16°	N
2135	21 Mar 2013	1/1	260	27°	N
			235	27°	P

CR #	Start Date	SEP/ICME ^a	ΔV_{sw}^b	ΔL^c	Polarity
2141	31 Aug 2013	1/0	089	20°	P
			213	20°	N
2142	28 Sep 2013	3/2	125	25°	N/P
			165	22°	P/N
2145	19 Dec 2013	3/1	190	17°	P
			241	22°	N
2154	21 Aug 2014	1/1	210	32°	P
			109	38°	N/P
			232	20°	P
2160	1 Feb 2015	1/0	118	19°	N/P
			116	17°	P

^aNumbers of SEP events and ICMEs during the CR.

^bWSA forecast increase in V_{sw} in km s^{-1} for each HSE.

^c-(WSA-PS) in degrees. In all cases the PS longitude lies west of the WSA longitude.

Fig. 1.— NSO GONG synoptic maps of three CRs of Table 1 with derived CHs color-coded for SW speeds. Gray areas are closed fields. Diagonal lines show the magnetic connections from the sub-Earth points on the $5 R_{\odot}$ outer coronal boundaries to the photospheric CHs at the dates at the top of each map. From top to bottom the maps show predominately high latitude, mid-latitude and low latitude photospheric connections.

Fig. 2.— Integral distributions of longitudinal size, in number of degrees along the heliographic equator, for the largest cluster of field lines identified in PFSS model maps for each day over a 14 year period extending from 1998 through 2011. Here, a cluster is defined as consisting of those field lines originating within a radius R at the solar photosphere and mapping to the heliographic equator on the source surface. Curves show the fraction of days when the largest longitudinal spread was greater than the value given by the abscissa. Curves correspond to five different criteria for the cluster radius at the photosphere, as indicated in the legend. From Wiedenbeck et al. (2013).

Fig. 3.— Three CRs of Table 1 showing Vsw at L1 from ACE (black profiles) and the WSA forecast values (blue squares) from GONG magnetograms. The times of rapid increases of Vsw are the high-speed events (HSEs)

Fig. 4.— Three CRs of Table 1 showing the WSA V_{sw} at L1 (green profiles), the Carrington longitudes (CLs) of the WSA sources (black profiles), and PS sources based on V_{sw} (red profiles).

Fig. 5.— Schematic of fast and slow solar wind flows from Richardson (2004). The compression regions at L1 result from the interactions of fast wind flows following slow wind, and the rarefaction regions are due to slow wind flows.

Fig. 6.— Three CR plots of the $\Delta L = (WSA-PS)$ versus V_{sw} from the WSA model at L1. The vertical columns of data points are the bunches with constant V_{sw} preceding HSEs. The PS CLs remain constant while WSA CLs move eastward, producing increasingly negative values of ΔL . We select those bunches with ΔL reaching -15° as our cases of HSEs listed in Table 1. These are the same CRs as in Figure 4.

Fig. 7.— Top left panel is the V_{sw} time profile of CR 2126 (from Figure 4) showing the four HSEs listed in Table 1. Upper right panel shows ΔV_{sw} (black points and lines; $10 \times$ left hand scale) and ΔL (red points and lines) for the sequential WSA data points, which form time bunches in the first panel. The WSA CLs move to lower (more eastern) values through the sequences, but the inferred PS CLs remain fixed due to the fixed values of V_{sw} at those times. The ΔL values reset to 0° whenever $\Delta V_{sw} \neq 0$. We take the maximum deviations as upper limits to the differences between WSA and PS CLs. Bottom panels show HSEs I and III on expanded scales.

Fig. 8.— Top: Scatter plot of ΔL versus V_{sw} for the constant speeds preceding the HSEs of Table 1. Bottom: plot of the maximum ΔL versus associated ΔV_{sw} for 58 HSEs of Table 1. Strong correlations in both plots are indicated by the least-squares best-fit lines. $\Delta V_{sw} > 100 \text{ km s}^{-1}$ corresponds to the HSE definition of Owens et al. (2008).

Fig. 9.— WSA data point plots of $\Delta L = (\text{WSA-PS})$ (red points) for three CRs showing the magnetic polarities (blue points, indicated as +10 or -10) and ΔV_{sw} changes (black points). Polarity changes are seen before the HSEs ($\text{WSA-PS} \leq 15^\circ$) in each of these rotations, and are also apparent before some smaller ΔL excursions (e.g., point 38 in CR 2106 and point 62 in CR 2142).

Fig. 10.— Top: Photospheric Carrington longitude (CLp) for WSA (black points) and PS (red points) for CR 2100 as functions of WSA data points. The sharp drops in the WSA CLp occur during the data point bunches at the boundaries of CHs. Magnetic polarities at bottom of the panel are positive or negative (green points). Bottom: The same CR plot as a function of time in the CR and including V_{sw} . The large values of ΔLp occur just preceding the HSEs.

Fig. 11.— The same format as Figure 10, but for CR 2154.

Fig. 12.— Histogram comparison of the $\Delta L = \text{WSA-PS CLs at } 5 \text{ Rs}$ (top) and at the 1 Rs photosphere (ΔL_p) (bottom). Each point of the log scale is a single WSA data point from each of the 21 CRs of the study, and the predominately negative values mean that the PS CLs and CLps are west (more positive) of the WSA CLs and CLps in both cases.