Solar Phys (2019) 294:90
https://doi.org/10.1007/s11207-019-1464-0

Solar Cycle Variation of the Heliospheric Plasma Sheet Thickness

Chin-Chun Wu[1] · **Kan Liou**[2] · **Ronald P. Lepping**[3]

Received: 3 September 2018 / Accepted: 21 May 2019 / Published online: 11 July 2019

Abstract Past independent studies of the heliospheric plasma sheet (HPS) have shown that the thickness is highly variable, ranging from $\approx 3.8 \times 10^5$ to 8.9×10^6 km. Here we conduct a survey of the previous results and find a solar cycle dependence – where the HPS tends to be wider during solar-minimum years and narrower during solar-maximum years. The HPS is thicker near solar minimum than near solar maximum by a factor of 1.6 (in Solar Cycle 23) and 8 (in Solar Cycle 24). We also found that the average HPS thickness in 2007 (near the minimum of Solar Cycle 23/24) was almost ten times larger than that in 1995 (near minimum of Solar Cycle 22/23), and it was associated with a weak polar magnetic field in 2007. Based on the solar-surface-field measurements, we found that the average solar magnetic-field strength [$|\boldsymbol{B}|$] at 2.5 solar radii [$\mathrm{R}_\odot$] was $\approx 40\%$ larger in 1995 than in 2007 (0.22 gauss *versus* 0.16 gauss). We also found a larger ($\approx 27\%$) magnetic pressure-gradient force in 1995 than in 2007. Because this magnetic gradient force points toward the Equator in the corona (which is probably also true farther out), a wider HPS is expected to occur in 2007 than in 1995, at least close to the Sun. This result supports the so-called heliospheric plasma-sheet inflation hypothesis, *i.e.* the HPS is wider if the Sun's polar field is weaker and narrower if the Sun's polar field is stronger.

Keywords Solar cycle variation · Heliospheric plasma sheet · Heliospheric current sheet · Heliospheric plasma-sheet inflation hypothesis · Interplanetary magnetic field

1. Introduction

The heliospheric current sheet (HCS) is a region where transitions of oppositely directed interplanetary magnetic field (IMF) occur and the proton density peaks (*e.g.* Fitzenreiter and

---

✉ C.-C. Wu
chin-chun.wu@nrl.navy.mil

[1] Naval Research Laboratory, Washington, DC 20375, USA

[2] Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20723, USA

[3] UMBC/NASA/GSFC, Greenbelt, MD, USA

Burlaga, 1978; Borrini *et al.*, 1981; Gosling *et al.*, 1981; Winterhalter *et al.*, 1994; Smith, 2001; Crooker *et al.*, 2004; Suess *et al.*, 2009; Simunac *et al.*, 2012; Intriligator and Webber, 2014). The proton density generally decreases as one moves away from the HCS but is still elevated compared to the ambient solar wind. Such a region is referred to as the heliospheric plasma sheet (HPS). The HPS is also a region of low proton temperature, decreased He/H ratio, enhanced plasma β (ratio of the plasma pressure to the magnetic pressure), and slow wind (*e.g.* Borrini *et al.*, 1981). Because of a low inclination orbit ($\pm 7.2^\circ$), the Earth often encounters the HPS/HCS. With an average Earth orbital speed of $30\ \mathrm{km\,s^{-1}}$, it takes hours to days for the Earth to cross the HPS. Therefore, the properties of the HPS significantly affect the near-Earth space environment.

Studies of HPS crossings exist, but they are sporadic with regard to HPS's thickness and its long-term variability (*e.g.* Winterhalter *et al.*, 1994; Lepping *et al.*, 1996; Zhou *et al.*, 2005; Smith and Zhou, 2007; Foullon *et al.*, 2009; Simunac *et al.*, 2012; Wu *et al.*, 2017). These studies of HPS crossing events have generally shown a wide range for the HPS thickness at 1 AU, ranging between $\approx 0.4 \times 10^6$ and 9.0×10^6 km and/or an angular span of $\approx 0.1^\circ - 3.4^\circ$ from the Sun's center [angular span $= \arcsin(\mathrm{HPS_{thickness}}/215\mathrm{R}_\odot)$]. For example, Winterhalter *et al.* (1994) studied data returned from the ISEE-3 (*International Sun-Earth Explorer*-3) spacecraft, which encountered 19 sector-boundary crossings during 1978 and 1979, and they found a median thickness of the HPS of 3.2×10^5 km. Using five months of *Wind* data, Lepping *et al.* (1996) estimated the thickness of the HPS to be $\approx 7 \times 10^5$ km. More recently, Wu *et al.* (2017) reported a thickness of $\approx 8.2 \times 10^5$ km for an HPS recorded on 09 September 2017 by the *Wind* spacecraft. Observations using multiple spacecraft to remove the temporal–spatial alias effect came later. Foullon *et al.* (2009) studied one HPS crossing event using multiple spacecraft during Carrington rotation (CR) 2053 and found its width along the Sun–Earth line to be $\approx 2.5 \times 10^6$ km. Using observations from *Wind* and the *Solar Terrestrial Relations Observatory* (STEREO)-A and -B over four solar rotations (April – June 2007 or CR2054 – CR2057), Simunac *et al.* (2012) concluded that the HPS had a radial width of $\approx 4.3 \times 10^6$ km. It is generally believed that the thickness of the HPS increases with the radial distance from the Sun due to the expansion of the solar wind. However, Smith and Zhou (2007) found that the median HPS thickness at 5 AU is $\approx 10^6$ km, which is smaller than many measurements of HPS made at 1 AU (*e.g.* Simunac *et al.*'s result at 1 AU) but close to the estimate of $\approx 7 \times 10^5$ km by Lepping *et al.* (1996).

Although estimates of the thickness of the HPS vary widely, there has been no attempt to address this question on thickness. Wu *et al.* (2013) conducted numerical MHD simulations, and their results led them to propose an "HPS inflation hypothesis" to explain why the HPS at 1 AU was denser in the solar minimum of Cycle 22/23 (1996) than that of Cycle 23/24 (2008). Later, Wu *et al.* (2016) used a solar magnetic field at 2.5 solar radii [$\mathrm{R}_\odot$] that was derived from photospheric-field measurements, to confirm their hypothesis. More recently, using long-term solar wind observations from both *Wind* and *Ulysses*, Liou and Wu (2016) showed that the slow wind region is wider in the solar minimum of Cycle 23/24 than in that of Cycle 22/23. The main conclusion of these three studies is that the solar wind is denser near the Earth's orbit in the solar minimum of Cycle of 22/23 than in the solar minimum of Cycle 23/24, and this can be attributed to a narrower HPS. Although these three studies did not observe the thickness of the HPS, their result suggests a wider HPS in the solar minimum of Cycle 23/24.

A survey of the previous observations of the HPS thickness indicated that they were recorded in different solar-activity periods. In this study we will first summarize previous results and correlate the HPS thickness with the sunspot number (SSN) to check for a possible solar cycle variation. We will focus on the two studies in which the thickness of the HPS measured in 2007 was almost ten times thicker than that in the earlier period (*viz.* 1994 – 1995). Both HPS data sets were taken approximately one year before the solar minimum (1994 – 1995 and 2007) and thus provide a quick test of the HPS inflation hypothesis.

The rest of the article is organized as follows: We explain how we analyze the data in Section 2. We discuss and compare results in the context of the HPS inflation hypothesis in Section 3. The conclusions are stated in Section 4.

2. Survey of Previous Results

The main purpose of this study is to find whether the HPS thickness varies with the solar cycle, using previous study results. A thorough survey results in a total of six previous HPS studies: Winterhalter *et al.* (1994), Lepping *et al.* (1996), Zhou *et al.* (2005), Foullon *et al.* (2009), Simunac *et al.* (2012), and Wu *et al.* (2017). Their results are chronologically summarized in Table 1. The table includes the observation period, the sunspot number (SSN), the reported HPS thickness, the number of HPS events studied, and references. Among these studies, Winterhalter *et al.* (1994), Lepping *et al.* (1996), and Zhou *et al.* (2005) only provided statistical results. No detailed information about each HPS event they studied (*e.g.* occurrence time, date … *etc.*) is given. Only four HPSs were studied (and listed) in 2007, and only one HPS was studied in 2011. Table 1 shows that the width of the HPS was smallest during 1978 – 1979 and 1994 – 1995 and largest in 2007 among these six data sets. The difference in the thickness of the HPS was about an order of magnitude, ranging from 3×10^5 to 4×10^6 km. Note that all of the listed values of HPS thickness in Table 1 are normal to the HPS except for the result of Simunac *et al.* (2012), who calculated the HPS thickness only along the radial direction. Here we assume that their HCS events were along the 45° Parker spiral fields to convert the radial thickness to normal thickness, for compatibility. Furthermore, the HPS thickness listed in Table 1 is the mean value except for Winterhalter *et al.* (1994) and Zhou *et al.* (2005), who published median values only. Because in both

Table 1 Characteristics of HPS events occurring in different periods, 1978 – 2011.

Observation period	SSN[a]	HPS thickness [km]	Number of events	References
(a) 1978 – 1979	177.6	[c]3.2×10^5	19	Winterhalter *et al.*, 1994
(b) 14 Nov. 1994 – 03 Apr. 1995	34.7	[d]7×10^5	212	Lepping *et al.*, 1996
(c) Dec. 2003 – Apr. 2004	67.6	[c]3.08×10^6	11	Zhou *et al.*, 2005
(d) Mar. 2007	7.2	[e]$(2.54 \pm 0.70) \times 10^6$	1	Foullon *et al.*, 2009
(e) Apr. – Jul. 2007[b]	13.3	[e]$(4.27 \pm 1.46) \times 10^6$	3	Simunac *et al.*, 2012
(f) 09 Sep. 2011	120.4	[f]8.2×10^5	1	Wu *et al.*, 2017

[a] Sunspot number. Arithmetic mean of the daily sunspot value from www.sidc.be/silso/ the World Data Center SILSO (WDC-SILSO), Royal Observatory of Belgium, Brussels to compute the average of SSN for each period. Monthly average was used for the single event, *i.e.* items d and f.

[b] Assume HCS along the 45° Parker spiral field.

[c] Median HPS thickness.

[d] Mean HPS thickness.

[e] Multi-spacecraft averaging.

[f] Single HPS thickness.

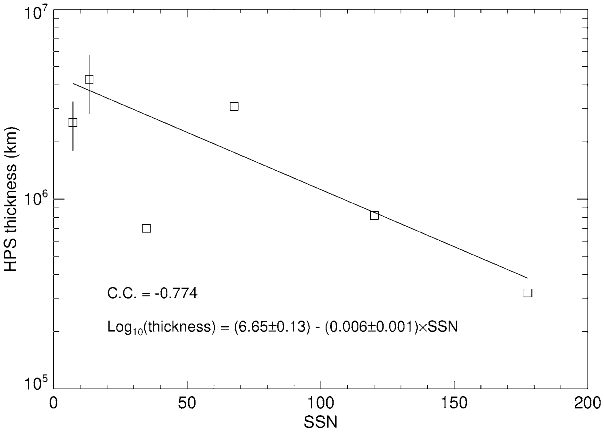

Figure 1 Relationship between the heliospheric plasma-sheet (HPS) thickness and the sunspot number (SSN). The *straight line* is the least-square linear regression fit to the log HPS thickness and linear SSN data. The *vertical bars* at the first two data points show one standard deviation of the sample distribution.

cases they did not publish the HPS thickness separately for each event that they studied, we have no choice but to use their published median values in our analysis.

To determine whether there is a solar cycle dependence, we check the sunspot number (SSN) for these observations. Figure 1 is a scatter plot that shows the relationship between the HPS thickness and SSN. In general, there is a trend that the logarithm of HPS thickness decreases linearly with increasing SSN. Using the p-value significance test method (*e.g.* Bevington and Robinson, 2003), a correlation coefficient of -0.774 with the degrees of freedom $\mathrm{dof} = N - 2 = 4$, where N is the sample size, the significance level is $\alpha = 0.057$. Therefore, the likelihood that the correlation coefficient that we found occurs by chance is less than $\approx 6\%$. Note that the work of Lepping *et al.* (1996) was preliminary because they assumed an average solar-wind speed of 420 $\mathrm{km\,s^{-1}}$ in their HPS thickness calculations. If we ignore the result of Lepping *et al.* (1996), the correlation coefficient increases significantly to -0.934 ($\alpha = 0.036$; $\mathrm{dof} = 3$).

It is important to note that there is a significant difference (by a factor of $\approx 5-13$) in the HPS thickness measured at different solar-minimum years (see Table 1). For example, the HPS thickness is smaller near the minimum of Solar Cycle 22/23 (1994–1995) than that near the minimum of Solar Cycle 23/24 (2007). In the next section, we will explore a possible cause of this anomaly.

2.1. Solar Magnetic-Field Profile at 2.5 Solar Radii

It is generally thought that the angular span of the HPS/HCS is determined close to the Sun and changes little further away (*e.g.* Bavassano, Woo, and Bruno, 1997). Therefore, in the low-β plasma corona, especially in solar active regions, the dynamics of the corona is controlled mainly by the solar magnetic field. It is suspected that there is a significant difference in the total field intensity and distribution between the two solar minima (22/23 and 23/24), leading to the large difference in the thickness of the HPS. To explore such a possibility, we will examine solar magnetic-field data.

Figure 2 shows several Carrington maps of the radial component of the solar magnetic-field intensity [B_r] at 2.5 solar radii [$\mathrm{R}_\odot$] in different periods of the solar cycle. The magnetic maps are derived from the photospheric-field measurements at Mount Wilson Observatory (MWO), assuming that the magnetic field is purely radial. Figures 2a–c show the longitudinal–latitudinal profile of B_r at Carrington rotations (CR) 1889 (CR1889), CR1891,

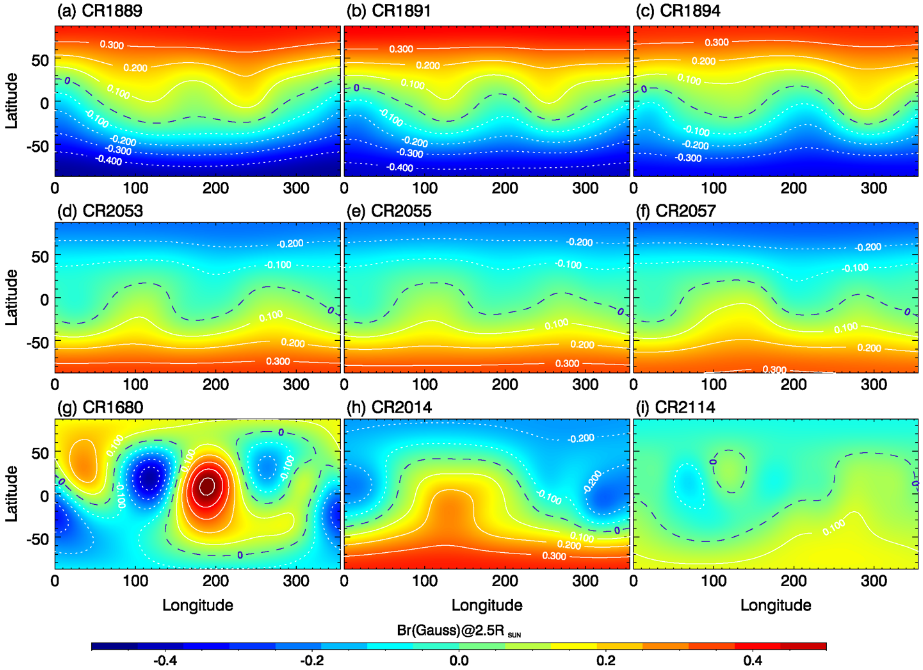

Figure 2 Magnetic-field intensity $|\boldsymbol{B}|$ maps at 2.5 $R_\odot$ derived from the photospheric-field measurements at Mount Wilson Observatory (MWO) for nine different solar rotations; Panels **a**–**c** CR1889, CR1891, and CR1894 during November 1994–April 1995; Panels **d**–**f** CR2053, CR2055, and CR2057 during March–July 2007; Panel **g** CR1680 in April 1979. Panel **h** CR2014 in April 2004; Panel **i** CR2114 in September 2011. The x- and y-axis represent the longitudinal and latitudinal directions, respectively. *Blue-dashed–contours* indicate the location of $|\boldsymbol{B}|$ equal zero, *i.e.* the heliospheric current sheet location. *White-solid contours* and *white-dotted contours* indicate outward and inward solar magnetic fields, respectively. The color key is for the magnitude of $|\boldsymbol{B}|$.

and CR1894 in the end of the solar declining phase of Solar Cycle 22 (or November 1994–April 1995). The magnitude of B_r was in the range from -0.4 gauss (in the southern area, latitude or $\theta = -90^\circ$) to 0.3 gauss (in the northern area, $\theta = 90^\circ$). Figures 2d–f show the B_r-profiles of CR2053, CR2055, and CR2057 (or March–July 2007) in the end of the declining phase of Solar Cycle 23. The magnitude of B_r was in the range from -0.2 gauss (in the northern area) to 0.3 gauss (in the southern area). The colors show that the solar magnetic field near solar minimum was stronger in Cycle 22 (Figures 2a–c) than in Cycle 23 (Figures 2d–2f). Both periods are near the solar minimum, and the shapes of the heliospheric current sheet (HCS, indicated in blue-dashed contours) were less wavy than in the higher solar-activity period (see Figures 2g–i). Figures 2g–i show the B_r-profiles of CR1680 (April 1979), CR2014 (April 2004), and CR2114 (September 2011) in the solar maximum, descending, and ascending phases, respectively. The colors in Figures 2g–i show that both maximum magnitude B_r occurred in April 1979, and the weakest B-field occurred in September 2011.

As shown in Figure 2, the magnitude of the solar magnetic field at 2.5 $R_\odot$ was larger in 1994 (top panels) than that in 2007 (middle panels). A stronger polar field may have resulted in a larger field gradient (*i.e.* magnetic force) toward the Equator, leading to a narrower HPS in 1994. In solar-maximum years, mixing of the solar dipole and higher-multipole field components produces a complex field structure. As a result, we expected a highly variable thickness for the HPS during solar-maximum years. We will provide more quantitative context later to justify this assumption.

2.2. Relationship Between the Solar Magnetic Pressure and HPS Thickness

The corona is a low-β plasma, meaning that the plasma dynamics is controlled by the solar magnetic field. If the HPS/HCS originates from the corona, and indeed many believe this to be the case, the force associated with the magnetic pressure across the HPS (*i.e.* magnetic pressure force) determines its width. Here we calculate the magnetic pressure force [$\boldsymbol{F}_B$] for the nine magnetic maps shown in Figure 2. The magnetic force can be expressed as the gradient of magnetic pressure [$\nabla P_B = \nabla(B^2/8\pi)$] where, in spherical coordinates, $\nabla = \hat{\mathbf{i}}_r \partial/\partial r + \hat{\mathbf{i}}_\theta r^{-1}\partial/\partial\theta + \hat{\mathbf{i}}_\phi (r\sin\theta)^{-1}\partial/\partial\phi$. Assuming $B = B_{\mathrm{r}}(\theta, \phi)$ and $\partial B/\partial r \ll \partial B/\partial\theta$ and $\partial B/\partial\phi$, at $r = a$, the magnetic force $\boldsymbol{F}_B = a^{-1}[\partial/\partial\theta, \sin\theta^{-1}\partial/\partial\phi]P_B = [g_\theta, g_\phi]$, where $g_\theta = \partial P_B/\partial\theta$ and $g_\phi = \partial(\sin\theta^{-1} P_B)/\partial\phi$. The magnitude of the magnetic force is expressed as $|\boldsymbol{F}_B| = (g_\theta^2 + g_\phi^2)^{1/2}$, and the direction of the force is $\Theta = \tan^{-1}(g_\theta/g_\phi)$.

Figure 3 shows the longitudinal–latitudinal profiles of the solar magnetic-field force [F_B] at 2.5 $\mathrm{R}_\odot$, corresponding to the magnetic maps of Figure 2. The color bar shows the magnitude of $|F_B|$ and small arrows represent the direction of F_B. Figure 3 shows that during solar-minimum years (the top and middle panels) the magnetic force along the current sheet (dashed lines) is generally small. However, during solar-maximum years (bottom panels)

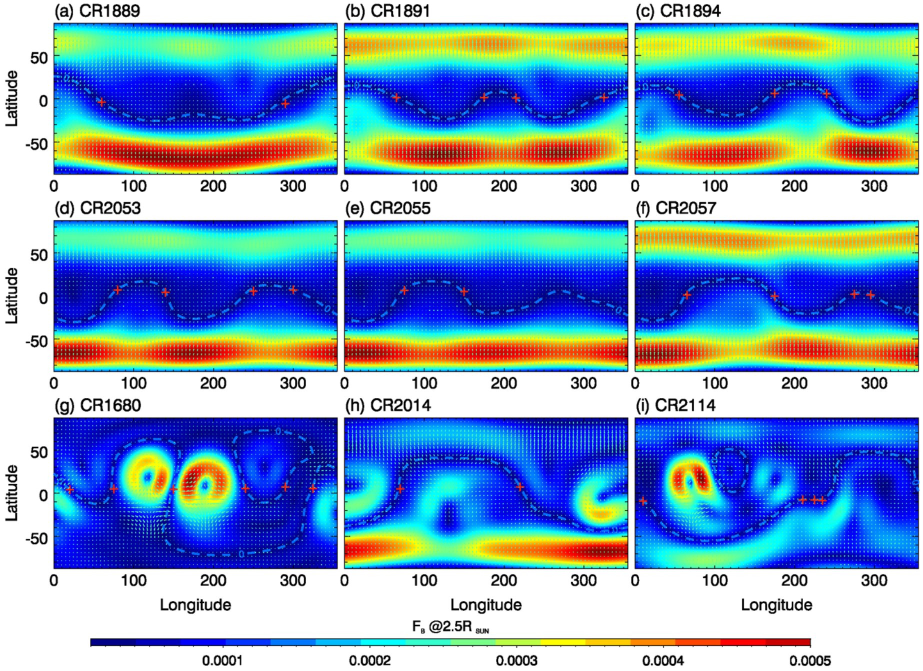

Figure 3 Magnetic force [$\boldsymbol{F}_B$] at 2.5 $\mathrm{R}_\odot$. Panels **a** – **c** CR1889, CR1891, CR1894, during November 1994 – April 1995. Panels **d** – **f** CR2053, CR2055, and CR2057 during March – July 2007. Panel **g** CR1680 in April 1979. Panel **h** CR2014 in April 2004. Panel **i** CR2114 in September 2011. The x- and y-axes represent longitudinal and latitudinal directions. The *blue-dashed contours* indicate the location of B_{r} when it is equal to zero: a possible location of the HCS. Because the Earth's orbit is limited to within ±7.5° of the solar Equator, the magnetic force that acts on the HPS is estimated at the projected Earth latitudes (*red crosses*).

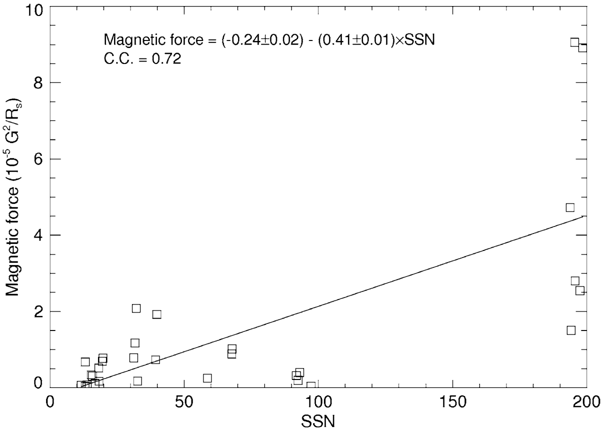

Figure 4 A scatter plot that shows the relationship between the magnetic force (y-axis) at the Earth's HCS crossings (shown as red cross signs in Figure 3) and the sunspot number (x-axis). The *straight line* shows a least squares regression fit to the data. The fitting result and the Pearson correlation coefficient are shown at the *top of the figure*.

the magnetic force can be both small (*e.g.* longitudes ≈ 30° and 60° in Panel g) and large (longitudes ≈ 120° and 230° and ≈ 260° in Panel i). Because the Earth's orbit is limited within 7.5° from the solar Equator, the magnetic force that acts on the HPS is estimated at the projected Earth latitudes (red crosses). The result is shown in Figure 4, which shows a scatter plot of the magnetic force *versus* the 30-day average of the daily SSN. A straight line is used to fit the scatter plot, with a Pearson correlation coefficient of 0.72.

As we mentioned earlier, there is a large difference in the HPS thickness in 1994 – 1995 and 2007. The average thickness of the HPS was found to be 7.0×10^5 km in 1994 – 1995 and $3.6 – 8.9 \times 10^6$ km in 2007. Now we wish to address this difference. The magnetic force shown in Figure 3 may provide a hint. The average magnetic force [gauss^2 $R_\odot^{-1}$] at the HCS crossings is 8.35×10^{-6} (std. $= 2.49 \times 10^{-6}$) for the three solar rotations in 1995 – 1995 (top panels) and 3.38×10^{-6} (std. $= 0.94 \times 10^{-6}$) for the three solar rotations in 2007 (middle panels). Therefore, the wider HPS in 2007 was associated with a smaller magnetic force, and the narrower HPS in 1994 – 1995 was associated with a larger magnetic force.

To explore whether there is a similar solar cycle variation in the magnetic force, we plot the magnetic force at the intersection of the current sheet and the projected Earth location, shown as red crosses in Figure 3, as a function of the SSN in Figure 4. It is found there is a good correlation between the two, with the Pearson correlation coefficient $r = 0.72$ ($p < 0.0001$, $N = 31$). This linear relation suggests that the magnetic forces tend to be larger during solar maximum than during solar minimum. Note that during solar maximum the magnetic forces vary significantly, but the average value is still significantly larger than a value indicative of the low SSNs.

3. Discussion

In the previous section, we conducted a survey of the past studies of the HPS thickness and found a solar cycle variation. It was found that the HPS tends to be thicker for smaller SSN and thinner for larger SSN. A good linear relationship between the logarithm of the HPS thickness and the SSN ($r = -0.78$) was found. The logarithmic relation means the HPS width is a strong function of the SSN. However, we do not know specifically why it is a logarithmic relationship. A solar cycle variation suggests that the HPS is controlled by its source at or near the Sun. Winterhalter *et al.* (1994) showed that the HPS at 1 AU is a pressure-balance structure and suggested that the HPS is a convective structure in the solar wind. It has been shown that the HPS convects with the solar wind and its structure at 1 AU is similar to that closer (0.3 AU) to the Sun, with a typical angular width of 2 – 3° (Bavassano, Woo, and Bruno, 1997). We examined the solar magnetic field close to the Sun (2.5 $R_\odot$), where the HCS is already formed, because at this altitude the plasma β is small and the dynamics of the coronal plasma is mainly controlled by the magnetic field.

We also found that the large difference (by a factor of ≈ ten) in the HPS thickness during different solar minima (1994 – 1995 *versus* 2007) is associated with a larger polar magnetic field in 1994 – 1995 than in 2007, resulting in a larger magnetic pressure force pointing toward the magnetic Equator in 1995 – 1995 than in 2007. Because the HPS is a convective structure, we expected a narrower HPS at 1 AU in 1994 – 1995 than in 2007. This is consistent with the observations and supports the plasma-sheet inflation hypothesis (Wu *et al.*, 2016), which is analogous to terrestrial magnetospheric plasma-sheet thinning (Baumjohann, Paschmann, and Nagai, 1992), and it is confirmed, to some extent, by the *Ulysses* data (Liou and Wu, 2016).

It is important to note that the magnetic force is likely to contribute ≈ 50% of the variations of the HPS thickness, as suggested by the Pearson correlation coefficient (0.72), and the other 50% is contributed by other factors, for example the plasma source of the HPS. If the polar magnetic field stays the same and if the Sun emits less material, one would expect a narrower HPS at 1 AU. However, there is no evidence indicating that such a scenario holds. Interaction of the HPS with coronal mass ejections (CMEs) and their driven shocks may also affect the structure of the HPS. Wu *et al.* (2017) found an HPS event associated with an extremely large density ($\approx 94\ \mathrm{cm}^{-3}$). They argue that it is caused by the compression of a CME-driven shock. The present study is based on a small number of samples (six), and one should consider our result to be tentative, because these studies were conducted by different scientists with different methods and different data sources. The present result provides a direction for future study. We intend to conduct a more detailed study of the HPS using long-term data from *Wind* in the future.

4. Conclusions

A quick survey and analysis of six previous studies of the HPS thickness have suggested that there is a solar cycle correspondence: the HPS tends to be thicker during solar minimum and narrower during solar maximum. We also analyzed the solar magnetic field at 2.5 $R_\odot$ and found that the magnetic forces that act on the plasma sheet also change with solar activity as indicated by the SSN. This study provides evidence for the effect of solar magnetic activity on the structure of the HPS.

Acknowledgments We thank the World Data Center SILSO (Sunspot Index and Long-term Solar Observations), Royal Observatory of Belgium, Brussels for proving sunspot data, and Y.-M. Wang of the Naval Research Laboratory for providing the derived solar magnetic-field data at 2.5 solar radii. The work of C.-C. Wu was supported partially by the Chief of Naval Research, and the NASA 80HQTR18T0023, HSWO2R17-0005, and 80HQTR19T0062 grants. The work of K. Liou was supported by the NSF grant 1743118 to the Johns Hopkins University Applied Physics Laboratory.

Disclosure of Potential Conflicts of Interest The authors declare that they have no conflicts of interest.

References

Baumjohann, W., Paschmann, G., Nagai, T.: 1992, Thinning and expansion of the plasma sheet. *J. Geophys. Res.* **97**, 17173. DOI.

Bavassano, B., Woo, R., Bruno, R.: 1997, Heliospheric plasma sheet and coronal streamers. *Geophys. Res. Lett.* **24**(13), 1655. DOI.

Bevington, P.R., Robinson, D.K.: 2003, *Data Reduction and Error Analysis for the Physical Sciences*, 3rd edn. McGraw–Hill, New York.

Borrini, G., Gosling, J.T., Bame, S.J., Feldman, W.C., Wilcox, J.M.: 1981, Solar wind helium and hydrogen structure near the heliospheric current sheet: A signal of coronal streamers at 1 AU. *J. Geophys. Res.* **86**(A6), 4565. DOI.

Crooker, N.U., Huang, C.-L., Lamassa, S.M., Larson, D.E., Kahler, S.W., Spence, H.E.: 2004, Heliospheric plasma sheets. *J. Geophys. Res.* **109**, A03107. DOI.

Fitzenreiter, R.J., Burlaga, L.F.: 1978, Structure of current sheets in magnetic holes at 1 AU. *J. Geophys. Res.* **83**, 5579. DOI.

Foullon, C., Lavraud, B., Wardle, N.C., Owen, C.J., Kucharek, H., Fazakerley, A.N., *et al.*: 2009, The Apparent layered structure of the heliospheric current sheet: Multi-spacecraft observations. *Solar Phys.* **259**, 389. DOI.

Gosling, J.T., Asbridge, J.R., Bame, S.J., Feldman, W.C., Borrini, G., Hansen, R.T.: 1981, Coronal streamers in the solar wind at 1 AU. *J. Geophys. Res.* **86**, 5438. DOI.

Intriligator, D.S., Webber, W.R.: 2014, Analyses of Voyager 2 plasma observations in the heliosheath: Near the heliospheric current sheet and streamer belt. In: Hu, Q., Zank, G.P. (eds.) *Outstanding Problems in Heliophysics: From Coronal Heating to the Edge of the Heliosphere*, **CS-484**, 84. Astron. Soc. Pacific, San Francisco. ADS.

Lepping, R.P., Szabo, A., Peredo, M., Hoeksema, J.T.: 1996, Large-scale properties and solar connection of the heliospheric current and plasma sheets: Wind observations. *Geophys. Res. Lett.* **23**, 1199. DOI.

Liou, K., Wu, C.-C.: 2016, A possible cause of the diminished solar wind during the solar cycle 23 – 24 minimum. *Solar Phys.* **291**, 3777. DOI.

Simunac, K.D.C., Galvin, A.B., Farrugia, C.J., Kistler, L.M., Kucharek, H., Lavraud, B., *et al.*: 2012, The heliospheric plasma sheet observed *in situ* by three spacecraft over four solar rotations. *Solar. Phys.* **281**, 42. DOI.

Smith, E.: 2001, The heliospheric current sheet. *J. Geophys. Res.* **106**, 15819. DOI.

Smith, E., Zhou, X.: 2007, Slow mode waves in the heliospheric plasma sheet. In: Shaikh, D., Zank, G.P. (eds.) *Turbulence and Nonlinear Processes in Astrophysical Plasmas*, *AIP* **CS-932**, 144. DOI.

Suess, S.T., Ko, Y.-K., Steiger, R., Moore, R.L.: 2009, Quiescent current sheets in the solar wind and origins of slow wind. *J. Geophys. Res.* **114**, A04103. DOI:10.1029/2008JA013704.

Winterhalter, D., Smith, E.J., Burton, M.E., Murphy, N., McComas, D.J.: 1994, The heliospheric plasma sheet. *J. Geophys. Res.* **99**(A4), 6667. DOI.

Wu, C.-C., Liou, K., Plunkett, S., Craig, D.F., Wu, S.T.: 2013, Investigation of solar/heliospheric anomalies associated with solar minimum during 2007 – 2008. *Terr. Atmos. Oceanic Sci.* **24**, 243.DOI. DOI.

Wu, C.-C., Liou, K., Wu, S.T., Dryer, M.: 2016, Heliospheric plasma sheet inflation as a cause of solar wind anomaly during the solar cycle 23 – 24 minimum. In: Wang, L., Bruno, R., Möbius, E., Vourlidas, A., Zank, G.P. (eds.) *Proc. Solar Wind 14*, *AIP* **CP-1720**, 040021. DOI.

Wu, C.-C., Liou, K., Lepping, R.P., Vourlidas, A., Plunkett, S., Socker, D., Wu, S.T.: 2017, Observation of an extremely large-density heliospheric plasma sheet compressed by an interplanetary shock at 1 AU. *Solar Phys.* **292**, 109. DOI.

Zhou, X.-Y., Smith, E.J., Winterhalter, D., McComas, D.J., Skoug, R.M., Goldstein, B.E., Smith, C.W.: 2005, Morphology and evolution of the heliospheric current and plasma sheets from 1 to 5 AU. In: Fleck, B., Zurbuchen, T.H., Lacoste, H. (eds.) *Proc. Solar Wind 11 / SOHO 16, Connecting Sun and Heliosphere* **SP-592**, ESA, Noordwijk, 659. ISBN 92-9092-903-0.