The Solar Wind Parker Spiral Angle Distributions and Variations at 1 au

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Abstract

Using the data from the Advanced Composition Explorer (ACE) and Wind spacecraft, we statistically studied the Parker spiral angle (PSA) of the solar wind magnetic field from 1998 to 2019 at 1 au. The PSA occurrences over both a Carrington rotation (CR) and a year can be well fitted by a Gaussian distribution. However, large-scale magnetic structures, such as interplanetary coronal mass ejections (ICMEs), can significantly deviate the PSA distribution of a CR from the Gaussian distribution. The PSA distributions of each CR and each year are affected by the solar activity: They are more concentrated at a relatively higher average PSA at solar maximum. There is also a weak anticorrelation between the yearly solar wind speed (vsw) and the average PSA. MESSENGER, Venus Express, and ACE observations at different heliocentric distances within 1 au show that the dominating polarities of the heliospheric magnetic field change greatly from year to year even when the solar activity is on the same level. Our results suggest that the PSA distribution in addition to the sunspot number can provide some new information on the magnetic field variation of the Sun.

Unified Astronomy Thesaurus concepts: Solar activity (1475); Solar wind (1534); Sunspots (1653); Solar magnetic fields (1503)

1. Introduction

Because it is frozen in the plasma flow, the large-scale solar wind magnetic field tends to lie along the direction of the Parker spiral (Parker 1958). It is assumed that beyond a critical distance, the solar wind flow speed becomes constant without affecting both solar gravitation and high coronal temperature. In fact, the solar wind speed decreases with distance due to the pickup ion effect, and the variation of the speed is affected by the solar activity (Richardson et al. 2001). Parker’s theory has been roughly confirmed by many previous observations from 0.29 to 8.5 au (e.g., Behannon 1978; Thomas & Smith 1980; Forsyth et al. 1996; Korth et al. 2011).

Based on the Parker spiral equation, the Parker spiral angle (PSA), defined as the azimuthal angle of the solar wind magnetic field, increases with the heliocentric distance. Slavin & Holzer (1981) simply calculated the average PSAs at different heliocentric distances when the solar wind speed is assumed to be 430 km s−1: approximately 25° at Mercury (0.47 au), 36° at Venus (0.72 au), 45° at Earth (1 au), and 57° at Mars (1.52 au). The PSA is expected to be 45° near Earth based on Parker’s theory, but the PSA varies with time in observations. The average PSA observed from 1965 to 1973 is very close to 45° and the average value of the PSA remains within 1° or 2° of 45° (Svalgaard & Wilcox 1974). The solar wind magnetic field orientations observed by Pioneer 10 and 11 at 1 au conform on average to the predicted PSA (45°) to an accuracy of approximately 1° (Thomas & Smith 1980). Smith & Bieber (1991) reported that the average PSA observed by OMNI of the two sectors is 44°±4° at 1 au in 1980. Gruessbeck et al. (2017) also reported that the PSAs spanning three solar cycles observed between 1 and 5 au from Juno, Voyager, and Ulysses are consistent with Parker’s prediction. But the long-term variation of the PSA at 1 au has not been reported.

Solar activities vary systematically with the solar cycle and the effect of the solar cycle on the PSA at 1 au has been discussed. The included angle (δ) is the angle between the two average opposite directions of the solar wind magnetic field and is 180° in theory. Svalgaard & Wilcox (1974) reported that the included angle is about 168° at 1 au and appears to have a solar-cycle-dependent trend. King (1976) compared the included angles from 1963 to 1974 with the angles reported by Svalgaard & Wilcox (1974) and confirmed the solar cycle variation of δ. Smith & Bieber (1991) also found a strong dependence of the PSA on the solar cycle, and they believed that much of the PSA variation comes from the solar wind speed variation with the solar cycle. However, Thomas & Smith (1980) displayed the included angle between 0.5 and 8.5 au and concluded that there is no clear solar cycle dependence. Using observations from multiple satellites, Borovsky (2010) statistically surveyed the effect of the solar cycle, solar wind speed, and heliocentric distance on the Parker spiral direction variation. They focus on the distribution of the Gaussian Parker spiral population: The angular width of the Gaussian Parker spiral population increases with increasing solar wind speed and increasing heliocentric distance, and the isotropic fraction increases with decreasing solar wind speed and increasing heliocentric distance, but the PSA shows no clear solar cycle dependence. However, they did not discuss the average PSA over the timescale of a Carrington rotation (CR)

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and the long-term PSA variation at 1 au. Besides, the characteristics and variations of the PSA distributions have not been studied. As the solar wind magnetic field lines are distorted into a spiral configuration due to the Sun’s rotation, and the solar rotation occurs once every CR, the PSA distribution of a CR can basically represent the whole picture of the solar wind magnetic field. The PSA variations from CR to CR can reflect the short-term change in the Sun’s magnetic field.

Observationally, the PSA is defined by the angle between \( B_r \) (pointing to the Sun) and \( B_t \) (pointing to the opposite direction of the planet’s motion around the Sun) of the heliospheric magnetic field (HMF; Luhmann et al. 1993; Masunaga et al. 2013; Chang et al. 2019). Based on a Gaussian fitting, the two positions of the peaks (\( b_1 \) and \( b_2 \)) in each PSA distribution represent the two opposite HMF polarities (Chang et al. 2019): positive (away from the Sun) and negative (toward the Sun). The HMF polarity proportion varies significantly with time, and a similar variation can be observed by different spacecraft at different heliocentric distances within 1 au, suggesting that the variation of the HMF polarity dominance is not a propagation effect.

The PSA distribution (including the polarity distribution) can be an important parameter besides the sunspot number (SSN) for studying the magnetic field variation of the Sun. It can reveal some important characteristics of the Sun’s magnetic field. Because the solar wind magnetic field orientation is highly variable, the statistically average PSA over a relatively long timescale needs to be obtained. In this work, we statistically study the PSA distribution, including the average PSA, the standard deviation (\( c \)), and the polarity distribution over a CR and a year at 1 au from 1998 to 2019 to investigate the long-term variation of the HMF. Because the inner HMF observations can generally be linked to the coronal sources (Balogh & Erdős 2013), the PSA distribution could also be a useful tool to study the Sun’s magnetic field.

### 2. Data and Instrumentation

The Advanced Composition Explorer (ACE) mission was launched on 1997 August 25 and is stationed around the Sun–Earth Lagrange point 1 (L1; Stone et al. 1998). The data used in this study are mainly from the magnetometers (MAG) on board ACE (Smith et al. 1998; Stone et al. 1998) with a resolution of 16 s from January 1998 to December 2019. This time interval contains 294 CRs: CR 1932 to CR 2225 http://umtof.umd.edu/pm/crm/). To investigate the interplanetary coronal mass ejection (ICME) input and the relationship between the PSA and the solar wind speed, the 1 hr resolution plasma data measured by the Solar Wind Electron Proton Alpha Monitor (SWEPAM) on board ACE are also used.

The Wind spacecraft was launched on 1994 November 1 (Ogilvie & Desch 1997). It has been also positioned at the L1 point since 2004 (Wood et al. 2015). To compare the PSA distribution in different time resolutions of the magnetic field at 1 au, the 3 s resolution magnetic field data measured by Wind (Lepping et al. 1995; Ogilvie & Desch 1997) in 2008 are also investigated. In addition, the magnetic field data from MESSENGER (Anderson et al. 2007; Solomon et al. 2007) and Venus Express (VEX; Svedhem et al. 2007; Zhang et al. 2007) are surveyed to confirm the HMF polarity dominance phenomenon is not a propagation effect. The magnetic field resolutions are 60 s and 1 s from MESSENGER and VEX, respectively.

The Geocentric solar ecliptic (GSE) coordinate system is used throughout this study unless indicated otherwise. In GSE coordinates, the origin is Earth. The X-axis points from Earth to the Sun. The Y-axis points to the opposite direction of Earth’s orbital velocity vector, and the Z-axis is perpendicular to the X–Y plane, forming a right-handed system.

### 3. Observation

To learn the long-term variation of the solar wind magnetic field configuration, we investigated the PSA distributions of the solar wind magnetic field at 1 au using ACE and Wind measurements. These observations span most of Solar Cycle 23 and the entire Cycle 24. As mentioned above, the PSA is defined as the azimuthal angle of the HMF, ranging from 0° to 360°. The PSA is 0° in the radial direction (\( B_r < 0 \) and \( B_t = 0 \)) and increases in a clockwise direction. Similar to the previous study (Chang et al. 2019), we fit the PSA distribution by the Gaussian function:

\[
y = a \cdot e^{-\frac{(y - y_c)^2}{2\sigma^2}},
\]

where \( x \) is the PSA, \( y \) is the occurrence, \( a \) is the peak of the fitting curve, \( b \) is the corresponding position of the peak and \( c \) is the standard deviation. For a double-Gaussian PSA distribution, we obtained two positions of the peaks: \( b_1 \) and \( b_2 \). The average PSA (\( \phi \)) is defined as follows:

\[
\phi = \frac{(|b_1| + |180° - b_2|)}{2}.
\]

#### 3.1. Features of the Parker Spiral Angle at 1 au

Figure 1 displays two examples of the PSA distributions measured by ACE and Wind for CR 2072 (2008 July 6–2008 August 3) and the year 2008. Each distribution contains two parts: an isotropic distribution in all pitch angles and a double-Gaussian distribution with peaks at the average PSAs representing the average magnetic field directions toward and away from the Sun. The histogram is in good accordance with the normal double-Gaussian distribution. All four panels in Figure 1 include two independent Gaussian fits, which are marked by red and magenta curves. Note that here the horizontal axis ranges of the two curves are not 0°–180° and 180°–360°; many earlier studies verified that the PSA at 1 au is around 45°. We choose these two horizontal axis ranges to fit the Gaussian curves: 140°–320° and 320°–360°/0°–140°. From each Gaussian fitting, we can obtain the position of the peaks: \( b_1 \) or \( b_2 \). Generally, \( b_1 \) lies between 0° and 90°, representing the average direction of the HMF away from the Sun. In contrast, \( b_2 \) lies between 180° and 270°, representing the average direction of the HMF toward the Sun. In general, the curve of the annual distribution should be much smoother than that of the distribution in each CR because of the data volume. According to Equation (2), the average PSAs observed by ACE are 44°61 for CR 2072 and 42°45 for 2008. Similarly, the average PSA measured by Wind was calculated to be 47°73 for CR 2072 and 45°23 for 2008. The observations of ACE and Wind as shown in Figure 1 are quite similar. Compared to the average PSA observed by Wind, the angles measured by ACE are smaller by 6.99% for CR 2072 and 6.15% for the year.
Figure 1. The examples of PSA distributions for a CR and a year by ACE and Wind. (a)–(b) The PSA distributions observed by ACE during CR 2072 and the year 2008, respectively. (c)–(d) The PSA distributions observed by Wind during CR 2072 and the year 2008, respectively.

Figure 2. The solar wind measurements of CR 2106 (2011 January 20–2011 February 16). (a) The histogram of the PSA occurrence. (b) Solar wind magnetic field strength (\(|B|\)). (c) The three components of the magnetic vector in GSE coordinates. (d)–(e) The azimuthal and latitudinal angles of the magnetic field in GSE coordinates, respectively. (f) The solar wind speed. (g) Proton temperature.

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The differences between the ACE and Wind measurements at 1 au are relatively small for both a CR and a year, consistent with the previous result by Chang et al. (2019). Therefore, only ACE measurements are used in this work.

It should be pointed out that the PSA distribution used for Gaussian fitting contains the isotropic portion (Borovsky 2010). However, the exact contribution of the isotropic PSA is hard to determine. Besides, the Gaussian fitting results of ACE after subtracting 1% and 1.2% for the year 2008 are about 41°55 and 41°50, which are very close to those of isotropic PSA contribution (42°45). Therefore, all the Gaussian fitting results are based on the PSA distributions without.

Using ACE observations, we surveyed all the PSA distributions from 1998 January to 2019 December for each year and each CR. However, for some CRs, the PSA distributions remarkably deviate from the normal Gaussian distribution.

The large-scale magnetic structures in the solar wind, such as ICMEs, sometimes have a vital impact on the short-term PSA distribution. Figure 2 shows a greatly deviated PSA distribution for CR 2106. Unlike the normal double-Gaussian distribution in Figure 1, the PSA occurrence during CR 2106 in Figure 2(a) obviously deviates from the double-Gaussian distribution. Therefore, in this case, the derived parameters from the Gaussian fit are meaningless. Figures 2(b) to (g) display the magnetic field and selected plasma measurements for CR 2106 from January 20 to February 16 in 2011. During this period, there are two ICMEs according to the ICME list by Richardson and Cane (Richardson & Cane 2010): January 24, 07:00 am–January 25, 12:00 am (ICME event 1) and February 4, 1:00 pm–February 4, 8:00 pm (ICME event 2). Actually, in Figure 2(d), the azimuthal angle variation shows a large-scale smooth rotation of the HMF direction during the period marked by the two magenta vertical dashed lines marked from about 2011 January 24 to February 1. It possibly represents a much larger-scale magnetic structure, which needs further investigation in the future. This could be one of the reasons why the PSA distribution is abnormal.

Figure 3. The variation of $b$, $c$, and the average PSA during each CR at 1 au with the monthly SSN. (a)–(d) $b_1$, $b_2$, $c_1$, and $c_2$ of a CR, respectively. (e) The average PSA of CRs. The removed CRs are marked by the black pentagrams on the bottom. (f) The monthly SSN.
Overview of the Average $b$, $c$, and PSA of a CR and Monthly SSN during Solar Minimum and Solar Maximum

| Period   | Solar Minimum | Solar Maximum |
|----------|---------------|---------------|
|          |                |               |
| 2006–2009 | 11.54         | 5.30          |
| 2018–2019 | 10.69         | 5.07          |
| 1999–2002 | 9.74          | 4.97          |
| 2012–2014 | 9.24          | 4.48          |

**Notes.**
- Potgieter et al. (2015).
- Girizian et al. (2021).
- Zhang et al. (2010).
- Chang et al. (2018).

### 3.2. Parker Spiral Angle Variation at 1 au

Based on the good double-Gaussian distributions selected manually, we can calculate the average PSAs. Figure 3 shows the fitted $b$, $c$ and the average PSA during each CR at 1 au with the monthly SSN. Solar minimums and solar maximums are marked by the dashed green lines. The corresponding average values of CRs are displayed in detail in Table 1. Here $a1$ and $a2$ show no obvious trend. Figures 3(a) and (b) display all the $b1$ and $b2$ of each CR, respectively. When the PSA distribution remarkably deviates from the normal Gaussian, which is like the distribution in Figure 2(a), the corresponding $b1$, $b2$, $c1$, and $c2$ are removed. However, we still show the temporal distribution of those CRs with non-Gaussian PSA distributions by black pentagrams in Figure 3(e). We can see that the removed CRs, which are identified manually, are distributed relatively homogeneously with time. In addition, because the number of the removed CRs is small, our statistical results would not be altered by them. Figure 3(f) shows the monthly mean total SSN. Here the monthly mean total SSN is a simple arithmetic mean of the daily total SSN over all days of each month. In the bottom panel, the SSNs are marked by the blue bars and vary from 0 in 2009 August to 244.3 in 2000 July. The SSN clearly displays that the time interval for statistics spans most of Solar Cycle 23 and the whole of Solar Cycle 24, which provides us with long-term HMF observations at 1 au. Figures 3(c) and (d) together with Table 1 show that $c$ is smaller at solar minimum than at solar maximum. This suggests that the PSA distribution is more concentrated at solar maximum. From Figure 3(e), we can see that most of the average PSAs significantly deviate from $45^\circ$ and vary much during different CRs. The mean value of all the average PSAs is calculated to be $46.5^\circ$. We can also find that most of the average PSAs during solar maximum are larger than $45^\circ$. By contrast, the average PSAs during solar minimum are relatively evenly distributed around $45^\circ$. The average PSAs of CRs during solar maximum (49.76°/50.22°) are larger than those during solar minimum (47.45°/45.26°). One of the possible reasons could be that the solar wind speed plays a role in the PSA. The average solar wind speed observed by ACE is $469.23$ km s$^{-1}$ during the solar minimum (2008–2009) and $417.17$ km s$^{-1}$ during the solar maximum (2012–2014) of Solar Cycle 24. According to the Parker Spiral theory, when the solar wind speed is higher, the PSA is smaller (Borovsky 2010). However, the solar wind speed difference is small. The corresponding average PSA difference is about $3^\circ.49$ according to the empirical model suggested by Borovsky (2010). Another reason could be that there are more rope-like structures during the solar maximum, which can increase the observed average PSA because the PSAs are near 90° or 270° in the leading and trailing portions of the rope-like structure. Therefore, the average PSA of each CR is dependent on solar activity.

Unlike the PSA distribution of each CR, all the yearly PSA occurrence appears in good agreement with a double-Gaussian distribution. Figure 4 displays the yearly $b1$, $b2$, $c1$, $c2$, and $\phi$ with the yearly mean total SSN. The fitted results of all 22 yr are displayed in Table 2. Here the yearly mean total SSN is an average value of the daily total SSN over all days of each year. Besides, the solar wind speed may be one of the important factors that are correlated to $\phi$, so we also display the yearly solar wind speed in 4(f). In Figure 4, the $b1$, $b2$, $\phi$, and the solar wind speed of all 22 yr vary significantly during different years. The average value of the PSA is $46.1^\circ$. Although the yearly average PSAs vary with time, most of them remain around $45^\circ$. This is caused by the relatively stationary distance from the Sun and is consistent with the result of many studies (e.g., Svalgaard & Wilcox 1974; Chang et al. 2019). The yearly average PSAs vary from 40°.62 in 2017 and 53°.04 in 2012, suggesting that the yearly average PSA can also be affected by solar activity. Compared to the large variation of the average CR PSA in Figure 3(e), the variation of the yearly average PSA is smaller. But similar to the average PSAs of CRs, the yearly average PSAs during solar maximum (48°.95/50°.12) are much larger than those during solar minimum (45°.57/42°.36). On average, the solar wind flow is faster at solar minimum than at solar maximum, and the average solar wind speed is 453.45 km s$^{-1}$ and varies from 409.66 km s$^{-1}$ in 2012 to 548.79 km s$^{-1}$ in 2003, which is consistent with earlier studies (King 1976; Richardson et al. 2001). From Figures 4(e) and (f), the average PSA appears smaller when the speed is higher most of the time. Table 2 also lists the average solar wind speeds during both solar minimum and maximum: The average PSAs are smaller when the speeds are higher except during 2018–2019. During these 22 yr, the correlation coefficient of the yearly solar wind speed and the yearly average PSA is −0.63, which indicates a weak anticorrelation. In addition, the yearly $c1$ (55.11/55.60) and $c2$ (56.50/51.46) are also relatively higher at solar minimum than $c1$ (42.50/44.06) and $c2$ (44.86/48.19) at solar minimum. It can be concluded that the average PSA is higher and the PSA distribution is more concentrated at solar maximum.

### 3.3. HMF Polarity Variation

As mentioned above, the HMF polarity can link to the coronal sources and reveal the characteristics of the Sun’s magnetic field. Using the MAG data measured by MESSENGER, VEX, and ACE, the PSA distributions at different heliocentric distances are presented. Similar to the GSE coordinate system at Earth, the Mercury-centered solar orbital (MSO) coordinate system is used in MESSENGER measurements and the Venus solar orbital (VSO) coordinate system is used in VEX measurements. In these coordinates, the X-axis
points from the planet to the Sun, the $Y$-axis is defined to be antiparallel to the direction of planet orbital motion, and the $Z$-axis is normal to the $X$–$Y$ plane, forming a right-handed system.

Because we focus on the solar wind magnetic field, the MESSENGER and VEX data measured in the magnetosphere or induced magnetosphere have been removed. The heliocentric distance of MESSENGER varies greatly from 0.31 to 0.47 au, which may result in diffusion in the PSA distribution. There, we only use the MESSENGER data from 0.31 to 0.39 au. The VEX mission ended in 2014 December. The MAG data of VEX and MESSENGER we used in this section are from 2012 January to 2014 November at the maximum phase of Solar Cycle 24. Figure 5 displays the PSA distributions during 2012–2014 of the MESSENGER (about 0.35 au), VEX (0.72 au), and ACE (1 au) observations, respectively. All nine subgraphs are in good accord with a double-Gaussian distribution. As mentioned above, there are two average PSAs of the two fitting curves for each year; the corresponding positions of the two PSA occurrence peaks are $b_1$ (in magenta) and $b_2$ (in red) as shown in Figure 5. The fitted $b_1$ and $b_2$ correspond to positive and negative HMF polarity, respectively. In Figure 5, during this same period, the distributions of the HMF polarity observations at 0.35 au, 0.72 au, and 1 au are quite similar. This suggests that the large-scale HMF polarity distributions at different heliocentric distances are consistent and thus are not a propagation effect. In 2012, as shown in Figures 5(a), (d), and (g), the dominating HMF polarity is negative as marked by the red curves. However, Figures 5(c), (f), and (i) show that the HMFs are dominated by positive polarity as marked by the magenta curves in 2014. Unlike in 2012 and 2014, the HMF polarity in 2013 shows no clear dominance. The years 2012, 2013, and 2014 were all in the solar maximum of Solar Cycle 24. However, the dominating polarities of the HMF change greatly.

Figure 4. The variation of the yearly $b$, $c$, PSA, and solar wind speed at 1 au with the yearly SSN. (a)–(d) $b_1$, $b_2$, $c_1$, and $c_2$ of each year, respectively. (e) The yearly PSA. (f) The yearly solar wind speed. (g) The yearly SSN.
from year to year. Because the HMF observed near Earth is the extension of magnetic fields of the Sun near the equator, the HMF polarity dominance, especially its variation, as revealed by the PSA distribution can basically reflect the Sun’s magnetic field near the equator. Here, we use the total occurrence of the PSAs from 140° to 320° (negative polarity, $P^-$) to represent the HMF polarity dominance in the ecliptic plane. The total occurrence of PSAs from 320°–360°/0°–140° (positive polarity, $P^+$) is therefore $1 - P^-$. If the $P^-$ of a certain period is significantly greater than 0.5, the negative HMF dominates; if $P^-$ is significantly less than 0.5, the positive HMF dominates. If $P^-$ is near 0.5, no HMF polarity dominates. This suggests that the Sun’s magnetic fields during these years are very different in polarity. Therefore, the PSA distribution can potentially be used as an indicating parameter of the Sun’s magnetic fields.

We also surveyed the long-term variation of the HMF polarity at 1 au. Figures 6(a) and (d) show the occurrence of the northward magnetic field ($B_z > 0$), the occurrence of $B_z$ ($P(B_z > 0)$) does not vary much with time and performs no clear role. We further statistically surveyed $P^-$ by ACE observations from 1998 to 2019. During the solar minimum of Solar Cycles 23 and 24, the SSN changes a little and solar activity is always weak, but the HMF polarity varies significantly. Both the HMF polarities of a year and a CR vary significantly even when the solar activity is on the same level. The HMF polarity variation appears random but has no significant solar cycle dependence.

In comparison with the variation of $P(B_z > 0)$, $P^-$ varies significantly as displayed in Figures 6(b) and (e). The $P^-$ variation over CRs is even greater at solar minimum, although the SSN changes a little and solar activity remains at a very low level. The $P^-$ variation dependence on the SSN is very low for both CR and year timescales. However, why the PSA polarity is not distributed evenly around 0.5 and why it undergoes great variation remains an open question. The distribution of PSAs can be used as an indicating parameter of the Sun’s magnetic field.

### Table 2

| Period            | Solar Minimum | Solar Maximum |
|-------------------|---------------|---------------|
|                   | 2006–2009$^a$ | 2018–2019$^d$ | 1999–2002$^c$ | 2012–2014$^a$ |
| SSN               | 11.58         | 5.30          | 161.05        | 97.27         |
| $a_1$             | 0.040         | 0.035         | 0.052         | 0.046         |
| $a_2$             | 0.041         | 0.048         | 0.042         | 0.045         |
| $b_1$ (°)         | 47.71         | 40.82         | 49.72         | 52.90         |
| $b_2$ (°)         | 223.42        | 223.91        | 228.18        | 227.35        |
| $c_1$             | 55.11         | 55.60         | 42.50         | 44.06         |
| $c_2$             | 56.50         | 51.46         | 44.86         | 48.19         |
| PSA (°)           | 45.57         | 42.36         | 48.95         | 50.12         |
| $v_{sw}$ (km/s)   | 469.34        | 423.84        | 450.60        | 417.17        |

**Notes:**

- $^a$ Potgieter et al. (2015).
- $^b$ Girazian et al. (2021).
- $^c$ Zhang et al. (2010).
- $^d$ Chang et al. (2018).
4. Discussion and Conclusions

In this paper, we statistically surveyed ACE measurements of the PSA distributions at 1 au from 1998 to 2019 (22 yr/294 CRs). The Gaussian fitting results are based on the PSA distributions without excluding the isotropic contributions (Borovsky 2010). All 22 yearly PSA distributions fit well with a double-Gaussian distribution. However, some PSA distributions of a CR remarkably deviate from a normal Gaussian distribution. Some large-scale magnetic structures, such as ICMEs, probably play an important role in this discordance.

The average PSAs during different CRs and different years at 1 au vary significantly and can be affected by solar activity: they are relatively higher at solar maximum. Statistically, most of the average PSAs during solar maximum are much larger than 45° but evenly distributed around 45° during solar minimum. The standard deviation (c) of the PSA distribution is smaller at solar maximum and thus the PSA distribution is more concentrated when solar activity is strong. Our result shows that there is a weak anticorrelation with a correlation coefficient of −0.63 between the yearly solar wind speed and the average PSA, suggesting that the average PSA can be affected by the solar wind speed. This is compatible with Parker’s theory. However, the contribution of the solar wind speed difference to the average PSA variation is not enough. We believe that the higher occurrence of rope-like magnetic structures at solar maximum could be another reason.

We also investigated the yearly PSA distributions at three different heliocentric distances (about 0.35, 0.72, and 1 au). All these three spacecraft observed similar HMF polarity variations within 1 au during the solar maximum of Solar Cycle 24. It can be confirmed that the HMF polarity dominance phenomenon is not a propagation effect. We found that the HMF polarity dominance changes greatly from CR to CR and year to year even when the solar activity is on the same level. The HMF polarity dominance variation appears no significant solar cycle dependence.

From the point of view of Earth, the Sun rotates once every CR. The PSA distribution of a CR by ACE at L1 can basically represent the whole picture of the HMF in the ecliptic plane. The two Gaussian distributions of each PSA distribution represent the directional distribution of the positive HMF (away from the Sun) near 45° and the directional distribution of the negative HMF (toward the Sun) near 225°. Therefore, the HMF polarity dominance, representing the relative possibility for observing the different average PSAs at 1 au, can reveal the occupation of the Sun’s two hemispheric magnetic fields near the equatorial region because the heliospheric current sheet (HCS) is the extension of the magnetic neutral curve ($B \approx 0$) on the source surface. At solar maximum, the magnetic field on the Sun seems randomly distributed. As a result, the HMF polarity observed near Earth should not dominate. However, the HMF polarity shows different dominances in different years (2012–2014) at the solar maximum of Cycle 23 as displayed in Figure 5. Multiple-spacecraft observations of the same HMF polarity dominance situations at different heliocentric distances confirm that this is not a propagational effect of the solar wind.

But, as Figure 5 illustrates, the HMF polarity at the solar maximum of Cycle 23 shows no significant dominance. Therefore, our results suggest that the PSA distribution, including the fitted parameters of the double-Gaussian distribution and the HMF polarity dominance, in addition to the SSN, can reveal some important characteristics and provide some new information about the magnetic field variation of the Sun. Further analysis of the PSA polarity variation over more solar cycles will be carried out in the near future.

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