*Solar-Terrestrial Physics. 2023. Vol. 9. Iss. 3. P. 112–117. DOI: 10.12737/stp-93202313.* 

UDC 523.98, 523.62
DOI: 10.12737/stp-93202313

Received May 01, 2023
Accepted June 18, 2023

# RELATION BETWEEN THE AREA OF POLAR CORONAL HOLES AND THE SOLAR WIND SPEED AT A MINIMUM BETWEEN SOLAR CYCLES 22 AND 23

**A.V. Borisenko**
*Lebedev Physical Institute RAS,*
*Moscow, Russia, sunw77@mail.ru*

**S.A. Bogachev**
*Space Research Institute RAS,*
*Moscow, Russia, bogachev.sergey@gmail.com*

**Abstract.** We have used data from the space telescope SOHO/EIT and the spectrometer VEIS on the Wind spacecraft to compare the solar wind (SW) speed near Earth's orbit with changes in the area of polar coronal holes (CHs) on the Sun during the 1996 solar activity minimum. We have found that in March 1996 the SW speed correlated with the southern CH area by a factor of 0.64. In September and October 1996, a correlation was revealed between the SW speed and the area of the northern CH (the coefficients are 0.64 and 0.85 respectively). We believe that this confirms the assumption that the solar wind from polar CHs can penetrate into the ecliptic plane at solar minimum. The SW speed was 460–500 km/s, which is lower than that from equatorial CHs (600–700 km/s).

**Keywords:** coronal holes, solar wind, solar cycle.

## INTRODUCTION

Coronal holes (CHs) are large-scale regions of the solar corona with open magnetic field lines. When observing the Sun in an extreme ultraviolet (EUV) spectral region (for example, in the 193 Å line), CHs are clearly seen on the solar disk as darker regions whose radiation is weaker than that from the quiescent solar corona due to a lower plasma density. CHs were probably first described in the 1950s by Max Waldmeier [Waldmeier, 1956], who discovered them in solar corona images in the green optical line 5303 Å. In the 1970s during scientific experiments at the station Skylab, a relationship was found between CHs and solar wind (SW) streams. In particular, it was shown that the appearance of large CHs at low latitudes near the central meridian of the Sun correlates with an increase in the SW speed (e.g., [Krieger et al., 1973]). Later on, the influence of low-latitude (equatorial) CHs on the fast SW component has been repeatedly confirmed (see, e.g., [Nolte et al., 1976; Rotter et al., 2012]).

In addition to low-latitude CHs, CH of another type is almost always observed on the Sun — polar CHs, located near the Sun's magnetic poles. Polar CHs are also linked with open magnetic field lines. At the same time, while large-scale regions with open field lines are formed relatively randomly at low and middle solar latitudes due to the interaction between magnetic fields, the open field lines almost always exist near the poles. That is why polar CHs tend to be more stable than the low-latitude ones. Nevertheless, the effect of polar CHs on the SW speed near Earth has received almost no attention because of their distance from the ecliptic plane.

During operation of the Ulysses spacecraft, which carried out measurements outside the ecliptic plane, it was found that polar CHs, as well as the equatorial ones, are sources of fast SW. For instance, during solar minimum in 1994, Ulysses instruments, when the spacecraft passed over the south pole of the Sun, observed a high SW speed of ~700 km/s for 100 days [Neugebauer et al., 1995; Ko et al., 1997]. Similar results were obtained in 1995 when the spacecraft passed over the north pole of the Sun [McComas et al., 1998]. Information about SW characteristics beyond the ecliptic can also be gained by observing interplanetary scintillations (see, e.g., [Chashei et al., 2020, 2022]). Such observations also confirm that at high latitudes in the heliosphere there may be SW streams associated with long-lived polar CHs (e.g., [Sime, Rickett, 1978; Baker, Papagiannis, 1982]).

The question about the possibility of penetration of SW from polar CHs into the low-latitude region up to the ecliptic plane has not yet been answered with certainty. So, Munro and Jackson [1977] have shown that the boundaries of polar CHs at a distance to five solar radii are at a latitude around 25°. Since, according to accepted concepts, SW propagates radially from such distances, this does not allow its penetration into the ecliptic. Nevertheless, Wang and Sheeley [1990] have observed that in 1985–1987 the total area of CHs, located at latitudes below 45°, decreased almost to zero, but the SW speed remained high, which can be considered as indirect evidence of the contribution of polar CHs. In [Borisenko, Bogachev, 2020], we have suggested that the SW streams associated with polar CHs can be detected in the ecliptic plane if two conditions hold: 1) measurements are carried out at solar minimum; 2) there are no CHs, except for the polar ones, on the side of the Sun facing Earth. In this case, in our opinion, the open magnetic field lines from the polar CHs can go down to the ecliptic plane. As a result, SW accelerated in the polar CHs can penetrate into the ecliptic. We have analyzed the data obtained in March 2019 (at a minimum between solar cycles 24 and 25), and have found a correlation coefficient of 0.82 between the SW speed and the area of southern polar CH. No studies have been carried out for other periods, and the question of whether this result is characteristic or an exception has not been resolved. In this paper, we conduct a similar study but for a different period — solar minimum between cycles 22 and 23. We have significantly improved the method of measuring the CH area, which made it possible to fully automate the data processing procedure and carry out a study for three series of images. In the paper, we describe the research method and present the results and conclusions.

## DATA AND METHODS

We have applied three main criteria when choosing time periods for the study. Firstly, the time periods considered should be near the solar minimum between cycles 22 and 23. Figure 1 shows the mean sunspot index measured from 1990 to 2000 (using data from the SILSO database of the Royal Observatory of Belgium [www.sidc.be/silso]). We have chosen 1996 for the study because during that year the number of sunspots was at the lowest level in the decade. Since Earth's orbit is tilted to the solar equator at an angle of ~7°, the polar CHs are maximally inclined toward Earth once a year (southern CH in March and northern CH in September). We believe that the influence of the polar CHs on Earth during this period is the strongest. For this reason, we have chosen two time periods in 1996: February–April for the southern polar CH and August–October for the northern one. The third criterion was the absence of any large CHs except the polar ones on the solar disk during the period of interest. We have made this check by visually examining an image. As a result, we have selected three series of images for the study; information about them is given in Table 1.

To measure the SW speed, we have used data from the Solar Wind Electron (SWE) instrument, which worked in 1996 on the Wind spacecraft. SWE included a Vector Electron and Ion Spectrometer (VEIS), which, inter alia, provided information about the SW speed, measured at an interval of ~2 min. Since the Wind measurements were made at the libration point L1, located at a distance of ~1 AU from the Sun, there is a delay between the time of formation of SW near the Sun and the time of its recording at L1. For this reason, we have employed the SW measurements obtained not at the time intervals indicated in Table 1, but at the intervals preceding them, shifted by $\Delta t = a/v$, where $a$ is the distance from the Sun to L1 (~148.0 million km), v is the experimentally determined mean SW speed during the period under study. The formula assumes that SW propagates radially with a constant velocity equal to the velocity near Earth. This assumption is not entirely correct, but it is often used for estimating the transit time of SW to Earth (e.g., [Macneil et al., 2019]). We averaged the SW speed at an interval of ±1 hr.

To measure the CH area, we employed solar images in the 195 Å spectral line, captured by Extreme ultraviolet Imaging Telescope (EIT) on the SOHO (Solar and Heliospheric Observatory) spacecraft in 1996. EIT provided full solar disk images 1024×1024 px with an angular resolution of 2.6′′/px. The 195 Å channel was chosen because, in our opinion, CHs in it have the greatest contrast as compared to the surrounding quiescent solar corona.

To search for the CHs and measure their area, we have developed a fully automatic procedure. In the first step, we selected a solar image segment for the south pole (March 1996) or for the north pole (September, October 1996). An example of the image (segment) is given on the left in the top panel of Figure 2. All segments for the entire series of images were summed to increase the signal-to-noise ratio. Then, we plotted the brightness distribution for the averaged image. This distribution for the southern CH in March 1996 (series No. 1) is shown in the bottom panel of Figure 2. The distribution has two maxima: the first corresponds to CH; the second, to the quiescent solar corona. The lower point (minimum) between the two maxima corresponds approximately to the level of emission intensity at the CH boundary. To find this point, we approximated the minimum area by a parabola. The CH thus found is shown at the top of the right panel. All pixels whose emission intensity is lower than the boundary we identified are painted white. The number of corresponding pixels is proportional to the CH area (without regard for projection effects).

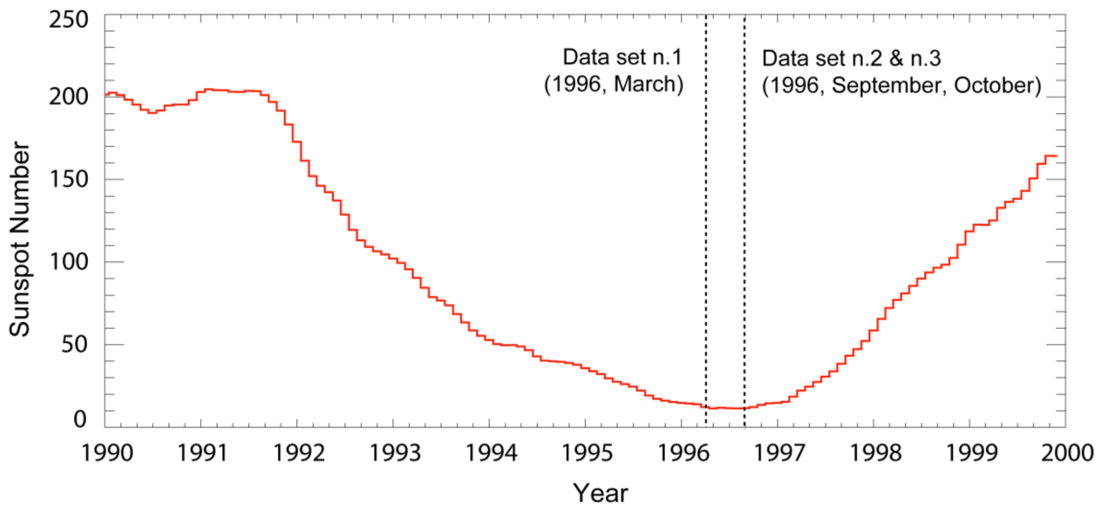


*Figure 1*. Change in the number of sunspots in 1990–2000. Vertical lines indicate the selected observation periods in March and September–October 1996

Table 1

Information about the selected image series

| No | Begin time, UT | End time, UT | Duration, day | Number of images | CH type |
|---|---|---|---|---|---|
| 1 | Mar. 05, 1996, 07:09 | Mar. 20,1996, 00:38 | 14.7 | 54 | southern |
| 2 | Sept. 16, 1996, 20:50 | Sept. 28, 1996, 23:01 | 12.1 | 111 | northern |
| 3 | Oct. 02, 1996, 01:05 | Oct. 11, 1996, 23:00 | 9.9 | 112 | northern |

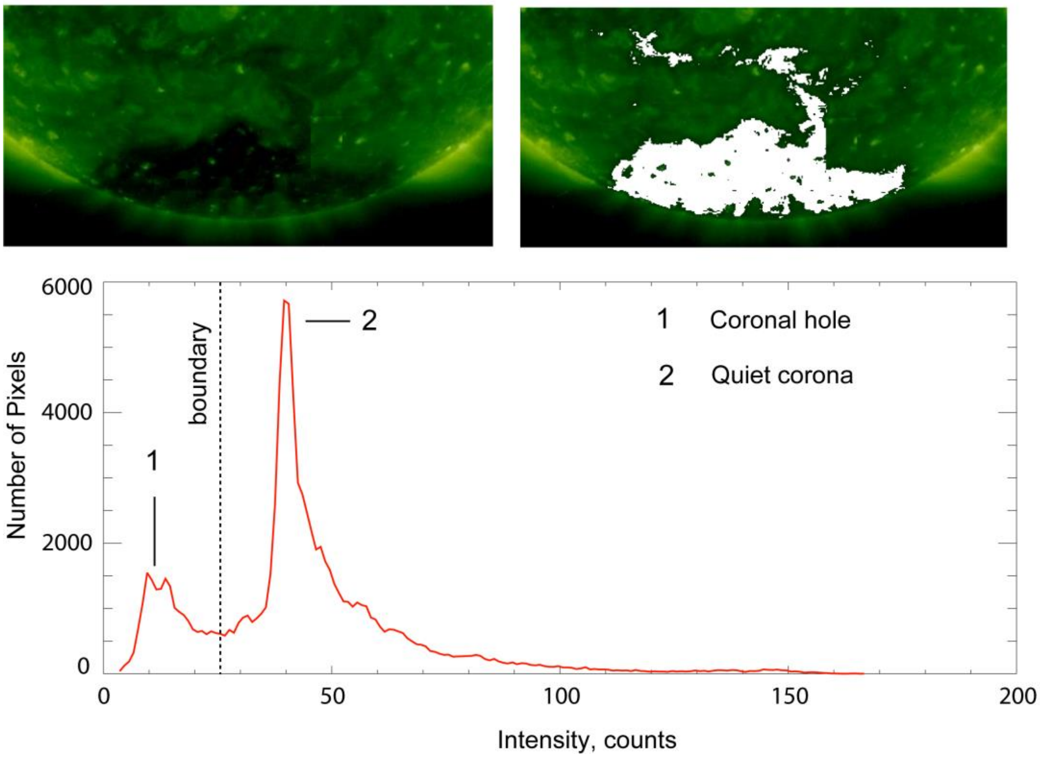


*Figure 2*. Determination of the position and area of polar CHs. Top panel: the original solar image in the 193 Å line (left); the same image of the CH we detected (right). The bottom panel is the intensity distribution over the image

The CH area essentially depends on the method of determining its boundary. Reiss et al. [2021] have demonstrated that depending on the method, parameters such as the CH area, the mean intensity of emission from CH, and the mean magnetic field strength in it can vary by a factor from 1 to 4.5. In the method we adopt, the CH area error is determined by the accuracy of finding the minimum between maxima 1 and 2 (see Figure 2). On the average, this accuracy is ±2 counts, which corresponds to a mean error of ~20 %. At the same time, since the same criterion for the boundary is applied to all CHs in each data series, the error is systemic, i.e. the area is either overestimated or underestimated for all CHs. Such a change in the CH area is equivalent to multiplying all measurements by a constant factor and should not affect the general form of the area dependence on time. For this reason, we believe that conclusions about the presence or absence of a correlation between the CH area and the SW speed will not essentially depend on minor changes in the position of the CH boundary. Note that the correlation coefficient $r(x, y)$ calculated by the Pearson formula, which is used in the work, does not change when multiplying $x$, $y$ by constant factors.

By employing the above procedure, we have processed all three series of images. The results are presented in the next section.

## RESULTS AND CONCLUSIONS

From observation of CHs at low and middle latitudes, it is well known that there is a relationship between the CH area and the speed of SW from the CH (e.g., [Hofmeister et al., 2020]). That is why we assume that if SW is formed in polar CH there should be a correlation between the SW speed and the polar CH area.

Figures 3–5 illustrate a change in the SW speed (bottom panel, left) and the polar CH area (top panel, left) for the three series of images listed in Table 1. On the right of each Figure is an image of the corresponding polar CH (the southern one for series No. 1 and the northern one for series No. 2, 3).

When measuring the area, we intentionally did not introduce a correction related to the projection effect. This is explained by our assumption that the low-latitude part of CH has the greatest effect on SW near Earth since it is the closest to the ecliptic plane. If no correction is made, the relative contribution of the low-

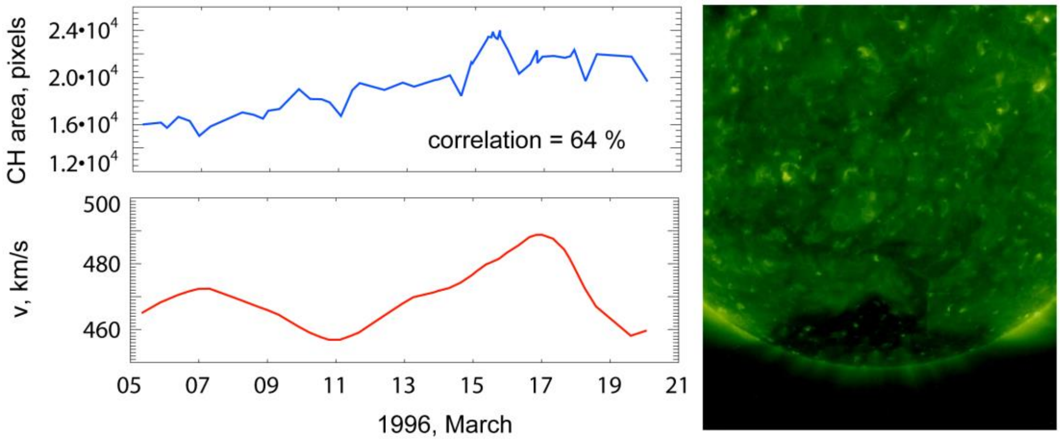


*Figure 3*. Variation in the CH area [px] (top left) and the SW speed [km/s] (bottom left) in March 1996. On the right is a CH image

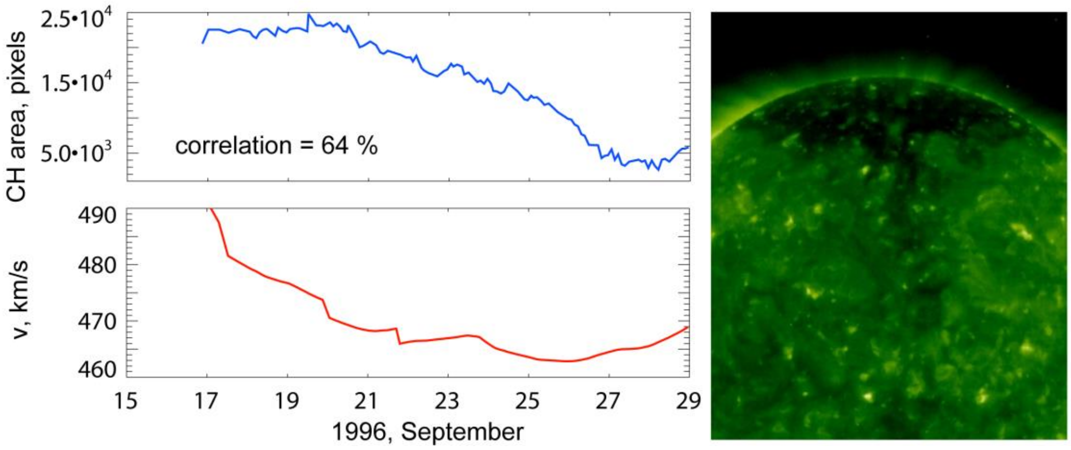


*Figure 4*. The same for September 1996

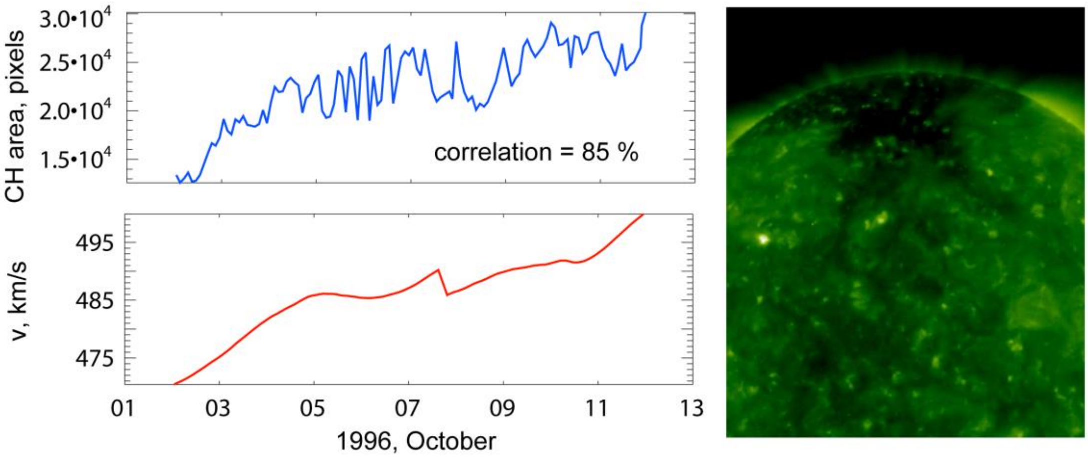


*Figure 5*. The same for October 1996

Table 2

Correlation coefficients between CH area and SW speed
for different longitude intervals relative to the central meridian (CM)

| No. | Observation period | Longitude interval | | | | | |
|---|---|---|---|---|---|---|---|
| | | CM±15° | CM±30° | CM±45° | CM±60° | CM±75° | CM±90° |
| 1 | Mar. 05–20, 1996 | –0.02 | 0.36 | 0.54 | 0.61 | 0.64 | 0.64 |
| 2 | Sept. 16–28, 1996 | 0.70 | 0.66 | 0.64 | 0.65 | 0.64 | 0.64 |
| 3 | Oct. 02–11, 1996 | 0.56 | 0.70 | 0.84 | 0.85 | 0.85 | 0.85 |

latitude part to the total CH area will be higher and the correlation, if any, will be more pronounced.

In all the three cases, we have found a noticeable correlation between the variation in the polar CH area inclined toward Earth and the variation in the SW speed near Earth. For series No. 1 (March 1996, southern CH) and for series No. 2 (September 1996, northern CH), the correlation coefficient is 64 %; and for series No. 3 (October 1996, northern CH), 85 %. We also observe similar general behavior of the plots for the CH area and the SW speed. We believe that the indicated correlation between the CH area and the SW speed for all the three periods we have studied cannot be accidental and indirectly confirms the possibility of SW penetration from the polar CHs into near-Earth space. Earlier in [Borisenko, Bogachev, 2020], as already noted, a high degree of correlation have been found between the SW speed and the area of the southern polar CH observed in March 2020. Notice that the study for March 2019 has been carried out on the basis of data from other instruments: the CH area was measured by SDO's AIA telescope in 193 Å; the SW speed was estimated from ACE SWEPAM data. Thus, this result is confirmed not only for another time period, but also for other instruments.

Since polar CHs can have "tongues" extending to latitudes lower than the main body of CH (see, e.g., Figure 4), of particular interest is the question about the SW correlation not only with the total area of polar CH, but also separately with its low-latitude parts, especially near the central meridian. To answer this question, we compare in Table 2 the correlation coefficients for the CH area measured in the longitude sectors ±15°, ±30°, ±45°, ±60°, ±75°, and ±90° relative to the central meridian. The last value (±90°) corresponds to the total CH area.

Thus, according to the data, the total area of polar CHs correlates better with the SW speed than the CH parts near the central meridian.

We would like to note that high-speed SW streams (600 km/s or higher) are usually associated with low-latitude CHs. The question concerning the sources of slow SW is still under discussion. The acceleration of slow SW in active regions on the Sun is considered as one of the possible mechanisms (see, e.g., [Stansby et al., 2021; Bogachev et al., 2022]). In this case, according to Figures 3–5, SW with speeds 460–500 km/s, which is close to the slow component, is formed in polar CHs. As far as we know, polar CHs as a possible source of slow SW has not been considered before. A lower speed of SW from polar CHs, as compared to low-latitude CHs, may be associated with a higher expansion factor $f$ (see, e.g., [Wang, Sheeley, 1990]). The point is that in the absence of low-latitude CHs the open field lines from polar CHs can fill the entire hemisphere up to the ecliptic plane, i.e. expand to the angle of $2\pi$. If the lower CH boundary is at ~60° (this roughly corresponds to the CHs we have studied), the respective solid angle is $2\pi(1-\cos 30°)\approx 0.27\pi$. The corresponding expansion factor $f=2\pi/(0.27\pi)\approx 7$, which, according to [Wang, Sheeley, 1990], fits the SW speed in the range 550–650 km/s. The values we have measured are somewhat lower and equal to 450–500 km/s. Perhaps this is due to the fact that the SW speed near the ecliptic is mainly affected by CH edges, in which the expansion exceeds the mean value, and hence the SW speed is lower.

It can be observed that according to some data along with the CH area the magnetic field flux can also affect the SW speed (see, e.g., [Prosovetsky, Myagkova, 2011; Akhtemov, Tsap, 2021]). It is, however, difficult to measure the magnetic field for polar CHs due to strong projection effects. For this reason, we did not conduct such a study in this paper.

Kirov et al. [2015] have discussed the possibility of formation of geomagnetic activity at solar minimum due to the effect of polar CHs. We observe a correlation between polar CHs and the SW speed and therefore do not exclude such a possibility. Yet, we did not detect increased geomagnetic activity in this particular case.

The work was financially supported by the Russian Science Foundation (Grant No. 23-72-30002, [https://rscf.ru /project/23-72-30002/].

## REFERENCES

Akhtemov Z.S., Tsap Y.T. On the Relationship between the Magnetic Field of a Low-Latitude Coronal Hole and Its Area. *Astronomy Lett*. 2021, vol. 47, no. 2, pp. 117–122. DOI: 10.1134/S1063773721010011.

Baker K.B., Papagiannis M.D. Correlation of high latitude coronal holes with solar wind streams far above or below the ecliptic. *Solar Phys*. 1982, vol. 78, pp. 365–372. DOI: 10.1007/BF00151616.

Bogachev S.A., Reva A.A., Kirichenko A.S., Ulyanov A.S., Loboda I.P. Influence of Active Regions on Solar Wind Characteristics at the Cycle Maximum. *Astronomy Lett*. 2022, vol. 48, no. 7, pp. 406–415. DOI: 10.1134/S1063773722070039.

Borisenko A.V., Bogachev S.A. Influence of Polar Coronal Holes on Solar Wind Characteristics at the Activity Minimum between Solar Cycles 24 and 25. *Astronomy Lett*. 2020, vol. 46, no. 11, pp. 751–761. DOI: 10.1134/S1063773720110018.

Chashei I.V., Lebedeva T.O., Tyul'bashev S.A., Subaev I.A. Corotating and propagating disturbances in the solar wind based on monitoring of interplanetary scintillations at the LPA radio telescope of the Lebedev Physical Institute in 2017. *Astronomy Rep*. 2020, vol. 64, pp. 66–81. DOI: 10.1134/S1063772920010084.

Chashei I.V., Tyul'bashev S.A., Subaev I.A. Solar Wind from Maximum to Minimum for Cycle 24 in Interplanetary Scintillation Monitoring Data. *Astronomy Rep*. 2022, vol. 66, no. 1, pp. 42–47. DOI: 10.1134/S1063772922010036.

Hofmeister S.J., Veronig A.M., Poedts S., Samara E., Magdalenic J. On the dependency between the peak velocity of high-speed solar wind streams near earth and the area of their solar source coronal holes. *Astrophys. J. Lett*. 2020, vol. 897, no. 1, p. L17. DOI: 10.3847/2041-8213/ab9d19.

Kirov B., Asenovski S., Georgieva K., Obridko V.N. What causes geomagnetic activity during sunspot minimum? *Geomagnetism and Aeronomy*. 2015, vol. 55, pp. 1033–1038. DOI: 10.1134/S0016793215080149.

Ko Y.-K., Fisk L.A., Geiss J., Gloeckler G., Guhathakurta M. An empirical study of the electron temperature and heavy ion velocities in the south polar coronal hole. *Solar Phys*. 1997, vol. 171, no. 2, pp. 345–361. DOI: 10.1023/A:1004943213433.

Krieger A.S., Timothy A.F., Roelof E.C. A coronal hole and its identification as the source of a high velocity solar wind stream. *Solar Phys*. 1973, vol. 29, pp. 505–525. DOI: 10.1007/BF00150828.

Macneil A.R., Owen C.J., Baker D., Brooks D.H., Harra L.K., Long D.M., Wicks R.T. Active region modulation of coronal hole solar wind. *Astrophys. J*. 2019, vol. 887, no. 2, p. 146. DOI: 10.3847/1538-4357/ab5586.

McComas D.J., Riley P., Gosling J.T., Balogh A., Forsyth R. Ulysses' rapid crossing of the polar coronal hole boundary. *J. Geophys. Res.: Space Phys*. 1998, vol. 103, no. A2, pp. 1955–1967. DOI: 10.1029/97JA01459.

Munro R.H., Jackson B.V. Physical properties of a polar coronal hole from 2 to 5 R sun. *Astrophys. J*. 1977, vol. 213, pp. 874–886. DOI: 10.1086/155220.

Neugebauer M., Goldstein B.E., McComas D.J., Suess S.T., Balogh A. Ulysses observations of microstreams in the solar wind from coronal holes. *J. Geophys. Res.: Space Phys*. 1995, vol. 100, iss. A12, pp. 23389–23395. DOI: 10.1029/95JA02723.

Nolte J.T., Krieger A.S., Timothy A., Gold R.E., Roelof E.C., Vaiana G., Lazarus A.J.,. Sullivan J.D., McIntosh P.S. Coronal holes as sources of solar wind. *Solar Phys*. 1976, vol. 46, pp. 303–322. DOI: 10.1007/BF00149859.

Prosovetsky D.V., Myagkova I.N. The correlation between geomagnetic disturbances and topology of quasi-open structures in the solar magnetic field. *Geomagnetism and Aeronomy*. 2011, vol. 51, pp. 1078–1082. DOI: 10.1134/S0016793211080342.

Reiss M.A., Muglach K., Möstl C., Arge C.N., Bailey R., Delouille V., Garton T.M., Hamada A., Hofmeister S.,, Illarionov E.. The Observational Uncertainty of Coronal Hole Boundaries in Automated Detection Schemes. *Astrophys. J*. 2021, vol. 913, pp. 28–36. DOI: 10.3847/1538-4357/abf2c8.

Rotter T., Veronig A.M., Temmer M., Vršnak B. Relation between coronal hole areas on the Sun and the solar wind parameters at 1 AU. *Solar Phys*. 2012, vol. 281, pp. 793–813. DOI: 10.1007/s11207-012-0101-y.

Sime D. G., Rickett B. J. The latitude and longitude structure of the solar wind speed from IPS observations. *J. Geophys. Res.: Space Phys*. 1978, vol. 83, no. A12, pp. 5757–5762. DOI: 10.1029/JA083iA12p05757.

Stansby D., Green L.M., van Driel-Gesztelyi L. Active region contributions to the solar wind over multiple solar cycles. *Solar Phys*. 2021, vol. 296, no. 8, p. 116. DOI: 10.1007/s11207-021-01861-x.

Waldmeier M. Analyse einer koronalen Kondensation. Mit 3 Textabbildungen. *Zeitschrift fur Astrophysik*. 1956, vol. 40, pp. 221–235.

Wang Y.M., Sheeley Jr N.R. Solar wind speed and coronal flux-tube expansion. *Astrophys. J*. 1990, vol. 355, pp. 726–732.

URL: https://rscf.ru/project/23-72-30002/ (accessed April 15, 2023).

*This paper is based on material presented at the 18th Annual Conference on Plasma Physics in the Solar System, February 6–10, 2023, IKI RAS, Moscow.*

Original Russian version: Borisenko A.V., Bogachev S.A., published in Solnechno-zemnaya fizika. 2023. Vol. 9. Iss. 3. P. 122–127. DOI: 10.12737/szf-93202313. 

*How to cite this article*

Borisenko A.V., Bogachev S.A. Relation between the area of polar coronal holes and the solar wind speed at a minimum between solar cycles 22 and 23. *Solar-Terrestrial Physics*. 2023. Vol. 9. Iss. 3. P. 112–117. DOI: 10.12737/stp-93202313.