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On the dependence of the solar wind velocity on the fractional area of coronal holes in latitude

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The relationship between the fractional area of coronal holes in latitude and the maximum velocity of the fast solar wind at 1 AU based on AIA/SDO and ACE/SWEPAM observations is considered for the period from June 2015 to March 2017. Coronal hole areas were determined within the meridional slice $\pm 10^\circ$. It has been shown that the coronal holes within $\pm 40^\circ$ in latitude give the greatest contribution to the fast ecliptic solar wind. The maximum correlation coefficient between the fractional area of coronal holes and the maximum velocity was found to be equal to 0.762 ± 0.145. The probable causes of the discrepancy between the predicted and observed values of the solar wind velocity are discussed.

Keywords: Sun: coronal holes, solar wind

1 Introduction

Coronal holes (CHs) are large regions ($\sim 10^{20}$ cm^2) in solar corona with open magnetic field structure (Cranmer, 2009). Due to their lower coronal temperature and low density compared to ambient plasma, CHs have reduced emission at X-ray and extreme ultraviolet wavelengths, and, hence, can be identified as dark regions in these wavelength images. CHs can be classified mainly into two categories depending on the position in solar coronal images viz. polar and equatorial CHs.

Solar wind (SW) is a continuous stream of electrons, protons and ionized particles emanating from the Sun (Cranmer, 2002). SW plays a vital role in shaping the heliosphere and substantially interacts in the near-Earth environment. It can be generally classified into three types: the steady fast wind with velocity $V > 500$ km/s originating from the open magnetic field regions in CHs, the unsteady slow ($V =$ 400–500 km/s) wind that emanates from the temporarily open streamer belt, and the transient wind caused by coronal mass ejections (CME).

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At present it is beyond doubt that CHs are the sources of the fast SW (Waldmeier, 1957; Krieger et al. 1973; Cranmer, 2002). The close relationship between the fractional area of CHs in the extreme ultraviolet (X-ray) range and the velocity of the fast SW has been established (Nolte et al., 1976; Zirker 1977; Cranmer, 2002; Vrsnak et al., 2007; Abramenko et al., 2009; Shugai et al., 2009; Rotter et al., 2012; Akiyama et al., 2013; Hegde et al., 2015). In particular, the velocity of the fast ecliptic SW at 1 AU can be calculated (predicted) as follows

$$V(S, T_V) = AS(T_{\rm ch}) + B,$$

where $S(T_{\rm ch})$ is the fractional areas of CHs taking in selected range in latitude and longitude at the time instant $T_{\rm ch}$, B corresponds to the minimum (background) velocity, A is a parameter depending, first of all, on the method of the fractional CH area calculation, and T_V is the time of arrival of the solar wind stream to the near-Earth orbit according the velocity prediction.

Correlation coefficient k between the area of CHs and the SW velocity varies over a wide range from 0.4 to 0.9 (e.g., Shugai et al., 2009). It seems to us that one possible reason for this may be related to the dependence of k on the selection of CH areas on the solar disk. It is usually considered that the fast SW is propagated radially (Nolte, Roelof, 1973; Luhmann, 2002). This suggests that CHs located near the central meridian should make the greatest contribution to fast solar wind. However, the selected ranges of CH boundaries, first of all, in latitude φ as well as in longitude L are very different. For example, Nolte et al. (1976) used the area of CHs within $\varphi = \pm 10^\circ$ of the ecliptic plane. Fujiki et al. (2005) and Vrsnak et al. (2007) considered the meridional slice with $L = \pm 10^\circ$. Rotter et al. (2012) also preferred the meridional slice embracing the central meridian at $L \pm 7.5^\circ$. Akiyama et al. (2013) selected the CH area within $L = \pm 10^\circ$ in longitude from the central meridian and $\varphi = \pm 30^\circ$ in latitude from the disk center (see also Luo et al., 2008). Shugay et al. (2017) considered the region near the central meridian separated $L = \pm 30^\circ$ and $\varphi = \pm 50^\circ$. Eselevich et al. (1990) analyzed near-equatorial coronal holes, i.e., holes whose centers of gravity lie at latitudes $\pm 20^\circ$ on both sides of the solar equator.

The aim of this work is to investigate the dependence of the fast SW velocity on the selected range in latitude φ for the meridional slice with $L = \pm 10^\circ$ (Akhtemov, Tsap, 2018) in longitude.

2 Data and processing method

CH boundaries and areas are determined based on the Coronal Hole Identification via Multi-thermal Emission Recognition Algorithm (Garton et al., 2018; https://solarmonitor.org/chimera.php?). This code uses the magnetograms in the absorption line 6173 Å and the extreme ultraviolet images in spectral lines 171, 193, and 211 Å obtained with Helioseismic and Magnetic Imager (HMI) and the Atmospheric Image Assembly (AIA), respectively, mounted to the the Solar Dynamic Observatory (SDO). The SW velocity data utilized in the present study were taken from the Solar Wind Electron, Proton, and Alpha Monitor (SWEPAM) onboard the Advanced Composition Explorer (ACE, https://omniweb.gsfc.nasa.gov/ftpbrowser/ace_merge.html).

The great coronal hole is dominated from June 2015 to March 2017 for Carrington rotations (CR) 2165–2188 on the solar disk (Fig. 1a). CH areas are determined at the moment in time when the "center of gravity" of CH passed through the central meridian due to the rotation of the Sun. We used the ballistic model which suggests that the SW motion in the heliosphere is radial and it occurs with constant velocity. Therefore we are restricted by CH areas within the meridional slice embracing the central meridian at ±10° in longitude (Fig. 1a). We limited areas of CHs by latitudes ±20°, ±40°, ±60°, ±90° (Fig. 2).

In order to estimate the time of arrival of the solar wind stream at the near-Earth orbit T_V the following relationship is used

$$T_V = T_{\rm ch} + 4 \pm 1.5 \text{ days},$$

where $T_{\rm ch}$ corresponds the time when the "center of gravity" of CHs passes the central meridian. Based on the last equation we selected the largest SW velocity V at time T_V for the smoothed curve of the peak (Fig. 1b). We also took into account that the observed fast SW at 1 AU can be caused by CME and excluded events for which the value of $A_{\rm p}$ index was greater than 70 (Shugai et al., 2009).

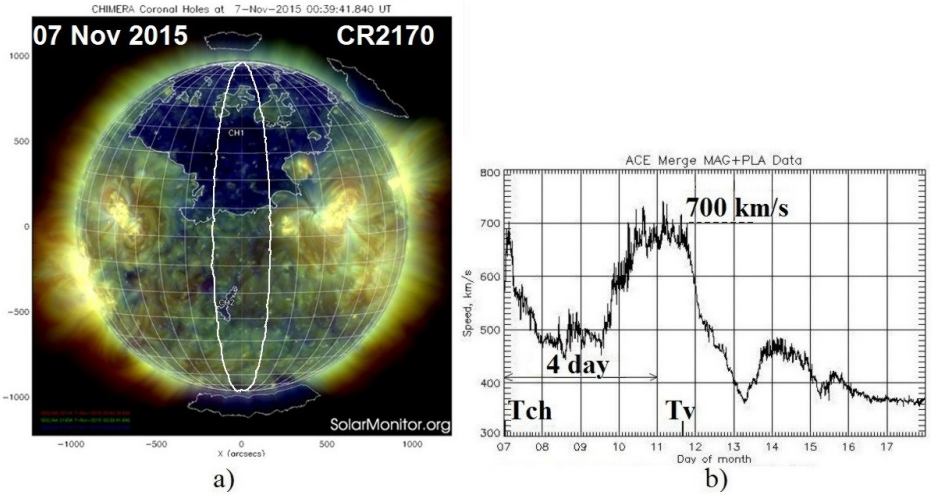


Figure 1 a) Sample of AIA/SDO image with the meridional slice (±10°) outlined in white on 2015 November 7 (00:39:18 UT). b) Temporal variation of the solar wind speed for the period from 2015 November 7 to 2018 November 18 obtained with SWEPAM/ACE. The horizontal solid line with arrows shows the moments when the "center of gravity" of CHs passes the central meridian ($T_{\rm ch}$) and the solar wind stream arrives at the Earth's orbit (T_V). The dashed horizontal line indicates the average maximum of solar wind speed within the peak.

The dependence of the maximum SW velocities and CH areas on Carrington rotation (CR) is presented in Fig. 3a. It is seen that the correlation between the fast SW velocity V and the fractional area S of CHs is quite good excluding the vicinity of CR 2185, where V and S varies "in antiphase", i.e., SW velocity increases with decrease in CH area and vice versa (Fig. 3a). However, we can elimi-

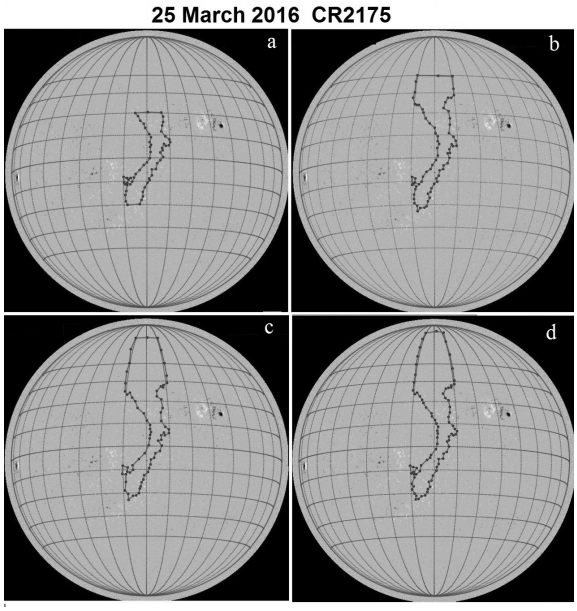


Figure 2 Sample of the HMI/SDO magnetograms overlaid with slices of CH near the central meridian separated ±10° in longitude and ±20° (a), ±40° (b), ±60° (c), ±90° (d) in latitude.

nate this point from our consideration since the A_p index achieved 80 (ftp://ftp.gfz-potsdam.de/pub/home/obs/kp-ap/wdc/) after the travel time $\tau = T_V - T_\mathrm{ch} \approx 4$ days (T_ch corresponds to 18 December 2016, 02:25 UT). This value of A_p index is too large for the magnetic field disturbances in the Earth's magnetosphere caused by the fast SW of CHs (Shugai et al., 2009). In addition, CME was observed on 18 and 19 December 2016 (https://cdaw.gsfc.nasa.gov/CME_list).

The results of a calculation performed for the correlation coefficient k at different values of φ are presented in Table 1. We can see that the coefficient k has the maximum at $\varphi = \pm 40°$. This means that CHs located at $|\varphi| > 40°$ do not make a significant contribution to the fast SW. Besides, as it follows from Table 1 the correlation coefficient strongly depends on the influence of the transient SW and the maximum value of k achieves 0.762 ± 0.145 without CR 2185. Thus, the obtained results agree quite well with inferences of Eselevich et al. (1990) which concluded that the plasma flows from polar CH, whose boundary is above 60–70° in latitudes, do not reach the Earth (but see Tlatov et al., 2014). The linear regression line in our case has the form (Fig. 3b)

$$V = (26.6 \pm 5.0)S + (405.5 \pm 32.1)\ [\mathrm{km/s}],$$

where the CH fractional area S is in 10^{10} km^2. This expression can be used to make a prediction of the SW velocity.

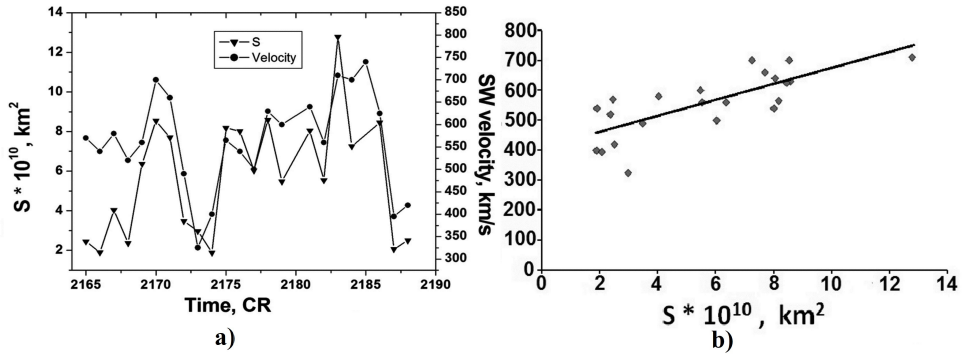


Figure 3 a) The dependence of fractional CH areas ($L = \pm 10°$, $\varphi = \pm 40°$) and SW velocities from June 2015 to March 2017 with regard to CR2185. b) Correlations between CH areas and SW velocities without regard to CR2185; the solid straight line represents the best linear fit to the data points.

Table 1 Correlation coefficients between fractional CH areas for the meridional slice ($L = \pm 10°$) and the SW velocity with and without regard to CR2185 within latitudes $\pm 20°$, $\pm 40°$, $\pm 60°$, $\pm 90°$.

CR2165–CR2188	$\pm 20°$	$\pm 40°$	$\pm 60°$	$\pm 90°$
with CR2185	0.66381	0.68722	0.63410	0.56894
without CR2185	0.72235	0.76231	0.71196	0.67671

Conclusions

We have considered the relationship between the maximum velocity of fast SW at 1 AU and the location of CHs. Assuming the ballistic model of the SW propagation we selected the CH area within $\pm 10°$ (Akhtemov, Tsap, 2018) in longitude from the central meridian. It has been shown that CHs within $\varphi = \pm 40°$ give the greatest contribution to the fast SW. We also found that CMEs significantly affected the correlation coefficient between the fractional area of CHs and the SW velocity. Despite that we obtained the quite modest correlation coefficient $k = 0.76$. This can be caused by the magnetic field of active regions located near CHs which provided a deflection of the high-speed SW stream from the radial direction (see also Shugay, 2017). Apart from the open magnetic field lines the properties of CHs can be strongly dependent on their inner structure. For example, the CH brightness indices display a fairly high correlation with the fast SW velocity (Obridko et al., 2009).

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References

Abramenko, V.I., Yurchyshyn, V.B., Watanabe, H., 2009, Solar Phys., 260, 43.
Akhtemov, Z.S., Tsap, Yu.T. Geomagn. Aeron., 2018, 58, 1187.
Akiyama, S., Gopalswamy, N., Yashiro, S., Makela, P., 2013, Pub. Astron. Soc. Japan, 65, 15.
Cranmer, S.R., 2002, Space Sci. Rev., 101, 229-294.
Cranmer, S.R., 2009, Liv. Rev. Solar Phys., 6, id. 3.
Eselevich, V.G., Kaigorodov, A.P., Fainshtein, V.G., 1990, Planet Space Sci., 38, 459.
Fujiki, K., Hirano, M., Kojima, M., Tokumaru, M., Baba, D., Yamashita, M., Hakamada, K., 2005, Adv. Space Res., 35, 2185.
Hegde, M., Hiremath, K.M., Doddamani, V.H., Gurumath, S.R., 2015, J. Astrophys. Astr., 36, 355.
Garton, T.M., Gallagher, P.T., Murray, S.A., 2018, J. Space Weather & Space Climate, 8, id. A02.
Krieger, A.S., Timothy, A.F., Roelof, E.C., 1973, Solar Phys., 29, 505.
Luo, B., Zhong, Q., Liu, S., Gong, J., 2008, Solar Phys., 250, 159.
Luhmann, J.G., Li, Y., Arge, C.N., Gazis, P.R., Ulrich, R.J. 2002, Geophys. Res. (Space Physics), 107, ID 1154.
Nolte, J.T., Roelof, E.C., 1973, Solar Phys., 33, 241.
Nolte, J.T., Krieger, A.S., Timothy, A.F., Gold, R.E., Roelof, E. C., Vaiana, G., Lazarus, A.J., Sullivan, J.D., 1976, Solar Phys., 46, 303.
Obridko, V.N., Shelting, B.D., Livshits, I.M., Asgarov, A.B., 2009, Solar Phys., 260, 191.
Rotter, T., Veronig, A.M., Temmer, M., Vrsnak, B., 2012, Solar Phys., 281, 793.
Shugai, Yu.S., Veselovsky, I.S., Trichtchenko, L.D., 2009, Geomagn. Aeronom., 2009, 49, 435.
Shugay, Yu.S., Veselovsky, I.S., Slemzin, V.A., Yermolaev, Yu.I., Rodkin, D.G., 2017, Cosmic Res., 55, 20.
Tlatov, A., Tavastsherna, K., Vasil'eva, V., 2014, Solar Phys., 289, 1349.
Vrsnak, B., Temmer, M., Veronig, A.M., 2007, Solar Phys., 240, 315.
Waldmeier, M., 1957, Die Sonnenkorona 2, Verlag Birkhuser, Basel.
Zirker, J.B. (ed.), 1977, Coronal Holes and High-speed Wind Streams, Colorado Assoc. Univ. Press, Boulder.