Solar coronal holes and their geo-effectiveness

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Abstract. Solar corona as the outermost part of the Sun is constantly emanating solar wind consisting of charged particles. Coronal holes are rigidly rotating phenomena in the solar corona that are magnetically open to interplanetary space, which allow the solar wind particles to escape from the Sun. The study of coronal holes and their associated high speed solar wind streams is important because they are the sources of space weather disturbances during minimum solar activity. We present some results on the relationship between large solar coronal holes close to the central meridian and solar wind stream with the aim to analyse their geo-effectiveness. The analysis were carried out by considering geomagnetic and solar wind parameters such as total geomagnetic field, $B_z$ component, proton density and plasma speed during Earth-side large solar coronal holes appearance. Using the data during declining phase solar activity we found that a solar coronal hole is geo-effective during and after its transit on the central meridian but not all of them can be the proxy of high speed solar wind.

1. Introduction

Solar corona is the outermost part of the Sun with density of $\sim 10^7$ m$^{-3}$ and temperature of millions of Celsius. This region of hot gas is constantly emanating solar wind, consisting charged particles (protons, electrons, and helium ions). Coronal holes are regions of low-density plasma on the solar corona that appear dark in EUV [1] or X-ray [2] images of the Sun. They have open magnetic field structures which allow solar wind particles to escape easily into interplanetary space [3].

Space weather often associated with transient events on the Sun such as flares and coronal mass ejections (CMEs) that can affect the Earth’s magnetosphere. Despite the importance of these transient events, coronal holes, especially during the minimum solar activity, also play important role in space weather because they are the source region of the high speed solar wind streams (HSSs) [4]. Combination of coronal holes and their associated HSSs with solar rotation are the dominant contributors to space weather disturbances at times of quiet solar activity because they are sources of recurrent geomagnetic storms [5]. The aim of this paper is to study the relationship between large solar coronal holes and solar wind streams in order to analyse their geo-effectiveness, i.e. their effects on the Earth’s environment.

2. Data analysis and methods

Our study is based on the following data sets: The interplanetary magnetic field ($B$ and $B_z$) and solar wind parameters (proton density and plasma speed) accessible at OMNIWeb Plus.
prepared by Goddard Space Flight Center/Space Physics Data Facility; Solar Dynamics Observatory (SDO) Atmospheric Imaging Assembly (AIA [6]) 193 Å quick-look images accessible at SDO (http://sdo.gsfc.nasa.gov/). We focus on large coronal holes in the declining phase of the Solar Cycle 24, when the coronal mass ejection (CME) and solar flare activity were very low.

3. Results
We have selected four coronal holes between February-May 2015 including equatorial, polar and trans-equatorial ones. The results are as follows.

3.1. Equatorial coronal hole on 6-15 February 2015
This coronal hole was transiting the central meridian around 11 February 2015 (Figure 1). Figure 2 shows the total magnetic field strength, z-component, proton density and plasma speed during its appearance on the SDO/AIA 193 Å images. The total magnetic field decreased significantly on 14 February 2015 around 3 UT and increased at 5 UT. Another fluctuation occurred on 15 February 2015 with minimum magnetic field of 4 nT around 4 UT coincided with proton density peak of 22.1 particles/cm$^3$ while the $B_z$ was negative (southward). Later, the total magnetic field reached its maximum of 10.9 nT around 13 UT followed by proton density enhancement up to 16.6 particles/cm$^3$ a day later around 13 UT. This fluctuating total magnetic field and peaking proton density are suggested to be originated from the large coronal hole as it rotated to the western hemisphere.

Figure 1. SDO/AIA 193 Å image showing an equatorial coronal hole (blue line) transiting the central meridian on 11 February 2015.

Figure 2. Time series (1-hour data resolution) of $B$ (nT), $B_z$ (nT), solar wind proton density (N/cm$^3$) and solar wind plasma speed (km/s), from top to bottom, respectively, during the appearance of equatorial coronal hole (6-19 February) on SDO/AIA 193Å images. The time is expressed in the day-of-year form, DOY, for 2015. The vertical dashed-line denote the approximate time of coronal hole transit.
Another enhancement on total magnetic field took place at 11 UT on 16 February 2015 to a maximum at 17 February 2015 at around 9 UT. This was also originated from the same coronal hole. As shown in figure 2, \( B_z \) was mostly negative during the maximum of total magnetic field coincided with proton density enhancement and followed by solar wind acceleration. The plasma speed increased from 400-460 km/s on 18 February 2015.

3.2. Polar coronal hole on 23 February-3 March 2015
The coronal hole on the Sun’s southern pole is a very large one (Figure 3). Figure 4 shows some parameters during the appearance of this coronal hole, similar to figure 2. The strong magnetic field, density and solar wind speed at the beginning of its appearance were affected by another coronal hole on the west limb.

Solar wind stream from the polar coronal hole caused proton density enhancement started on 27 February 2015 and peaked on 28 February 2015 at around 11 UT with maximum of 24.6 particles/cm\(^3\). This enhancement was followed by increasing total magnetic field and plasma speed starting from 28 February 2015. The total magnetic field peaked at 12.6 nT on 1 March 2015, while solar wind speed was fluctuating between 560-640 km/s and \( B_z \) was mostly negative and oscillating between -8 to 3 nT.

3.3. Trans-equatorial coronal hole on 26 March-6 April 2015
This large coronal hole stretched from the solar north-pole to equator (Figure 5). During its appearance, there were no strong events and the Dst index was relatively stable. However, there was plasma speed enhancement on 3-5 April 2015 (Figure 6). This enhancement to about 550 km/s was originated from our trans-equatorial coronal hole. It is interesting that the proton density was rapidly declining when the solar wind speed was maximum on 3 April 2015. A rapid decrement also shown in the total magnetic field while \( B_z \) was slightly oscillating between -1 and 3 nT. The relatively quiet total magnetic field and proton density were continued to occur until the proton speed decreased to about...
320 km/s on 9 April 2015. After that, all considered parameters were highly fluctuated as the effect of CME on 6 April 2015.

![Figure 5](image1.png) Figure 5. SDO/AIA 193 Å image showing a trans-equatorial coronal hole (blue line) transiting the central meridian on 31 March 2015.

![Figure 6](image2.png) Figure 6. Similar to figure 2, during the appearance of trans-equatorial coronal hole (26 March-10 April 2015) on SDO/AIA 193Å images.

3.4. Equatorial coronal hole on 19-30 May 2015
There were no large events occurred during this equatorial coronal hole appearance. However, there was an enhancement in the proton density on 23 and 26 May 2015 (Figure 8). Proton density enhanced from around 5 to around 12 particles/cm³ only within 4 hours on 23 May 2015. The Solar Influences Data Analysis Center (SIDC-http://sidc.oma.be/) reported it as a sector boundary crossing (SBC) of the interplanetary magnetic field, i.e. when the interplanetary magnetic field reversed from positive to negative. Another SBC, interplanetary magnetic field reversal from negative to positive, occurred on 26 May 2015 with stronger enhancement of proton density up to 21 particles/cm³. The solar wind plasma speed was considerably low, i.e. around 300 km/s, during both SBCs.
Figure 7. SDO/AIA 193 Å image showing an equatorial coronal hole (blue line) near the central meridian on 23 May 2015.

Figure 8. Similar to figure 2, during the appearance of equatorial coronal hole (19 May-3 June 2015) on SDO/AIA 193Å images.

4. Discussion and conclusion

Based on four coronal holes considered in this study, we found that a solar coronal hole can be geo-effective, i.e. producing high-speed solar wind stream affecting the Earth’s magnetic field, during and after its transit on the central meridian when the z-component (B_z) is negative (southward). The effect of the coronal hole can be seen as significant changes in plasma speed, proton density, and total magnetic field.

However, the equatorial coronal hole on 19-30 May 2015 produced a relatively low plasma speed during its appearance. This suggested that not all of the large coronal holes can be the proxy of high speed solar wind. We suppose that this is because we did not consider the polarity of the coronal holes, as a recent study found that coronal holes with opposite polarity (southern negative, and northern positive) has the smallest geo-effectiveness [7].

Further analysis on the coronal holes evolution is necessary in order to study their possible impact to Earth’s magnetic field. We need to collect more data with various positions, i.e. equatorial, polar and trans-equatorial, to get a comprehensive conclusion on the relationship between solar coronal hole evolution and its potential to disturb the Earth’s magnetic field.

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