A Study of an Equatorial Coronal Hole Observed at the First Parker Solar Probe Perihelion

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Abstract

In this study, we present an observational analysis of a coronal hole (CH) observed on 2018 November 1 and solar wind (SW) that originated from it, using the Solar Dynamics Observatory, the Parker Solar Probe (PSP) observations at 68 solar radii, ACE and WIND data at 1 au, and interplanetary scintillation (IPS) observations from 0.2 to 1 au. The CH-originated SW stream was observed by L1 on 2018 November 4 and by PSP on 2018 November 15. We examined the CH for nine Carrington Rotations (CR) and find that the SW stream to reach L1 varied from one CR to other. We find that the pressure, temperature, and magnetic fields increase as the speed of the SW increases and the density decreases with distance. We noticed suprathermal particle enhancement at and after the stream interaction region in both PSP and L1 observations, but the enhancement lasted longer in PSP compared to measurements made at L1. The multiple-rotation observations of the CH imply that any differences in observations between PSP and spacecraft at L1 are due to the radial evolution of the solar wind stream rather than of the CH or the source plasma itself. In addition, IPS measured the radio signal irregularities driven by the SW. Furthermore, we employed a standard analytical model to extrapolate the magnetic field at larger heights. We find that the extrapolated magnetic field at 68 $R_\odot$ and 1 au matches well with the magnetic field measured by PSP and OMNI.

Unified Astronomy Thesaurus concepts: Solar coronal holes (1484); Solar wind (1534); Corotating streams (314)

1. Introduction

Coronal holes are regions of open, unipolar magnetic fields along which ionized atoms and electrons are accelerated into interplanetary space, forming high-speed solar wind streams (Krieger et al. 1973; Nolte et al. 1976; Cranmer 2009). They appear as dark areas in the solar corona in extreme-ultraviolet (EUV) and soft X-ray solar images (Cranmer 2009; Karna et al. 2014). Coronal holes can appear at any time and location. Around the time of solar maximum coronal holes develop more often at lower latitudes and are called equatorial coronal holes. Around solar minimum, coronal holes are more common and persistent at higher latitudes; these are commonly known as polar coronal holes. Polar coronal holes can grow and expand to lower solar latitudes. The solar wind originating from coronal holes can be characterized as having low number densities (Belcher et al. 1971), low heavy-ion charge state ratios (Zurbuchen et al. 2002; von Steiger et al. 2010), and high proton entropies (Burlaga et al. 1990; Borovsky & Denton 2010). Also, protons and alpha particles in the wind exhibit heating and increasing specific entropy with distance from the Sun in the inner heliosphere (Schwenn 1981; Freeman & Lopez 1985; Hellinger et al. 2011; Borovsky & Gary 2014).

Coronal holes exhibit an important phenomenon: stream interaction regions form when the high-speed solar wind interacts with the preceding ambient slow solar wind. If the coronal hole persists over multiple rotations, the interactions result in both magnetic field and plasma compressions at their interfaces, developing into corotating interaction regions (CIRs; Wilcox 1968; Tsurutani et al. 2006 and references therein). The interaction between the fast and slow wind streams leads to enhanced levels of turbulence and shock formation propagating away from the stream interface in both outward (forward) and inward (reverse) directions (Mason et al. 2008). In addition to an increase in solar wind speed, CIRs are characterized by enhanced magnetic field magnitudes and enhanced plasma temperatures. These transient features can cause weak to medium geomagnetic storms at Earth (Tsurutani et al. 1995).

Since the Skylab era, many studies have been made in association with geomagnetic storms with coronal holes (Nolte et al. 1976; Bohlin 1977). In this paper, we present the observational study of the coronal hole observed on 2018 November 1 from the surface of the Sun to 1 au using multiplescatter data. We used the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012) to investigate the equatorial coronal hole region. The solar wind originating from the coronal hole is examined from 35 solar radii to 1 au using the Parker Solar Probe (PSP; Fox et al. 2016) observations, the OMNI database, and the interplanetary scintillation (IPS) observations.

This paper is outlined as follows. In Section 2, we present the observations and analysis based on multiple data sets. In Section 3, we present a description of a simple solar wind model and a modeling result. We conclude with a summary of our findings and discussion in Section 4.

2. Observations

During the first perihelion of PSP, a coronal hole was observed in the EUV observation. The high-speed solar wind
stream that originated from this coronal hole was encountered by PSP on 2018 November 14 and by both L1 spacecraft (ACE and Wind) on 2018 November 4. The coronal hole region was first observed on the eastern limb on 2018 October 26 and the rotated backside from the western limb on 2018 November 7. On 2018 November 1, it was centered on the central meridian with an extension on both north and south direction as seen by AIA 193 Å in Figure 1. Two bright magnetic islands marked by red arrows in Figure 1 were also seen inside the coronal hole. The studied coronal hole was a persistent coronal hole, as it persisted over several solar rotations, we include WIND data persisted over several solar rotations, we include WIND data recorded during CR 2213 in Figure 3 owing to the long period spent in the appropriate heliospheric hemisphere. We can see good qualitative agreement between the projections of the plasma stream measured by PSP (inner ring) and that measured by WIND (outer ring) in Figure 3.

The FIELDS suite provides in situ electric and magnetic fields and plasma waves, the spacecraft potential, quasi-thermal noise, and low-frequency radio waves. In this paper, we utilize the measurements of the radial component of the magnetic field (Br) from FIELDS.

ISoIS comprises the two-instrument suite Energetic Particle lower (EPI-Lo) and higher (EPI-Hi) to measure energetic particles over a very broad energy range of ions from 20 keV nucleon\(^{-1}\) to 200 MeV nucleon\(^{-1}\) total energy and electrons from 25 keV to 6 MeV. EPI-Lo comprises 80 tiny apertures with fields of view (FOVs) that sample over nearly a complete hemisphere. EPI-Hi combines three telescopes that provide five large-FOV apertures: high energies (HETA, HETB) and low energies (LET1A, LET1B, and LET2C). A and B denote sunward-facing and antisunward-facing measurements, respectively, while C is orthogonal to LETA and LETB, allowing the full range of particle pitch angles to be observed. We used a 30-minute average of the “IonToF” product averaged over all 80 EPI-Lo apertures, which allows for suprathermal ion measurements from 30 keV nucleon\(^{-1}\) to 586 keV nucleon\(^{-1}\) from EPI-Lo, and LETA and LETB from EPI-Hi, which measures particles with energies as low as 1 MeV nucleon\(^{-1}\).

We use simple ballistic mappings of solar wind plasma along magnetic field lines in a Parker spiral configuration to compare observations made by PSP and the WIND spacecraft. Figure 3 shows the projection of these spiral field line mappings in the inner heliosphere using the radial plasma speeds measured by PSP (inner annulus) and WIND (outer annulus). The position of PSP while recording these measurements is outlined in black. These sets of measurements were made during periods of positive radial magnetic field, implying that they are both on the same side of the heliospheric current sheet (Hoeksema et al. 1983). While from Figure 2 we can see that the coronal hole persisted over several solar rotations, we include WIND data recorded during CR 2213 in Figure 3 owing to the long period spent in the appropriate heliospheric hemisphere. We can see good qualitative agreement between the projections of the plasma stream measured by PSP (inner ring) and that measured by WIND (outer ring) in Figure 3.

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Figure 1. Close-up view of the coronal hole in AIA 193 Å wavelength observed on 2018 November 1.
Figure 4 shows the bulk radial plasma speed measured by each spacecraft during the same periods as for Figure 3 as a function of longitude, mapped back to a distance of $25 R_E$. The plasma observed at PSP demonstrates a finer structure of fast streams, and it is likely that merging between and evolution of smaller-scale streams leads to the simpler fast structure observed at WIND.

2.1. OMNI Observations

We obtained solar wind magnetic field and plasma parameters at 1 au from the Operating Missions as a Node on the Internet4 (OMNI) database that records near-Earth solar wind information from many spacecraft in geocentric or L1 orbits and covers from 1963 to the present. The data are mostly used from ACE (Stone et al. 1998) and WIND (Acuña et al. 1995) spacecraft.

We used the Solar Wind Ion Composition Spectrometer (SWICS; Gloeckler et al. 1998) on ACE for chemical and isotopic composition measurements of the solar wind at 1 au. Also, we used the Electron, Proton, and Alpha Monitor (EPAM) instrument (Gold et al. 1998) to measure suprathermal ions. The present study uses an hourly magnetic field, 5-minute temperature and pressure, and 1-minute velocity and density data from OMNI. In addition, the study employs 2 hr averages.
of the SWICS data and 5-minute ion intensity averages measured in the EPAM LEMS120 channels P2–P6, covering the energy range of 66–1050 keV.

Figure 5 shows the solar wind stream parameter measurements at 1 au. The bulk flow velocity, He ++ beam velocity (top panel), and thermal speed (second panel) started rising on 2018 November 4, denoted by the orange dashed–dotted line. We noted from the top panel that the He++ beams (maximum represented by the blue dotted–dashed line) moved a couple of hours ahead of the protons or bulk velocity (represented by the red dotted–dashed line). In the high-speed solar wind region, an increase in the temperature was observed (third panel). Both pressure (fourth panel) and density (fifth panel) were observed to be lower in the fast stream (region around the red dotted–dashed line) compared to the slow solar wind (region around the orange dashed–dotted line). Before the decline in pressure and density, an increase in pressure and density was noticed (around 2018-11-4 20 UT, between the orange and blue dashed–dotted lines). The magnetic field strength of the fast stream is positive in magnitude and observed to be less than 6 nT (around 3–4 nT), indicating that the coronal hole had a positive polarity. All these signatures indicate that the fast stream is associated with the stream interface region (SIR).

Next, we analyzed the ACE EPAM ion observations for energies between 66 and 1050 keV. A bump in the energies between 66 and 580 keV, indicated by the red shaded region in Figure 6, was observed before and during the rise in the bulk flow speed velocity. This indicates that this region corresponds to the SIR interface. The peak is centered at the base of the rising solar wind speed. The suprathermal enhancements keep on extending throughout the SIR.

In Figure 7, proton density and the superposed averages of some heavy-ion density ratios are plotted. After 2018 November 4 12:00 UT, indicated by the orange dotted–dashed line, we noticed a decrease in (i) solar wind charge state ratios like O7+/O6+ and C6+/C5+ (second panel); (ii) solar wind elemental abundance ratio, e.g., Fe/O (third panel); and (iii) solar wind average charge state, e.g., Fe (bottom panel), with the increase of stream speed (top panel). This decrease may be due to plasma transitions from streamer belt origin to coronal hole origin. The black dotted–dashed lines point to the peak of the He++ ion speed.

2.2. PSP Observations

Allen et al. (2020) used the Sumerian God of wind and storms (ENLIL; Odstrcil et al. 2004) model simulations driven by the Global Oscillation Network Group (GONG; Harvey et al. 1996), the Air Force Data Assimilative Photospheric Flux Transport (ADAPT; Arge et al. 2010; Henney et al. 2012), and Wang, Sheeley, and Arge (WSA; Arge et al. 2004) and followed PSP observed streams backward in time to check for any preexisting CIRs, which may have been observed at L1 prior to any PSP observations as the stream corotated. They found that the stream observed on November 4 at L1 matches with the stream observed by PSP on November 15. Though there was a delay of 11 days between the two observation points, it did not affect our study since the coronal hole survived for another four Carrington rotations without much change in the area (see Figure 1). The area of the coronal hole computed on CR 2210 was 11.8 × 10¹⁰ km² ± 0.5 × 10¹⁰ km², and that on CR 2211 was 11.6 × 10¹⁰ km² ± 0.6 × 10⁹ km².

Figure 8 shows the PSP in situ data for a 4-day period around the first perihelion previously observed at L1 on November 4. With the increase in wind speed (top panel), thermal speed (second panel), temperature (third panel), pressure (fourth panel), and magnetic field (bottom panel) increase while density (fifth panel) decreases. The temperature and pressure are computed using Allen et al. (2020), Equations (1) and (5), respectively. The yellow dotted–dashed line indicates the starting time of wind stream rise. Magnetic field strength is positive.

The relative drift rate of the He++ component is not confirmable in the PSP data during this time range as in L1. The SPC instrument is not calibrated to record the low-density He++ streams, and the plasma distribution was largely outside of the SPAN-ion field of view.

In Figure 9, particle energies are plotted along with the velocity. The suprathermal particle count rate enhancement is observed at the interface in the EPI-Lo (top panel) indicated by the red shaded region. The peak is centered at the rise of the solar wind speed (middle panel) around 2018 November 14–15. No change in the high energy was noted in EPI-Hi (bottom panel). However, after around 2 days, higher-energy
enhancement was observed on EPI-Hi (bottom panel) as indicated by the blue shaded region from 2018 November 16 to November 20, along with the suprathermal enhancement, which is discussed in detail in Cohen et al. (2020).

2.3. IPS Observations

IPS measures a density irregularity along a line of sight from an observer to a natural compact radio source. We used multisite IPS observation data at the Institute for Space–Earth Environmental Research (ISEE), Nagoya University, Japan (Kojima & Kakinuma 1990). The ISEE-IPS measures intensity fluctuations of a radio wave from natural compact radio sources caused by the density irregularity of solar wind plasma. The observation frequency is 327 MHz and covers radial distances of 0.2–1.0 au from the Sun. The routine observation took place from April to early December.

By applying tomographic analysis, we obtain a two-dimensional velocity distribution (Kojima et al. 1998; Fujiki et al. 2003; Tokumaru et al. 2021). The top panel of Figure 10 shows the velocity distribution in CR 2210 (2018 October 27–November 23). The solar velocities measured by IPS are mapped on the source surface (2.5 $R_\odot$). The IPS map is magnetically separated into three areas, as shown by the magnetic neutral lines (MNL; black curves). The solar wind structure appears to be changing as it crosses the MNL. The hourly PSP data in CR 2210 are ballistically mapped on the source surface with the same velocity color scale. The PSP measures the increasing solar wind velocity on November 4–5, corresponding to longitudes around 320° on the map. The velocity increases up to 600 km s$^{-1}$ and decreases gradually to below 400 km s$^{-1}$ on November 23. This corresponds to longitudes around 260° on the map. The temporal variation of solar wind velocity measured with the PSP is clearly due to changes in the solar wind origin compared to the global structure observed with IPS. In this comparison, PSP measured the radial distances of 36–106 $R_\odot$, which overlaps the IPS observations. The bottom panel of Figure 10 shows the corresponding footpoint of PSP measurements on the solar surface by computing magnetic connectivity from the source surface to the solar surface using the PFSS model. The solar wind originates from three different origins in this interval.
Figure 6. Top: solar wind stream at 1 au. Bottom: the ACE EPAM ion observations for energies between 66 and 1050 keV (with colors indicating the energy channel in keV). The red shaded region corresponds to suprathermal particle enhancement at the interface.

Figure 7. He++ speed (top), charge state ratio (second and third), and heavy-ion (bottom) measurements from ACE SWICS. The orange dotted–dashed line denotes the starting of the fast solar wind stream. The black dotted–dashed line denotes the maximum bulk flow speed measured by the L1 spacecraft.
Here we only indicate the possibility of joint research between PSP and IPS observations, but in the future, perihelion getting closer to the Sun will be taken during the period of good observing conditions for IPS (June–September) so that it can be compared with IPS observations, which allows us to reveal the radial evolution of the solar wind structure.

3. Simple Wind Model

We employed a standard analytical model to extrapolate the magnetic field at larger heights. Consider a thin magnetic flux tube extending into the solar wind, positioned in the middle of a coronal hole. We adopt a simple model where the large-scale magnetic field $B$ is axisymmetric and has no azimuthal component (in spherical coordinates $(r, \theta, \phi)$, $B_\phi = 0$).

We assume a $\cos^8 \theta$ flux distribution at the photosphere, consistent with observations of the Sun’s magnetic field near cycle minimum (DeVore et al. 1984; Sheeley et al. 1989). This distribution is highly concentrated in the polar regions. Thus, in the northern hemisphere $B_z(R_\odot, \theta) = B_{\text{pole}} \cos^8 \theta$, where $B_{\text{pole}}$ is the magnetic field strength at the pole.

As the sign of the large-scale flux reverses at the equator, we assume that a current sheet exists at the equatorial plane, consistent with observations of narrow coronal streamers (e.g., Wang et al. 1997; van Ballegooijen & Asgari-Targhi 2016, 2017).

Above and below the equatorial plane the magnetic field is assumed to be potential, $B = -\nabla \Phi$ with $\nabla^2 \Phi = 0$. For $r \gg R_\odot$ the field becomes nearly radial and falls off like a monopole, $B_z \propto r^{-2}$. We solve for $\Phi$ using a Legendre polynomial expansion. Thus,

$$\Phi(r, \theta) = R \sum_{m=0}^{\infty} \left( \frac{r}{R} \right)^{-(m+1)} a_m P_m(\cos \theta);$$  \hspace{1cm} (1)
Given \( \cos^8 \theta \), only even harmonics survive. Letting \( m = 2(n - 1) \) and using the orthogonality of the Legendre polynomials, we find

\[
B_r(r, \theta) = \sum_{m=0}^{\infty} (m + 1) \left( \frac{r}{R} \right)^{(m+2)} a_m P_m(\cos \theta).
\] (2)

where \( B_n = B_{\text{pole}}[715, 2600, 2160, 832, 128]/6435 \).

For field lines in the equatorial plane (slow solar wind), we have \( \theta = \pi/2 \), and the coefficients are \( B_n = B_{\text{pole}}[2600, -1300, 810, -260, 35]/6435 \) with \( n = 1, \ldots, 5 \). The field strength \( B_0(r) \) inside the flux tube is assumed to be equal to that of the background field.

Looking at Figure 8, the PSP observations at 68 solar radii give a mean \( B_0(68 R_\odot, \pi/2) \) of about 30 nT. Fitting this to our model gives \( B_{\text{pole}} = 1.25 \times 10^6 \text{nT} \). We can then ask what the expected field strength at 1 au would be. The model gives \( B_s(215.03 R_\odot, \pi/2) = 3.001 \text{nT} \). This value is broadly consistent with the level of \( B_s \) seen in Figure 5 from the OMNI database, although the fluctuations there are much higher.

The modeled flux tube extends along the solar rotation axis from the coronal base outward into the heliosphere. The base is assumed to be located at radial distance \( r_{\text{base}} = 1.003 R_\odot \), and we follow the tube out to \( r_{\text{max}} = 70 R_\odot \). Figure 11 shows the magnetic field strength \( B_0(r) \) as computed from Equation (3) with \( B_{\text{pole}} = 10 \text{ G} \). Note that \( B_0(r) \) drops off faster than \( r^{-2} \), which is due to the \( \cos^8 \theta \) distribution of magnetic flux on the photosphere.

4. Discussion and Conclusion

We investigated a fast-speed stream emerging from a coronal hole observed on 2018 November 1, from the surface of the Sun to 1 au using multispacecraft data, observed during the first orbit of PSP. This event was compared with simple solar wind simulations, as well as observations at 1 au from WIND and ACE. Our conclusions are as follows:

1. The coronal hole survived for nine Carrington rotations (Figure 1).
2. The solar wind stream took 2.5–3.5 days to reach L1, implying that the solar wind observations originate from the same coronal hole. The solar wind speed differs in each rotation (Figure 2).
3. Decrease in density with a radial distance is clearly seen from both PSP and OMNI data sets. The solar wind
Figure 10. Top: a velocity distribution obtained from the ISEE-IPS observations in CR 2210 (2018 October 27–November 23). The black line denotes the heliospheric current sheet. Color plots represent PSP data ballistically mapped on the source surface with the same color scale. Bottom: photospheric magnetic field obtained by GONG. Color plots represent PSP data traced down along magnetic field lines calculated by using the PFSS model.

Figure 11. Radial dependence of the magnetic field strength from $r_{\text{base}} = 1.003 \, R_\odot$ to $r_{\text{max}} = 215 \, R_\odot$ in a polar coronal hole. The red triangle and the blue circle are overplotted magnetic field measurements made from PSP and L1 spacecraft, respectively.
density measured at 68 solar radii is on the order of 10 times denser than that measured at 1 au (Figures 5 and 8).
4. Pressure, temperature, and magnetic field increase as the speed of the solar wind increases (Figures 5 and 8).
5. The studied coronal hole is positively charged, and the field strength measured at 68 solar radii and 1 au is all of the positive polarity (Figures 5 and 8).
6. The suprathermal particles with energies less than 600 keV are accelerated in both PSP (Figure 9) and L1 (Figure 6) observations at and after the SIR. At the interference region (red shaded region in Figures 6 and 8), the peak is centered at the base of the rising solar wind speed in the L1 observation, whereas in PSP the peak is centered at the apex of the rising solar wind speed. After the SIR, the suprathermal ion flux at L1 is less broad than at PSP.
7. High-energy MeV suprathermal particles are enhanced after the interaction region, and the enhancement lasted several days following the SIR in the PSP observation (blue shaded region Figure 9). In the L1 observation there were no significant increases in the MeV suprathermal particles (Figure 6).
8. An increase in density corresponding to the suprathermal particle enhancement region was observed, and then density declined as the speed reaches its maximum (Figures 5 and 8).
9. Thermal speed (Figure 5) and suprathermal particle enhancement (Figure 6) start rising at the same time at 1 au.
10. Solar wind charge state ratios, elemental abundance ratio, and average charge state all decrease with the increase in stream speed (Figure 7).
11. The He ++ beam moves a couple of hours ahead of the protons (Figure 5).
12. The extrapolated magnetic field using a simple magnetic model at 68 R$_\odot$ (Figure 13) and 1 au matches well with the magnetic field measured by PSP (Figure 8) and OMNI (Figure 5).
13. IPS measured the radio signal irregularities driven by the solar wind (Figure 10).

We noticed that the fast wind stream had He++ beams moving ahead of the protons, low number densities, and low heavy-ion charge state ratios, which are characteristic of coronal-hole-originated solar wind. It should be noted that although the solar wind stream originates from the same coronal hole, the speed and the stream arrival time to 1 au varied from one Carrington rotation to another as was seen in Figure 2. The timing of the coronal-hole-originated solar wind observation aligned well with the PSP orbit. PSP started passing through the leading edge of the high-speed stream, continued as the high-speed stream corotates over the spacecraft, and ended passing the trailing edge of the stream as seen in Figure 3, standing as a perfect classic CIR/SIR event (Cohen et al. 2020). The decrease in crossing width and steepening of the increasing velocity profile at L1 versus at PSP is unlikely to be a product of the evolution of the coronal hole and is most likely a product of the faster wind stream overtaking the slower plasma at the interface during propagation (Burlaga 1974). Analyzing the SIR observed at ACE on 2018 November 4 to the corresponding SIR observed at PSP around 2018 November 15 indicated the enhancement of low-energy (keV) suprathermal ions (Figure 6) at the stream interface as the keV range ions are enhanced by local acceleration. The keV ions were enhanced again after the interface region, but for a short period of time compared to the PSP observation (Figure 8), while high-energy (MeV) suprathermal ions propagate along field lines to the inner heliosphere (Filwett et al. 2019) and are enhanced after the interface region in which articles accelerated at distant shocks dominated (see Desai et al. 2020; Joyce et al. 2021) and lasted longer in time in PSP. Minor enhancements in MeV particles were inconsistently observed over various Carrington rotations at ACE (not shown), but these were often at or just above the instrument noise floor. We cannot make any conclusive inferences as to the evolution of higher-energy ions in the coronal wind from these observations. In the future, as we approach solar maximum, it is likely that there will be more equatorial coronal holes observed during upcoming PSP orbits, which will allow us to compare more in depth the evolution of the solar wind structure at 1 au with PSP.

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