Large-density (>50 cm$^3$) heliospheric plasma sheets recorded by the Wind spacecraft between 1995 and 2017

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Abstract. A survey of previous studies of the heliospheric plasma sheet (HPS) suggests a bimodal distribution for the occurrence of the HPS peak plasma density. While the majority of HPS events have a peak density smaller than ~30 cm$^{-3}$, there is evidence that large density (>50 cm$^{-3}$) HPS events can exist. A bimodal distribution would suggest a two-source scenario for the HPS observed at 1 AU. In this study we focus on large density HPS events. We survey the solar wind data acquired from the Wind spacecraft between 1995 and 2017 and identify 108 large-density HPS events with a distribution peak at 55 cm$^{-3}$, confirming the bimodal distribution. We also find that 80 (74%) of these large-density HPS events are associated with interplanetary shocks. The yearly occurrence of these large-density HPS events nearly follows the yearly occurrence of interplanetary shock. This result suggests that large-density HPS events are likely caused by compression of interplanetary shocks within 1 AU.

1. Introduction

The heliospheric plasma sheet (HPS) is a region of slow flows with enhanced plasma density surrounding the heliospheric current sheet (HCS), where density commonly peaks and separation of oppositely directed open magnetic field lines occurs [e.g. 1,2,3,4,5,6,7,8]. Slow and dense solar wind streams of HPS/HCS dominate in the ecliptic plane during solar minimum [e.g., 5] and is believed to originate somewhere inside coronal streamers [e.g., 9,10].

An important aspect of the HPS/HCS in space weather is its geoeffectiveness. Sudden compression of the magnetosphere by large density/dynamic pressure solar wind structures can enhance dayside magnetic field merging [11] and night reconnection [12], enhance auroral intensity [e.g., 13,14,15], and drive sawtooth oscillations of the magnetotail [e.g. 16]. Sudden enhancements of the Chapman-Ferraro currents due to the impact of the magnetosphere by solar wind dynamic pressure pulses have been identified as one of the primary causes of geomagnetically Induced currents (GICs) at the equator [e.g., 17].

The peak density of the HPS at 1 AU is typically a few tens of particles per cubic centimeter [e.g., 4,6]. Figure 1 shows the peak density distribution of HPS events derived from previously published results [4,6]. It is shown that most of the HPS peak density fall within ~30 cm$^{-3}$, with a mean (median) value of 18.7 (18.0) cm$^{-3}$, which is 3 – 4 times the average density of the solar wind [e.g., 18].
However, Figure 1 also shows that a density peak of ~50 cm\(^{-3}\) is also possible. A recent study [19] shows an HPS event with a peak density greater than 80 cm\(^{-3}\), suggesting a bimodal distribution for the HPS density peak. Note that a bimodal distribution may suggest two sources for HPS events observed at 1 AU. It was found that the extremely larger density HPS event is associated with an interplanetary shock and attributed it to the compression of the shock [19].

![Figure 1. Density distribution of the heliospheric plasma sheet (HPS) observed at ~1 AU. Events are adopted from previously published result [4,6].](image)

These previous work results raise a few important questions in studying HPS events at 1 AU. First, are high-density HPS events common at 1 AU? This is certainly important to the study of space weather, as high-density HPS events are expected to have a profound impact to space weather. Secondly, how often are high-density HPS events accompanied by an interplanetary shock? This is motivated by our previous study that suggests compression of interplanetary shocks may enhance the HPS density. Thirdly, is there a solar cycle dependence in the occurrence of large-density HPS events? This question is closely tied to the second question because most of IP (forward) shocks are observed in solar maximum years [e.g., 20]. Therefore, we expect a similar solar cycle variation in the occurrence of large-density HPS events at 1 AU. The main objective of this study is to attempt to answer these questions.

2. Data analysis

2.1 Data set and a case study

In situ solar wind plasma and field measurements from the Wind spacecraft are used to identify HPS events. The Wind spacecraft was launched in 1994 and has provided solar wind observations nearly continuously since then. We will use the Magnetic Field Investigation (MFI) [21] and Solar Wind Experiment (SWE) [22] acquired from 1995 to 2017 for the present study. This nearly continuous data set covers two solar cycles of a full solar magnetic cycle and is suitable for the purpose of the present study.

Identification of HPS events is performed visually. We survey daily solar wind plasma and magnetic field data plots and search for large-density (> 50 cm\(^{-3}\)) candidate events. These candidate events are further examined for their characteristics that fit the typical property of the HPS/HCS: slow solar wind flows, small magnetic field intensity, large plasma density and plasma beta, and reversal of the azimuthal magnetic field near the minimum magnetic field intensity. Figure 2 shows an example of the surveyed event on September 17, 2011. The start and stop of the HPS crossing is at 06:55 UT and
07:36 UT, respectively. The HCS can be identified at 07:21 UT when the minimum of the magnetic field intensity and the azimuthal magnetic field changes sign occurred (see Figure 1d). The peak density (~60 cm$^{-3}$) location took place at 07:15 UT, which did not coincide with the HCS, however. A forward fast-mode shock was recorded a few hours earlier at 2:57 UT. Given the typical Parker structure of the current sheet, a collision of the shock with the current sheet is likely to occur within 1 AU. Because the shock propagates faster than the solar wind, it must have entered the other side of the current sheet before it was observed by Wind. Therefore, the current sheet is in a compressed region downstream of the shock.

2.2 Statistical result

We have surveyed 22 years worth of the Wind plasma and field data from 1995 to 2017 using the guideline mentioned above and have identified 108 large-density HPS events. Figure 3 shows the density distribution of the large-density HPS events (blue). The density distribution shows a clear peak (~30%) at ~55 cm$^{-3}$, with an average density of 68.2 (s.t.d = 19.8) cm$^{-3}$ and a median density of 61.6 cm$^{-3}$. We have also looked for IP shocks in association with these HPS events, e.g., shocks that occurred within one day of the density peak. We found 80 (~74%) of these HPS events are associated with an interplanetary shock. The density distribution for shock-associated HPS events (red) shows a small shift toward high density from the whole events, with the average density of 69.4 (s.t.d. = 20.8) cm$^{-3}$ and the median density of 63.1 cm$^{-3}$. A clear peak at 55 cm$^{-3}$ found in the density distribution suggests that this is a different type (or source) of HPS from those shown in Figure 1 with a peak around 10 cm$^{-3}$.

![Figure 2. In situ measurements of solar wind parameters by the Wind spacecraft that show an example of HPS event associated with an interplanetary shock on September 17, 2011: (a) solar wind plasma beta ($\beta = n k T / \mu B^2$, where $T$ is solar wind temperature and $B$ is the magnetic field intensity), magnetic field (b) intensity in nT, (c) polar angle ($\theta_B$, degree), (d) azimuthal angle ($\phi_B$, degree), (e) proton thermal speed ($V_{th}$, km/s), (f) solar wind speed ($V$, km/s), and (g) proton density ($N_p$, cm$^{-3}$). The vertical lines mark the arrival time of the shock (02:56 UT), the start of the HPS (06:55), density peak (07:15 UT), HCS (07:21 UT), and the stop of the HPS (07:36 UT), respectively. Values of each parameter at the vertical lines are provided next to the vertical lines.](image)
Figure 3. Density distribution of large-density HPS events (blue) and of those associated with IP shocks (red). The bin size is 5 cm$^{-3}$.

Figure 4 shows the yearly histogram of the large-density HPS events (blue color). A strong solar cycle dependence is found. The minimum occurrence rate took place during solar minimum years (1996-1997 for SC 23 and 2007-2008 for SC 24), whereas the maximum occurrence rate took place in solar maximum years (2001 for SC 23 and 2014 for SC 24). There are a few occurrence peaks at 2005, 2007, and 2011 that do not fall into the solar active years, however. Furthermore, there are more events observed in SC 23 than in SC 24. This is consistent with the more active Sun in SC 23 than in SC 24. The histogram for shock-associated high-density HPS events is also shown in Figure 4 (red). This result clearly suggests that large-density HPS events are closely associated with IP shocks.

3. Discussion

Solar wind pressure pulses are one of the key parameters that have profound impacts on the near-Earth space weather [e.g., 11,12,13,14,15,16] and the HPS is one of the important sources of pressure pulses. We have performed a survey of ~22 years worth of solar wind plasma and field data from Wind and identified a total of 108 large-density HPS events with a peak density greater than 50 cm$^{-3}$. Assuming an average number of HCS crossing ~4 per solar rotation or ~50 per year, the present result suggests an average of ~10% for the yearly occurrence of these large-density HPS events. The occurrence rate...
can be much larger (~30%) during solar maximum years and much smaller (zero) during solar minimum years. Although these occurrence rates are relatively small, because of their very large density these HPS events are expected to induce large geomagnetic activity [e.g., 18] and increase exposure of geosynchronous satellites in solar wind.

We have also explored a possible association of the large-density HPS events with interplanetary shocks. It is found that 80 (74%) of these large-density HPS events are accompanied by an interplanetary shock. While a detailed examination of these IP shocks’ property is not yet completed, it is reasonable to suspect that they may play a role in the enhanced HPS density. We found that the majority (68 or 85%) of the shock-associated events were seen to occur earlier than the HPS events did. This means that the majority of the HPS events were observed downstream of the shock. Therefore, it is reasonable to suspect that compression of the IP shocks may play a key role, perhaps an important one, to the existence of large-density HPS at 1 AU. Of course, we cannot rule out the possibility that these large-density HPS events originate from their sources in the corona.

Assuming that the previously reported HPS events are mostly not associated with interplanetary shocks, a rough estimate of the shock compression effect can be done by multiplying the average compression ratio with the average peak HPS density of these events. The average compression of the present 68 events is 2.7. Multiplying it by the average HPS peak density 18.7 cm$^{-3}$, it yields 50.5 cm$^{-3}$, which is close to the observed 55 cm$^{-3}$ shown in Figure 3. Note that this simplified analysis result may not be conclusive because our assumption may not be valid. The HPS events collected from Winterhalter et al. [4] were based on ISEE 3 measurements taken during the ascending years (1978 and 1979) of solar cycle 22. It is possible that some of their HPS events were accompanied with shocks but were not reported. We will extend our survey of HPS events to include HPS events with density smaller than 50 cm$^{-3}$ in the near future to provide a conclusive result.

The close association of the large-density HPS events shown in the present study clearly suggests a solar cycle effect on their occurrence. Interplanetary shocks observed at 1 AU are driven mainly by coronal mass ejections, which occur predominantly during solar maximum years. Indeed, most of the forward IP shocks are observed in solar maximum years (e.g., 19). It is expected that large-density HPS events can contribute to intense geomagnetic activity during solar maximum. However, whether or not their contribution is significant remains dependent upon more studies. A study has been planned to correlate all HPS events with geomagnetic activity.

4. Conclusions
The present analysis of 108 large-density (>50 cm$^{-3}$) HPS events that were identified from the Wind data acquired from 1995 to 2017 has revealed two possible types of HPS events when combining some previously reported HPS events. Based on the present study result, there is high association between the occurrence of large-density HPS events and IP shocks at ~1 AU. We suspected that interactions of the HPS with IP shocks may be the source of those large-density HPS events. Further studies are required to understand the interactions.

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