Latitudinal Dependence of Coronal Hole-Associated Fast Solar Wind

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Abstract. The fast solar wind can have at least two different coronal sources: high-latitude, polar coronal holes (PCH) and low-latitude, equatorial coronal holes (ECH). The in-situ differences in the PCH and ECH winds have not been well studied, nor have the differences in their evolution over the solar cycles. Ulysses’ 19 years of observations from 1990 to 2009, combined with ACE observations from 1998 to the present, provide us with measurements of solar wind properties that span two entire solar cycles, which allow us to study the in-situ properties and evolution of the coronal hole-associated solar wind at different latitudes. In this work, we focus on the PCH and ECH solar winds during the minima between solar cycles 22–23 and 23–24. We use data from SWICS, SWOOPS, and VHM/FGM on board Ulysses, and SWICS, SWEPAM, and MAG on board ACE to analyze the proton dynamics, heavy ion composition, elemental abundance, and magnetic field properties of the PCH wind and ECH wind, with a special focus on their differences during the recent two solar minima. We also include the slow and hot, streamer-associated (ST) wind as a reference in the comparison. The comparison of PCH and ECH wind shows that: 1) the in-situ properties of ECH and PCH winds are significantly different during the two solar minima, and 2) the two types of coronal hole-associated solar wind respond differently to changes in solar activity strength from cycle 23 to cycle 24.

1. Introduction

The solar wind plays a fundamental role in shaping the heliosphere and governing the interactions in the near-Earth space environment, and it ultimately drives the conditions in the region of interplanetary space. Generally, after interplanetary coronal mass ejections (ICMEs) are excluded, the solar wind can be categorized as two main types (Zhao et al. 2009): cold and fast streams from coronal holes (CH, characterized by low X-ray and EUV emissions due to their lower density and coronal electron temperature compared to the surrounding corona (Wilhelm & Bodmer 1998; Karachik et al. 2010)), and hot and slow streams from heliospheric current sheet (HCS) associated streamer regions (ST, where the plasma is denser and the coronal electron temperature is higher than CHs (Zhao & Fisk 2011)). The CH wind can be further divided into two sub-groups based on the different latitudes of their source regions in the corona: wind from equatorial coronal holes (ECH, coming from CHs regions at heliographic latitudes within \( \pm 20^\circ \)) and wind from polar holes (PCH, coming from CH regions at heliographic latitudes above \( 70^\circ \) in the two hemispheres (von Steiger & Zurbuchen 2011)).

So far, no systematic study has ever been carried out to determine whether these two types of CH-associated fast wind are different, and whether they respond to the
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solar cycle in the same way. In particular, it is important to understand whether the anomalous minimum between solar cycles 23 and 24 affected these two types of fast wind in the same way.

In this paper we compare the characteristic of the PCH and ECH winds, by studying their in-situ properties and their time evolution along two successive solar minima. This paper is organized as follows: in section 2, we will introduce the criteria by which we identify the ST, ECH, and PCH wind; in section 3, we compare the PCH and ECH winds based on in-situ observations of Ulysses and Advanced Composition Explorer (ACE) spacecraft, and we also show the observations of ST wind as a reference in this comparison; we discuss our results and give conclusions in section 4.

2. Identification of PCH and ECH Wind

In this study, we use data from SWICS (Solar Wind Ion Composition Spectrometer), SWOOPS (Solar Wind Observations over the Poles of the Sun), and VHM/FGM (Vector Helium Magnetometer & Fluxgate Magnetometer) on board Ulysses (Bame et al. 1992; Gloeckler et al. 1992; Balogh et al. 1992), and SWICS, SWEPAM (Solar Wind Electron, Proton, and Alpha Monitor), and MAG (Magnetic Field Experiment) on board ACE (Gloeckler et al. 1998; McComas et al. 1998; Smith et al. 1998) to analyze the dynamics, composition, and magnetic field properties of the ST, PCH and ECH winds, with special emphasis on the PCH and ECH winds and their differences during the solar minima between cycles 22–23 and between cycles 23–24.

2.1. Criterion to Differentiate CH and ST Winds

The non-transient solar wind contains at least two components: ST wind and CH wind. ST and CH winds can be differentiated not only by their proton speeds, but also by their very different compositional properties (von Steiger et al. 2001; Zurbuchen et al. 2002; Zhao et al. 2009; Landi et al. 2012a). von Steiger et al. (2010) used Ulysses observations to introduce a new parameter, \( P = (O^{7+}/O^{6+}) \times (C^{6+}/C^{5+}) \), which can discriminate between these two solar wind types. They found that the solar wind observed by Ulysses could be easily and effectively separated into CH (fast) and ST (slow) components by adopting a threshold value of \( P = 0.01 \): ST wind is defined as the wind where \( P > 0.01 \), and CH wind is the wind where \( P < 0.01 \). Interestingly, the proton speed distributions of the CH and ST winds identified by this criterion are well separated at 600 km/s (See Figure 2a in von Steiger et al. (2010)), which suggests that \( P = 0.01 \) is a convincing criterion that we can use to identify the fast, CH-associated wind and slow, ST-associated wind observed by Ulysses.

However, equatorial ACE observations tell a slightly different story. We apply the criterion of \( P = 0.01 \) to ACE data during the solar minimum (2006–2010) between solar cycle 23 and 24, and find that the proton speed distributions of CH wind (\( P < 0.01 \)) and ST wind (\( P > 0.01 \)) significantly overlap in the range of 400 ~ 600 km/s (Figure 1a). Interestingly, if we plot the distributions of solar wind with proton speed (\( V_p \)) less than 400 km/s (in red) and the wind with \( V_p \) greater than 600 km/s (in blue) versus the logarithm of \( P \) in the bottom of Figure 1, we find that the distributions of these two groups of wind (\( V_p < 400 \text{ km/s} \) and \( V_p > 600 \text{ km/s} \)) are well separated around \( P = 0.01 \). Thus, Figure 1 suggests that in order to select CH and ST winds from ACE measurements, we need to also consider their proton speed. Therefore, in this study, we
use a combined criterion to identify CH and ST winds: CH wind occurs when \( P < 0.01 \) and \( V_p > 600 \) km/s; while ST wind is found when \( P > 0.01 \) and \( V_p < 400 \) km/s.

![Proton speed distribution of the solar wind with \( P > 0.01 \) (\( P < 0.01 \)) in red (in blue); (b) P distribution of the solar wind with \( V_p > 600 \) km/s (\( V_p < 400 \) km/s) in blue (in red) at the solar minimum between cycles 23 and 24 (2006–2010).](image)

Figure 1. (a) Proton speed distribution of the solar wind with \( P > 0.01 \) (\( P < 0.01 \)) in red (in blue); (b) P distribution of the solar wind with \( V_p > 600 \) km/s (\( V_p < 400 \) km/s) in blue (in red) at the solar minimum between cycles 23 and 24 (2006–2010).

### 2.2. Criterion to Identify ECH and PCH Winds

The CH wind can be further separated into two subgroups, ECH and PCH winds, by requiring that ECH wind is measured at heliographic latitudes within \( \pm 20^\circ \) from the ecliptic plane (thus including Ulysses data and the entire ACE database), and that the PCH wind is measured from regions at latitudes higher than \( 70^\circ \) in the two hemispheres, mostly observed by Ulysses (e.g., as in von Steiger & Zurbuchen (2011)). We compare the in-situ properties of these two categories of coronal hole-associated fast wind, with a special focus on their behaviors during the recent two solar cycle minima.

### 3. In-situ Observational Results

We choose two time periods during the recent two solar minima. Hereafter we refer to the minimum between solar cycles 22 and 23 as the first minimum and the minimum between 23 and 24 as the second minimum. To maximize our database, we use an extended interval for the first minimum (1995–1998) to include as much ECH wind as possible measured by Ulysses, since ACE was not available then. In the second minimum (2006–2010), we choose the start date as the time when the sunspot number was at the same level as at the start date of the first minimum, and the end date is chosen as the time when the sunspot number started to rise. The fact that the second minimum is longer than the first one is due to the fact that the second minimum is the historically most prolonged and weakest minimum in the modern space age (Cionco & Compagnucci 2012; Nandy et al. 2011). During the first minimum before 1998, PCH and ECH winds were measured only by Ulysses; while during the second minimum the PCH wind was observed by Ulysses only, and the ECH wind data is a combination of both Ulysses and ACE measurements. Figure 2 shows the comparative results between
the ECH and PCH winds at the two minima, with PCH wind shown in blue, ECH wind in green. Note that the ST wind is also included in red for comparison purposes.

Figure 2. Comparison of ST wind (red), ECH wind (green), and PCH wind (blue) at the solar minimum between cycles 22 and 23 (1995–1998) and at the minimum between cycles 23 and 24 (2006–2010), in (a) proton speed, (b) proton number density (normalized by the squared heliocentric distance), (c) proton flux ($V_p \cdot N_p$, normalized by the square of the heliocentric distance), (d) O$^{+7}$/O$^{+6}$ ratio, (e) C$^{+6}$/C$^{+5}$ ratio, (f) average charge state of Fe ($<Q>$Fe), (g) Fe-to-O density ratio (Fe/O), (h) helium-to-proton density ratio (He/P), and (i) the radial component of the magnetic flux (Br flux, normalized by the square of the heliocentric distance). Solid circles are the averaged values in the two minima intervals, vertical bars represent the standard deviations of the averages on both sides.

3.1. Summary of the In-situ Results

The main results of the comparison between the ECH and PCH winds are that they are two very different types of wind existing during the same period of time, and their time evolution along the solar cycle is also different. In particular, we find:

1. The ECH wind was generally about 100 km/s slower than the PCH wind at the two minima, both PCH and ECH were faster than ST all the time, and all of the wind speeds were slower during the second minimum compared to the first minimum (Figure 2a).

2. The proton number density ($N_p$, normalized by the squared heliocentric distance) was lower in PCH wind than in ECH wind at the two minima; they are all lower than the density in the ST wind, and they were all lower during the second minimum compared to the first one (Figure 2b).
3. The proton flux (the product of normalized proton number density and proton speed) of ECH, ST, and PCH winds behaved in the same way as the proton density: PCH has the lowest proton flux among these three types of wind, and they were all lower during the second minimum compared to the first minimum (Figure 2c).

4. $O^{7+}/O^{6+}$ and $C^{6+}/C^{5+}$ were comparable in ECH and PCH during the first minimum, but during the second minimum they evolved very differently: they significantly decreased in the PCH wind but they remain roughly the same in the ECH wind (Figure 2d and 2e). They show their highest values in the ST wind during the both minima.

5. The average charge state of Fe ($Q_{Fe}$) in PCH and ECH winds evolved very similarly in all three types of wind during these two minima: they all decreased significantly during the second minimum. The ordering of $Q_{Fe}$ in these three types of wind is worthy of being noticed. At all times, the $Q_{Fe}$ value of the ST wind was intermediate between the values for the PCH and ECH winds (Figure 2f).

6. The Fe/O and He/P ratios were almost constant in PCH wind and ST wind during the two minima, while in the ECH wind Fe/O increased and He/P decreased dramatically during the second minimum compared to the first minimum (Figure 2g and 2h).

7. The radial component of the radial magnetic field strength (Br flux, normalized by the squared heliocentric distance) decreased in all three types of wind during the second minimum compared to the first minimum. The decreasing rate of Br flux in PCH wind was much lower than in the other two types of wind.

4. Conclusion and Discussion

In conclusion, the comparison of the dynamics, composition, and magnetic properties of the PCH- and ECH-associated solar wind during the recent two solar minima, shows that not only do the PCH and ECH winds have different in-situ characteristics over the same time period, but they also evolve differently along the solar cycles. This study for the first time provides a detailed comparison between the PCH and ECH winds at solar minimum conditions, which can shed light on uncovering the mechanism of the fast solar wind acceleration process in different latitudinal regions of corona. For example, the substantial difference in the speed and density between the ECH and PCH wind is consistent with the early finding based on the Solar and Heliospheric Observatory (SOHO) observations that the $O^{5+}$ outflow from ECH is slower and denser than from PCH regions at three solar radii (Miralles et al. 2001). This consistency of the in-situ measurements with the spectroscopic observations supports that the ECH wind can be accelerated at lower height than the PCH wind. In addition, the significant compositional difference between the PCH and ECH winds implies that the properties of their coronal sources, the PCH and ECH regions, are also different.

A more comprehensive comparative study, for the next step, can also include the intermediate wind between ST and CH winds (i.e. pseudostreamer wind (Zhao et al. (2013a))) and the transient winds (i.e., ICMEs), and can be extended to the two successive solar maximum phases (Zhao et al. 2013b). The spectroscopic observations at
the coronal source regions of the PCH, ECH and ST wind (e.g. Landi et al. (2012b,c)), would definitely help make this study more complete in the future.

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**References**


