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# One-Parameter Representation of the Daily Averaged Solar-Wind Velocity

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**Abstract**—An empirical formula was found to describe the dependence *V*(*S*) of the daily average solar-wind velocity *V* on the coronal-hole area *S* on the visible side of the Sun in the form of first- and second-order Taylor expansions. The results can be used for approximate evaluation of the solar-wind velocity at the Earth's orbit from coronal-hole observations.

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## INTRODUCTION

It is now well known that some regions inside coronal holes on the Sun are sources of the fastest quasistationary solar-wind fluxes, while the slower wind is emitted from the entire surface surrounding the Sun at rather large distances. Hence, there is a considerable correlation between the observed average velocity of the solar wind and the area of coronal holes on the Sun (Wang and Sheeley, 1990). The details of formation of the solar-wind fluxes are very complicated and are the subject of many present-day theoretic and experimental studies (Schwenn, 1990; Hollweg, 2003: Obridko et al., 2004).

The aim of the present paper is to attempt to find rather simple empirical relations between the solar-wind velocity at the Earth's orbit and the coronal-hole area based on experimental data and to evaluate their accuracy.

## DATA AND THEIR ANALYSIS

We analyzed daily solar images obtained in 1997–2004 with the Extreme Ultraviolet Imaging Telescope (EIT) onboard the *Solar and Heliospheric Observatory* (*SOHO*) at a wavelength of 284 Å. The coronal holes are seen as dark regions in the images because of the low plasma density and temperature there (Fig. 1). We developed an algorithm for automatic identification of coronal holes in the solar images and implemented it on a computer.

The method for determination of the area and location of coronal holes is based on the classification of the image points by threshold intensity. The coronal holes are characterized by a low brightness as compared to other objects observed on the solar disk. However, the *SOHO* images can differ substantially in their total brightness. That is why the threshold value is automatically determined for each image from the analysis of the brightness histogram. First, the intensities of all pix-

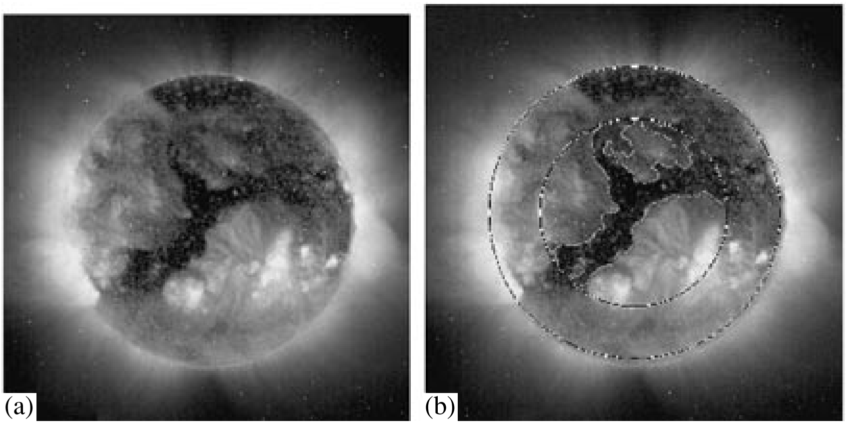

**Fig. 1.** Right panel: the solar image obtained by the EIT telescope at 284 Å onboard the *SOHO* spacecraft on August 9, 2003. Left panel: the results of searching for coronal holes in the central part of the solar image.

els in the image are normalized to fill the interval from 0 to 255. Then the histogram is constructed for the pixel intensity and its maximum is determined ($I_{\max}$). The threshold intensity is calculated by the formula

$$I_t = kI_{\max},$$

where $k$ is the threshold coefficient, equal to 0.6 for images obtained at a wavelength of 284 Å, and $I_{\max}$ is the intensity corresponding to the distribution maximum.

Pixels with intensities below the threshold are pooled together to form objects. After the threshold classification, we obtain a bicolor (black-and-white) image. The black points are assumed to belong to the required object. The following algorithm is used to remove the high-frequency noise in the image. Some region (a square with a side equal to $2r + 1$, where $r$ is the radius of smoothing) is examined around each pixel, starting from the upper left corner of the image, and the number of black and white pixels in the region is calculated. The central pixel is given the color of the majority of pixels in the region of smoothing. If the pixel changes its initial color as a result of this procedure, the algorithm goes back, and the calculations are repeated after displacement by $r + 1$ pixels to the left and upward. The obtained black pixels are combined and classified as coronal holes (Fig. 1).

Calculating the coronal-hole area, it should be kept in mind that the solar surface is spherical, whereas we have plane images to examine. That is why we calculated the area of coronal holes in pixels with allowance for the spherical shape of the Sun. The coronal-hole area $S$ is normalized by the total area of the visible solar-disk image. The area of the solar disk is assumed to be equal to unity.

We used the program described above to determine the areas and locations of coronal holes in the solar images earlier archived in the database of EIT/*SOHO* daily solar images at 284 Å. The program automatically creates a new database, which contains daily information about the number of coronal holes and their parameters (coordinates, area, etc.). A similar method has already been applied by Veselovsky et al. (2005) to investigate the global asymmetry of the Sun in 2003 based on various data. The database applied in the present study covers the period from January 1997 to September 2004. The information related to the coronal holes was collected for both the entire image of the visible solar disk and the most important central region of the Sun, which was bounded by a circle about the center of the solar-disk image with a radius equal to 0.6 radii of the solar image (Fig. 1).

The EIT/*SOHO* daily images of the solar surface were taken from the site http://sohowww.nascom.nasa.gov. The solar-wind parameters were recorded on the *Advanced Composition Explorer* (*ACE*) spacecraft. We took them from the site http://www.srl.caltech.edu/ACE/. Note that both satellites were between the Earth and the Sun near the first Lagrange libration point.

The daily averages of the measured solar-wind velocities were compared to the calculated coronal-hole areas with allowance for the time shift. This shift was, on average, four days and was calculated every time based on the current daily average velocity as the time necessary for the solar wind to come from the Sun to the Earth's orbit. The introduction of this time shift naturally improves the accuracy of the required empirical dependence. We were able to make sure of this by direct trial computations and comparisons. All the empirical dependences presented below include this time shift.

## EMPIRICAL APPROXIMATIONS

The conjectural dependence of the solar-wind velocity $V$ on the area of coronal holes $S$ calculated for the central part of the solar disk is described by the function $V(S)$, which is tried in the form of the Taylor expansion

$$V(S) = V_0 + a(S - S_0) + 0.5b(S - S_0)^2 + r, \qquad (1)$$

where $V_0$ is the solar-wind velocity corresponding to a certain coronal-hole area $S_0$. The constant coefficients $a$, $b$, and $r$ are the first and second derivatives of the function and the remainder of the expansion, respectively. The remainder term (the mean absolute error) is calculated by the formula $r = \Sigma|V - V(S)|/N$, where $V$ is the measured solar-wind velocity, $V(S)$ is the calculated solar-wind velocity, and $N$ is the number of daily measurements of the area of coronal holes during the study period.

We constructed and tested a number of such approximations. Assuming $S_0 = 0$, we determined the corresponding coefficients $a_0$, $b_0$, and $r_0$. Setting $S_0 = S_1$, we found another set of coefficients $a_1$, $b_1$, and $r_1$. The area averaged over the entire observation period from January 1997 to September 2004 was taken as $S_1$. The results of the first- and second-order expansions in Taylor series around the zero area ($S_0 = 0$) are presented in Table 1. The average solar-wind velocity $V_0$ for zero coronal-hole area ($S_0 = 0$) was equal to 391.1 km/s. Table 2 presents the parameters and errors of the first and second-order expansions in Taylor series around the average area $S_1$, which was equal to 0.018 relative units during the study period. For this area, the average solar-wind velocity $V_1$ was 452.5 km/s.

The errors of the coefficients of the Taylor expansion were also estimated for the period from January 1997 to September 2004. The expansion coefficients in Tables 1 and 2 correspond to the minimum root-mean-square absolute error of the calculated function $V(S)$ relative to the measured daily average solar-wind velocity. The root-mean-square absolute error was calculated by the formula $((\Sigma(V - \mathrm{V}(S))^2/N)^{1/2}$, where $V$ is the measured solar-wind velocity, $V(S)$ is the calculated solar-wind velocity, and $N$ is the number of available

**Table 1.** The coefficients of the Taylor expansion by formula (1) at $S_0 = 0$

| Coefficient<br>Approximation | $a_0$ | $b_0$ | $r_0$ | $R^2$ | Root-mean-square error |
|---|---|---|---|---|---|
| Linear | 2365.61 | – | 65.1 | 0.38 | 86.9 |
| Quadratic | 3050.3 | −19312 | 65.1 | 0.39 | 86.4 |

**Table 2.** The coefficients of the Taylor expansion by formula (1) at $S_0 = S_1$

| Coefficient<br>Approximation | $a_1$ | $b_1$ | $r_1$ | $R^2$ | Root-mean-square error |
|---|---|---|---|---|---|
| Linear | 2102.1 | – | 67.1 | 0.38 | 86.8 |
| Quadratic | 2516.7 | −18126 | 66.1 | 0.39 | 86.2 |

daily values of coronal-hole areas for the period in view.

The model error was estimated using a statistical indicator $R^2$, which allowed us to compare the accuracy of the resulting models with the accuracy of the trivial reference model, whose prediction is a simple average over all the cases. If our predictions perfectly coincide with the true (measured) values, $R^2$ is equal to 1. It is close to 1 for good coincidence and close to 0 for a very bad match. The indicator $R^2$ was calculated by the formula $R^2 = 1 - \Sigma(V - \mathrm{V}(S))^2/\Sigma(V - V_{\mathrm{aver}})^2$, where $V$ is the measured solar-wind velocity, $V(S)$ is the calculated solar-wind velocity, and $V_{\mathrm{aver}}$ is the average solar-wind velocity over the study period.

The data presented in Tables 1 and 2 show that the relation between the solar-wind velocity and the area of coronal holes in 1997–2004 obeys a linear law with an average accuracy of up to 86.9 km/s and that the value of $R^2$ is equal to 0.38. The application of the second-order Taylor expansion does not considerably improve the accuracy. The second-order corrections are, on average, substantially smaller than the root-mean-square error of the expansion, as the average area of the coronal holes during the period considered in our study is small and makes up only about 2% (0.018 relative units) of the solar-disk image.

We also considered individual first- and second-order Taylor expansions for each year in order to examine the dependence $V(S)$ at different phases of the solar cycle. We found that the relation $V(S)$ can be satisfactorily described by a linear approximation and that the additional quadratic term only negligibly (by 9% maximum) reduces the root-mean-square absolute error. It is of no use to consider more precise approximations, because their positive contribution will be within measurement errors. In addition, it is worth noting that the maximal value of the linear term does not exceed the error of expansions for 1997, 1998, and 2001. This indicates that the solar-wind velocity in these years was practically independent of the coronal-hole area. This agrees well with general ideas about the formation of high-speed solar-wind fluxes. The coronal holes were mostly on the poles during the growth phase of solar activity in 1997–1998 and could not be considered as sources of the solar wind measured near the Earth. At the solar activity maximum in 2001, sporadic processes on the Sun most efficiently contributed to the high-speed solar wind.

## DISCUSSION

We investigated the relation between the daily average solar-wind velocity and the areas of equatorial coronal holes for the period from January 1, 1997, to September 1, 2004, which covers the rising phase, the maximum, and the declining phase of the 23rd solar cycle (Fig. 2). The correlation between the data on solar-wind velocity and the area of coronal holes, shifted with allowance for the time necessary for the solar wind to propagate from the Sun to the Earth, was equal to 0.51 for the entire period in view. It has already been mentioned that the data on areas of the coronal

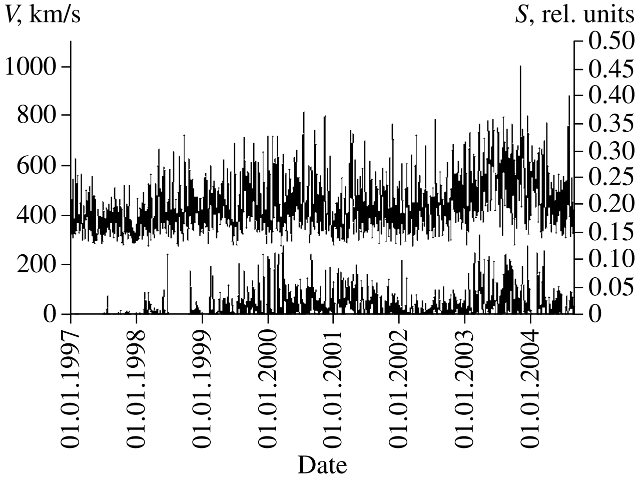

**Fig. 2.** The daily average solar-wind velocity $V$ (km/s, upper curve, left scale) and the coronal-hole area $S$ (relative units, lower curve, right panel) for the period from January 1, 1997, to September 1, 2004.

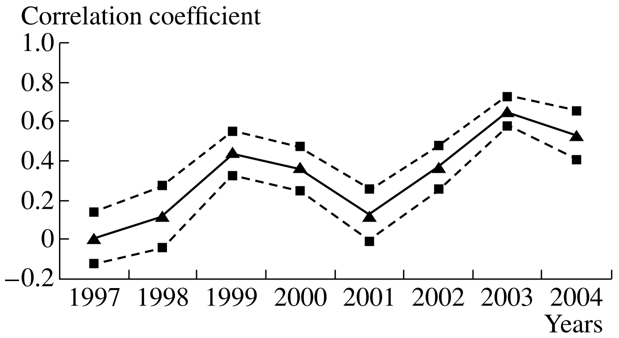

**Fig. 3.** The annual mean coefficient of correlation between the coronal-hole area and the solar-wind velocity from January 1997 to September 2004 and the 98% confidence band.

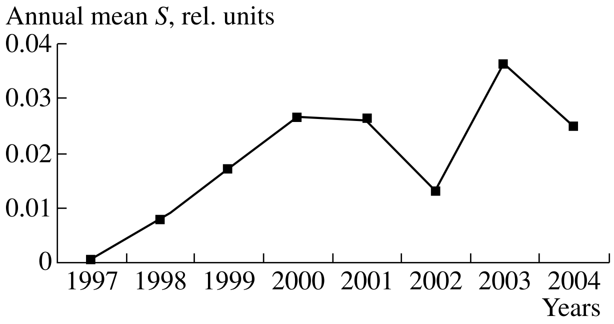

**Fig. 4.** The annual mean total area of equatorial coronal holes calculated for the central region of the solar disk.

holes correspond to moments of time shifted by approximately four days in order to allow for the time of the solar-wind propagation from the Sun to the Earth. This allows us to apply the empirical relations obtained in this study to predict the daily average solar-wind velocities with the lead time equal to this shift and with the prespecified accuracy, which we have estimated above in several ways.

The correlation between the solar-wind velocity and the coronal-hole area was calculated by the formula

$$\rho_{VS} = \sigma_{VS}/(\sigma_{VV}\sigma_{SS})^{1/2},$$

where $N\sigma_{VS} = N\Sigma(VS) - (\Sigma V\Sigma S)$, $N\sigma_{VV} = N\Sigma V^2 - (\Sigma V)^2$, $N\sigma_{SS} = N\Sigma S^2 - (\Sigma S)^2$, $V$ is the measured solar-wind velocity, $S$ is the calculated area of coronal holes, and $N$ is the number of daily measurements of the coronal-hole area over the period under consideration.

To study the relation between the area of the equatorial coronal holes and the daily average solar-wind velocity at different phases of the solar cycle, we calculated the coefficients of correlation for individual years from January 1997 to September 2004 (Fig. 3). During the rising phase of the solar cycle in 1997 and 1998, the coronal holes were mainly located in subpolar regions, and the correlation coefficient was close to zero (Fig. 3). The correlation between the area of the equatorial coronal holes and the measured solar-wind velocity grows in 1999–2000 and 2003–2004 (up to 0.42–0.59), namely, during the rising and declining phases of the 11-year cycle. The good correlation between the area of the equatorial coronal holes and the solar-wind velocity during this period was associated with increasing number and area of the near-equatorial coronal holes (Fig. 4).

At the solar maximum in 2001, the correlation coefficient was equal to 0.16, although the annual mean area of the near-equatorial coronal holes was relatively large (Fig. 4). Sporadic processes on the Sun, rather than quasi-stationary fluxes from coronal holes, contributed most to the high-speed solar wind during this period. This explains the low correlation over this period.

Therefore, the results of our analysis of the annual mean correlations are in good agreement with the annual mean results of the first-order Taylor expansions. It can be seen from the plot in Fig. 4 that the annual mean areas of the equatorial coronal holes make up less than four percent of the area of the solar image. That is why the second-order corrections in the Taylor expansion are, on average, much smaller than the root-mean-square error of the expansion.

## CONCLUSIONS

The one-parameter representation of the daily average solar wind velocity as a function of the coronal-hole area was verified against the entire volume of the 1997–2004 observations and showed an accuracy of about 90 km/s. The dependence of the annual mean solar-wind velocity on the coronal-hole area can be reasonably fitted by the first-order Taylor expansion. The formulas obtained in the present study can be used for predictions of daily average velocities with a lead time of several days with the preestimated accuracy.

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