Solar Phys (2009) 260: 191–206
DOI 10.1007/s11207-009-9435-5

Contrast of Coronal Holes and Parameters of Associated Solar Wind Streams

V.N. Obridko · B.D. Shelting · I.M. Livshits · A.B. Asgarov

Received: 1 December 2008 / Accepted: 2 August 2009 / Published online: 2 October 2009

Abstract It is shown that the contrast of coronal holes, just as their size, determines the velocity of the solar wind streams. Fully calibrated EIT images of the Sun have been used. About 450 measurements in 284 Å have been analyzed. The time interval under examination covers about 1500 days in the declining phase of cycle 23. All coronal holes recorded for this interval in the absence of coronal mass ejections (CMEs) have been studied. The comparison with some other parameters (*e.g.* density, temperature, magnetic field) was carried out. The correlations with the velocity are rather high (0.70 – 0.89), especially during the periods of moderate activity, and could be used for everyday forecast. The contrast of coronal holes is rather small.

Keywords Coronal hole · High-velocity streams · Solar wind

1. Introduction

Shortly after the discovery of coronal holes (CHs) in the Sun, it became clear that they were associated with high-speed streams (HSS) of the solar wind (SW). Nolte *et al.* (1976) established a close relationship between the CH area and the speed of the solar wind outflow from the CH. CHs are sources of fast solar wind (Gosling and Pizzo, 1999; Zhang *et al.*, 2002, 2003; McComas and Elliott, 2002; Bromage, Browning, and Clegg, 2001), forming high-speed streams near the Earth.

Coronal holes are mainly observed in X-rays, extreme ultraviolet, and radio wavelengths and appear as dark regions (Bromage, Browning, and Clegg, 2001; Kahler and Hudson, 2002) in the images.

V.N. Obridko (✉) · B.D. Shelting · I.M. Livshits
Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation (IZMIRAN), Russian Academy of Sciences, Troitsk, Russia
e-mail: obridko@izmiran.ru

A.B. Asgarov
Shemakha Astrophysical Observatory (ShAO), National Academy of Sciences of Azerbaijan Republic, Shemakha, Azerbaijan

There are also physical reasons to believe that the brightness (contrast) of CH must correlate with some characteristics of the associated high-speed solar wind; first of all, with its velocity. This suggestion was made about ten years ago (Obridko, 1998; Obridko *et al.*, 2000) but has not been verified ever since. Another relationship, *i.e.*, the correlation between the velocity and CH area, has been verified repeatedly (Veselovsky *et al.*, 2006; Robbins, Henney, and Harvey, 2006; Vrsnak, Temmer, and Veronig, 2007a, 2007b). In particular, Robbins, Henney, and Harvey (2006) have shown that the correlation between the solar wind velocity and CH area decreases in the epochs of high solar activity. This should be expected, because coronal mass ejections (CMEs) not related directly to coronal holes produce sudden bursts of speed that upset the correlation with the CH area. Besides, the role of the closed-field lines responsible for the particularly slow solar wind streams increases in the periods of high solar activity. Vrsnak, Temmer, and Veronig (2007a, 2007b) studied the relationship between the solar wind velocity and CH area in a relatively quiet period – from January to May, 2005, and obtained a reasonably high correlation coefficient (0.62) at a transport time of 4 days.

The relationship between the magnetic field in the coronal hole and the solar wind velocity was analyzed by many authors. Thus, Obridko, Shelting, and Kharshiladze (2004, 2006) and Belov, Obridko, and Shelting (2006) obtained quite a high correlation between the magnetic-field parameters in the Sun and the speed of the solar wind. Predictions of the solar wind speed at the Earth are regularly made by several groups based on solar potential-field extrapolations. This set of forecasts is based on extrapolation of photospheric longitudinal magnetic-field measurements using a potential-field assumption to locate open-field lines. Using one of these models, a modified Wang and Sheeley (1990, 1992) expansion-factor model, Arge and Pizzo (2000) studied a three-year period centered about the May 1996 solar minimum. They compared the predicted solar wind speed and magnetic polarity with observations near the Earth. Their three-year sample period had an overall correlation of ≈ 0.4 with the observed solar wind velocities. Later on, the model was updated significantly. In this model, the SW velocity at the Earth orbit depends on the local expansion of the magnetic field calculated under the potential approximation (Arge *et al.*, 2003, 2004). The results of the regular forecast of SW velocity by this method are available at the Internet site http://solar.sec.noaa.gov/ws/.

The flow speeds near the coronal base are not necessarily directly connected with the wind speeds at 1 AU. However, since the CH brightness (contrast) probably depends on the magnetic-field structure, which also determines plasma outflow from CH, some correlation between the CH contrast and HSS velocity is physically expected, and it could be a reasonable parameter for geophysical forecast.

Today it is fairly clear that these zones are dominated by open magnetic-field lines. They act as efficient conduits for flushing heated plasma from the corona into the solar wind. Because of this efficient transport mechanism, coronal holes are empty of plasma most of the time and thus appear much darker than the other places of the corona.

This coarse temperature characterization of the corona already shows an interesting trend. Open-field regions, such as coronal holes, have the coolest temperatures of $T \approx 1$ MK; closed-field regions, such as the quiet Sun, have intermediate temperatures of $T \approx 2$ MK; while active regions exhibit the hottest temperatures of $T \approx 2-6$ MK. Open-field regions seem to be cooler because plasma transport is very efficient, while closed-field regions seem to be hotter because the heated plasma is trapped and cannot easily flow away. The temperature difference between the quiet Sun and active regions is a consequence of different magnetic emergence rates, heating rates, conductive loss rates, radiative loss rates, and solar wind loss rates (Cushman and Rense, 1976; Rottman, Orrall, and Klimchuk, 1982; Orrall, Rottman, and Klimchuk, 1983; Cranmer, 2002a, 2002b).

It is still unknown to what extent the solar wind is fed by flux tubes that remain open (and are energized by footpoint-driven wavelike fluctuations), and to what extent much of the mass and energy is input more intermittently from closed loops into the open-field regions. It is notable that present-day models agree by and large with observations. The currently available models have been shown to be able to produce fast ($v \approx 700\ \mathrm{km\,s^{-1}}$), low-density wind from coronal holes and slow ($v \approx 400\ \mathrm{km\,s^{-1}}$), high-density wind from streamers rooted in quiet regions. Note here that, unlike the regular corona where the heat conduction loss is dominating, the loss in the coronal holes is mainly through the solar wind outflow (Withbroe and Noyes, 1977). Thus, the very fact of darkening in the coronal holes is, undoubtedly, associated with the outgoing high-speed streams. This conclusion was also drawn by Badalyan and Obridko (2004, 2007).

Many uncertainties that will be discussed below have prevented us so far from using directly the hypothesis of correlation between the CH brightness and solar wind velocity proposed in our earlier work (Obridko, 1998; Obridko *et al.*, 2000). The brightness ("darkness") of coronal holes was used as a subsidiary qualitative prognostic factor at the Center of Forecasts of IZMIRAN. However, it was difficult to verify this correlation and obtain quantitative characteristics.

The advantage of this method in comparison with the method by Wang – Sheeley – Arge based on the magnetic-field model is that we establish a correspondence between two directly observed events without any additional theoretical assumptions.

Lately, Luo *et al.* (2008) used the CH brightness at the wavelength of 284 Å to calculate the solar wind velocity at the Earth, and rather a high correlation was obtained during a relatively short time interval from 21 November to 26 December 2003. It should be noted, however, that the authors did not use as a prognostic index the CH brightness as such, but rather the inverse brightness in each pixel averaged over a fixed circle at the center of the Sun. This value may differ significantly from the mean brightness. Its physical interpretation is not an easy matter, since in all mechanisms of heating and energy transport we are dealing with the brightness rather than with its inverse value. Besides, averaging all inverse brightness values inside a fixed circle may involve nonstationary processes, such as flares and coronal mass ejections, and thus, corrupt the index obtained. Note here that not too much credit should be given to the high correlation coefficients obtained from the analysis of relatively short, trial intervals of the order of one or two rotations. As a rule, only a few coronal holes appear in the Sun during such interval. Since the mean brightness inside an individual coronal hole changes little with time, high correlation coefficients can be obtained using both the area and the contrast of CH as the prognostic indices.

Therefore, we have chosen to use the pixel brightness directly and to investigate the potential sources of uncertainty associated both with the physical analysis of CH brightness and with its prognostic application. Check calculations have been performed for several periods, including those analyzed in Vrsnak, Temmer, and Veronig (2007a, 2007b) and Luo *et al.* (2008).

Below, in Section 2, we will present the main requirements to and limitations on the solution of this problem. The results of the preliminary analysis will be given in Section 3, and the relationship between the CH contrast indices and solar wind velocity will be investigated in Section 4. In what follows, the correlation revealed is used as a basis for the daily forecast of some parameters of the solar wind.

2. Basic Requirements and Limitations

One of the difficulties in this research is due to the fact that many characteristics and even terms are poorly defined. Unfortunately, no quantitative criteria have been used until now to precisely locate CH from observations (Zhao, Hoeksema, and Scherrer, 1999).

In particular, it is not clear where the CH boundary passes, what wavelengths it should be studied at, how it can be discriminated from the filament-type features, how the contrast is determined, what is the undisturbed region, and how the potential degradation of detectors can be allowed for. We do not know whether the polar and equatorial holes must be analyzed separately.

Figure 1 illustrates the situation on the disk as observed on 28 November 2002 at the wavelength of 284 Å. One can see a complex feature of CH with its multi-connected peripheries which are extremely difficult to identify. Since the inner structure of the hole is highly inhomogeneous, it is not clear whether we should find the minimum brightness, mean

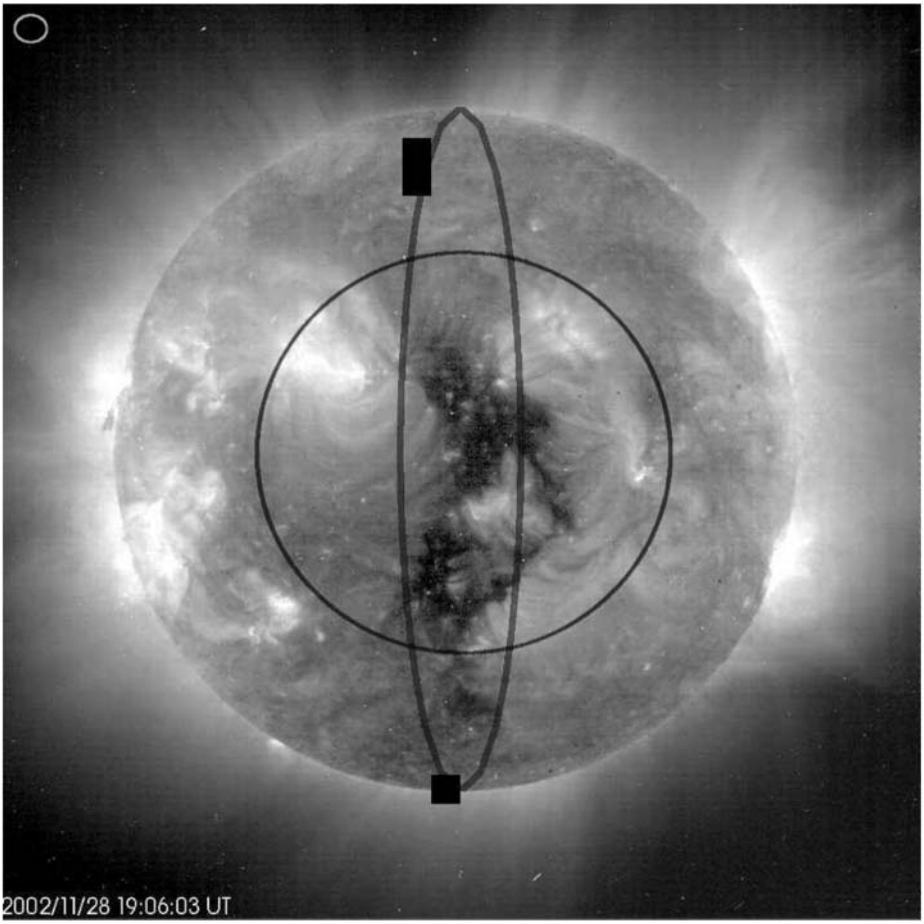

Figure 1 The coronal hole observed at the wavelength of 284 Å on 28 November 2002. The area for the evaluation of the background level on this image is marked with a circle in the upper left corner. The boundaries of the spherical sector and the circle of radius 0.6 R_0 are indicated.

brightness, or complete integral deficit of brightness. Correlation with the solar wind parameters involves additional difficulties in identifying the CH effect and eliminating the other processes, first of all, coronal mass ejections. Therefore, the problem will have to be solved in several steps.

There is also another problem to be solved. The CH brightness and solar wind velocity can be compared directly on the days of real passage of CH over the disk. This approach would clarify the degree of the physical relationship between the CH brightness and solar wind streams. At the second stage, we can simulate the everyday forecast by calculating the prognostic indices for each day no matter whether any CH was observed or not. In doing so, we must, naturally, exclude the days when coronal mass ejections were recorded.

Correlation with the solar wind parameters involves one more source of uncertainty, *i.e.*, the transport time. Note that the optimal transport time may not be the same for different parameters.

3. Preliminary Analysis

The optimal wavelength (spectral line) for our task turned out to be 284 Å (Shen *et al.*, 2006). Among the four EIT channels, this one observes the corona at the greatest height. The temperature of this line is closest to the coronal temperature. The fast expansion of coronal holes with height may enhance the relationship between their contrast and the solar wind parameters. Besides, the EIT 284 Å images of CHs are almost as informative as the soft X-ray emission (Chertok *et al.*, 2001). It is true that according to Scholl and Habbal (2008), the contrast of images in 284 Å is lower than in the other EIT channels. For our problem, however, the expected degree of relationship between the CH contrast and SW parameters is more important than the absolute value of the contrast.

The contrast is determined by the method commonly used in photometry of the spectral lines or sunspot contrast. In order to calculate the contrast, we need the measurements of the background brightness (in our case, outside of the disk) and the time variation of an undisturbed region (equivalent of the continuum in the spectral photometry). Even so, it is not clear if the deficit should be attributed to the mean brightness of the disk, which contains many isolated, very bright features, or to the immediate environment of the CH. A review of the data for 2005 has shown that the background does not virtually change during the year and is determined with an error less than 0.2%.

The brightness of the undisturbed region is extremely uncertain and, therefore, can hardly be used.

As the reference level, we used, conventionally, the brightness of the undisturbed CH environment. In our preliminary analysis we have selected this to be 1.03 times the background value. As shown by preliminary estimates, this does not affect much the result. By using the indices obtained from the assumed values of 1.035 and 1.04 of the background brightness, the correlation with the solar wind parameters remains virtually unchanged. Shen *et al.* (2006) suggested using the brightness gradient to determine the CH boundaries. In doing so, it is assumed that the gradient is maximum at the boundary. This is a very interesting idea, though it is difficult to apply to the everyday forecasting practice. Besides, coronal holes are complex, multi-connected regions, and one cannot be sure *a priori* that the CH boundary is precisely where the gradient reaches its maximum value.

As shown in the early work by Nolte *et al.* (1976), Gosling and Pizzo (1999), Zhang *et al.* (2002, 2003), McComas and Elliott (2002), and Bromage, Browning, and Clegg (2001), the solar wind velocity correlates with a 3 – 5-day shift with the CH passage through the center of the Sun. Therefore, we have performed two calculation procedures. The calculations for each day were performed for a spherical sector of ± 1 day from the central meridian (in which case, the polar CH were also involved), and for a circle of radius equal to 0.6 solar radii. The boundaries of the spherical sector and the circle of radius 0.6 R_0 are marked in Figure 1.

We did not introduce a correction for the projection, and all areas were calculated in terms of the number of the pixels.

The defects like those seen in Figure 1 were dealt with by taking the mean disk value for the pixels involved. This virtually did not affect the mean contrast.

In this preliminary analysis we have used SOHO data in fits-format 1024×1024 from the Internet (http://sohowww.nascom.nasa.gov/cgi-bin/summary_query_form). The list of coronal holes was taken from the site http://www.solen.info/solar/coronal_holes.html (hereafter referred to as CH list). Correlation was analyzed with the daily mean velocity V, magnetic field B, density n, and temperature T at the transport time equal to 2, 3, and 4 days. These data were downloaded from the Internet site http://nsssdc.gsfc.nasa.gov/omniweb/.

The results of this preliminary analysis are described in Obridko *et al.* (2009).

138 coronal holes for the period 2002 – 2006 were selected from the CH list for which the increase of the solar wind velocity at the Earth orbit was not associated with CME.

For each day, we calculated

N_1 the relative number of pixels with the counts per pixel less than a conventional reference level in the units of the total number of pixels in the central sector or central circle, and

d_m the mean deficit of emission from the pixels with counts per pixel less than a conventional reference level.

From a comparison of these CH indices and four solar wind parameters one infers the following.

1. The index most appropriate for SW velocity calculations at a transport time of 4 days is the mean deficit d_m (correlation coefficient $\rho = 0.63$).
2. The parameters under discussion are not as good as expected for the density calculations. We can only note that all of them display negative correlation with density on the fourth day, when the correlation with the velocity is the greatest.
3. A fairly good positive correlation between the mean deficit d_m and temperature is obtained if we use a 3-day shift ($\rho = 0.51$).
4. Calculating the magnetic field from CH brightness does not seem reasonable. The traditional methods of calculating the source-surface field from magnetographic data are more promising. In particular, such a technique was applied in Belov, Obridko, and Shelting (2006).

4. Analysis with the Use of Fully Calibrated Images

For a detailed analysis, we have used data from the Internet site http://umbra.nascom.nasa.gov/eit/eit-catalog.html treated with the Solarsoft program eit_prep, which was downloaded from the site http://sohowww.nascom.nasa.gov/solarsoft/soho/eit/idl/anal/eit_prep.pro. In this case, we need not make allowance for the background value based on the brightness at the outer corner of the image. The Solarsoft program eit_prep returns a fully-calibrated

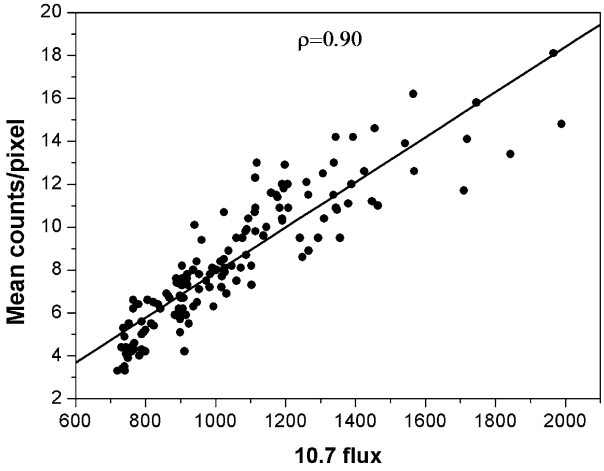

Figure 2 Correlation of the 284 Å counts per pixel averaged over the total solar disk and the 10.7-cm radio flux.

image taking into account that the CCD saturation and degradation are highly nonuniform over the image.[1]

We have treated all of the CH observations listed in CH list and daily observations obtained in 2005. Before studying the relationship between the CH contrast and SW parameters, we shall consider some other correlations.

4.1. The Mean Brightness in 284 Å and 10.7-cm Flux

Figure 2 compares the 284 Å counts per pixel averaged over the total solar disk and the 10.7-cm radio flux. The linear correlation coefficient is 0.90, though at the beginning and at the end of the interval under examination, the points somewhat depart from the straight line. However, one could hardly expect a full coincidence, since the emissions compared come from different temperature regions. The 284 Å image represents a plasma of 2×10^6 K, while the 10.7-cm radio flux originates at the temperatures of a few times 10^5 K. Besides the temperature, these emissions differ also by the density and magnetic-field parameters in their effective sites of origin. Nevertheless, a good agreement of these indices of solar emission is the criterion of accuracy of our estimates.

4.2. Method of Calculation of CH Contrast Index

Figure 3 illustrates two coronal holes observed at the center of the disk on 19 November 2002 and on 6 January 2003. One can see that they differ significantly not only in brightness but also in the inner structure. A typical coronal hole is strongly inhomogeneous with sprinkles of numerous bright points inside it. The CH contrast changes markedly from its center to the periphery. The definition of the CH boundary as the line of maximum brightness gradient proposed by Shen *et al.* (2006) obviously restricts the range of the points that belong to CH. Moreover, the notion of CH area itself becomes somewhat vague.

The solution of this problem might be sought for by turning to magnetic-field measurements. It is well known (see, *e.g.*, Obridko and Shelting (1999) and references therein) that

[1] The authors are grateful to the referee who recommended to use this program, which increases significantly the reliability of the results.

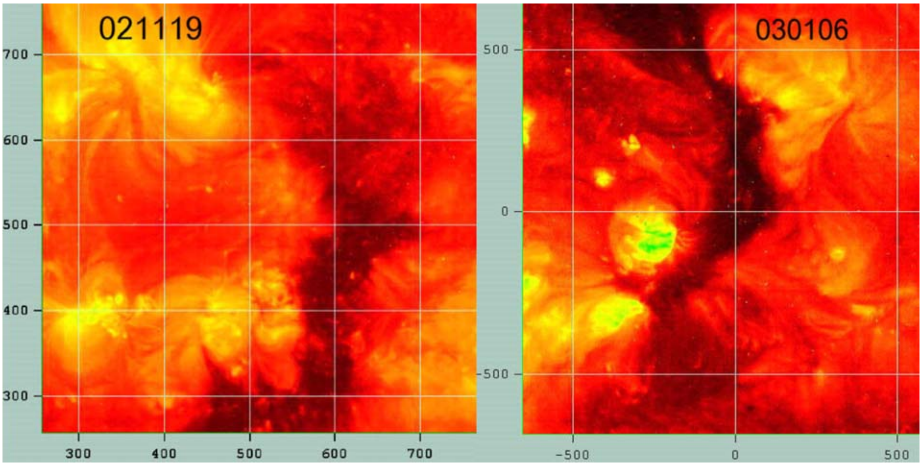

Figure 3 Two coronal holes observed at the center of the disk on 19 November 2002 and on 6 January 2003.

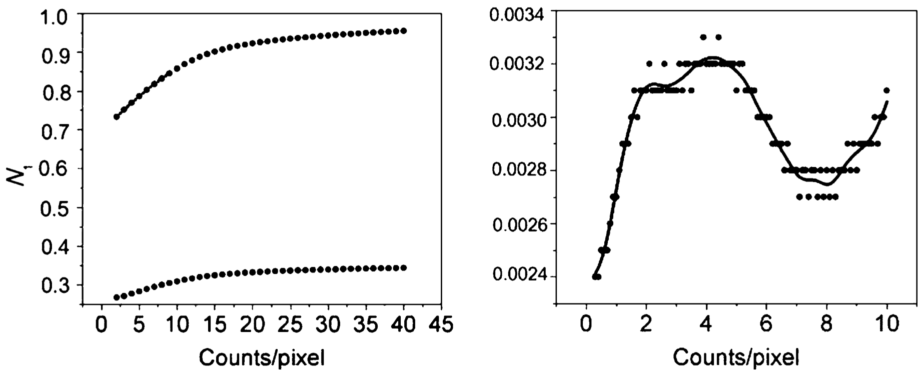

Figure 4 (a) Relative number of the pixels which have brightness lower than the threshold x (value indicated at the abscissa) and are inside a circle of radius 0.6 R_0 (upper curve) or inside the entire disk (lower curve). (b) Relative number of the pixels which have brightness in the range $\{x, x-0.1\}$ and are inside a circle of radius 0.6 R_0.

the coronal holes are open magnetic configurations. We can calculate the footpoints of the open-field lines and compare them with CH images. This method was proposed by Scholl and Habbal (2008). However, a large number of the magnetic-field harmonics must be calculated to give the inner fine structure of CH. Besides, we tried to study the relationship between the CH contrast and solar wind parameters without invoking additional theoretical considerations. Anyway, one can hardly expect complete agreement between the magnetic and inner photometric structure of CH, since the latter depends not only on the magnetic structure but also on many other parameters of the solar plasma.

Figure 4a shows the relative number of the pixels which have brightness lower than the threshold x (the value indicated at the abscissa) and are inside a circle of radius 0.6 R_0 (red curve) or inside the entire disk (black curve). Figure 4b represents the relative number of the pixels which have brightness in the range $\{x, x-0.1\}$ and are inside a circle of radius 0.6 R_0. The calculations were performed for the coronal hole observed on 12 November

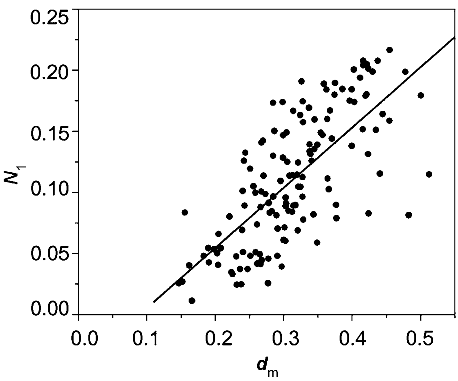

Figure 5 Correlation of indices N_1 and d_m.

2002 (see Figure 1). One can see a local maximum in the vicinity of $x \approx 3.0$. On the whole, the relative number of the pixels whose brightness is in the range $\{x, x - 0.1\}$ changes little in the range $x = 1.75 - 4.0$.

Therefore we shall take, as the working indices, the following two:

N_1 the relative number of the pixels whose brightness is lower than a certain threshold value referred to as the conventional reference level (RL),

d_m the ratio of the mean deficit of brightness of these pixels to RL.

Then, the problem is reduced to an adequate choice of the reference level (RL). It is obvious that the indices we find can change significantly depending on the RL. The problem is simplified by the fact that we are rather interested in the relationship between the CH brightness and SW parameters than in the absolute value of the contrast.

Thus, to avoid uncertainty, we have estimated the correlation between the solar wind velocity and our indices at different reference levels. The correlation coefficients were calculated for RL values of 2.0, 2.5, 3.0, and 3.5 separately for years 2003, 2004, and 2005, both for the sector of ± 1 day from the central meridian and for the circle of radius 0.6 R_0. It turned out that the correlation coefficient in the RL range under examination was, on the average, about 60% and changes by less than 4% for different RL values. On the other hand, though the correlation coefficient in each particular year is rather high, the linear regression line somewhat changes from year to year.

A special question is how independent our indices N_1 (close to CH area) and d_m are. Since both are based on the brightness distribution of the pixels, they are, obviously, much alike. Figure 5 shows the correlation of these indices for 138 coronal holes observed during 2002 – 2006. The correlation coefficient is 0.72. Nevertheless, these two parameters are not identical, since there are a lot of coronal holes with a large area and low contrast.

4.3. CH Contrast and Solar Wind Speed

Based on the results obtained above, we have compared the solar wind velocity with the CH brightness calculated for the period 2002 – 2006. The calculations were performed separately for each year. The reference level was taken equal to 3.0. As seen from the previous section, the result depends weakly on the choice of RL, but an additional argument was that RL = 3 corresponds approximately to the RL value assumed in our preliminary analysis (Obridko *et al.*, 2009). The calculations were performed for all CHs whose passage across the disk was not accompanied by coronal mass ejections. The total of 138 coronal holes

Table 1 Correlation between the CH indices in the central sector and solar wind parameters.

Sector			Circle		
Years	N_1	d_m	Years	N_1	d_m
2002	0.28	0.63	2002	0.62	0.59
2003	0.61	0.57	2003	0.77	0.57
2004	0.55	0.61	2004	0.71	0.75
2005	0.57	0.75	2005	0.57	0.72
2006	0.37	0.54	2006	0.27	0.48

was analyzed. Since we are interested in the physical relation between the CH contrast and solar wind velocity, the velocity was taken at the instant when it reached its maximum value. Thus, the transport time was ignored. The analysis was performed both for the sector of ± 1 day from the central meridian and for the circle of radius 0.6 R_0 (see Figure 1). The results are given in Table 1.

As seen from Table 1, the mean contrast of CH (d_m) correlates with the solar wind velocity somewhat better and more stably than the relative number of the pixels with the brightness below RL does. The results of calculations for the sector of ± 1 day from the central meridian (*i.e.*, inclusion of the polar zone) and for the circle of radius 0.6 R_0 do not differ noticeably. In the years when a sufficient number of CH was observed (2004 – 2005), the correlation with d_m makes up 0.72 – 0.75, which allows us to use this index in the everyday forecasting practice.

The use of the fully-calibrated images has somewhat increased the maximum correlation coefficient (up to 0.75) compared to that obtained from uncalibrated images (see Section 3 above).

5. Calculation of Solar Wind Parameters in Everyday Forecast

At first sight, this problem is similar to direct correlation of the CH brightness deficit and solar wind characteristics. However, there are two items that make the situation somewhat different.

1. In the forecasting practice, we do not know in advance the transport time, which may vary within 2 – 4 days.
2. The everyday forecast involves the days when no coronal holes are observed on the Sun. This means that the total dynamic range of data is expanded.
3. On some days, coronal mass ejections are observed on the disk alongside with coronal holes, changing the velocity range dramatically. As will be seen below, the correlation between the brightness and solar wind velocity of such days breaks down completely.

5.1. Correlation Analysis in the Absence of CME

First, we have analyzed the time interval from 20 January to 5 May 2005 (days of the year DOY 20 – 125), except for DOY 70 – 90, when no 284 Å data were available. Since the halo CME were absent in that period, we can assume that solar wind was undisturbed, and its parameters were controlled solely by CH. The first part of the interval under examination coincides with that analyzed in Vrsnak, Temmer, and Veronig (2007a, 2007b).

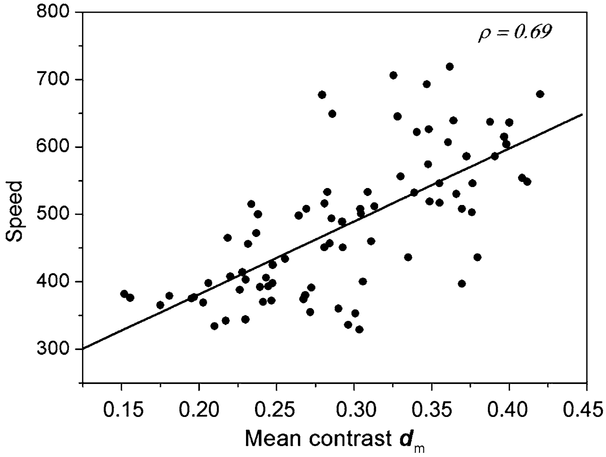

Figure 6 Correlation between the SW speed and daily mean contrast d_{m} (20 January to 5 May 2005).

Table 2 Correlation between the CH brightness indices and the solar wind parameters.

Sector	$\Delta t = 2$				$\Delta t = 3$				$\Delta t = 4$			
	B	V	n	T	B	V	n	T	B	V	n	T
N_1	0.30	0.37	0.11	0.28	0.11	0.61	0.14	0.47	−0.18	0.63	−0.35	0.42
d_{m}	0.35	0.24	0.25	0.19	0.17	0.56	−0.06	0.50	−0.13	0.62	−0.27	0.44
Circle	$\Delta t = 2$				$\Delta t = 3$				$\Delta t = 4$			
	B	V	n	T	B	V	n	T	B	V	n	T
N_1	0.35	0.40	0.12	0.29	0.13	0.62	−0.17	0.49	−0.16	0.64	−0.35	0.41
d_{m}	0.53	0.32	0.29	0.29	0.28	0.67	−0.12	0.62	−0.13	0.69	−0.42	0.41

Figure 6 represents the correlation between the solar wind velocity and the daily mean contrast d_{m} for this interval under the assumption that the transport time is 4 days. The correlation coefficient is 0.69. Detailed information on the relationship between the daily contrast indices and solar wind parameters is given in Table 2.

The parameter d_{m} is, obviously, the best one. The highest correlation with V is observed on the fourth day. A fairly good correlation with the temperature T has been revealed at $\Delta t = 3$. No reliable correlation was established with the magnetic field and plasma density in SW. The correlation between the CH contrast indices and SW velocity is somewhat lower, because, in this case, the analysis involved the days when coronal holes at the center of the disk were absent.

Figure 7 represents the solar wind velocity both measured (blue) and calculated (red). The abscissa shows the observation time in the Sun; the solar wind data are given with a shift of 4 days. At the end of 2005, there was a relatively long period when no significant full halo frontside CME were observed (DOY 250 – 365). Figure 8 illustrates the measured and calculated SW velocities for DOY 266 – 361, also with one data gap. The correlation between the measured and calculated values is quite satisfactory.

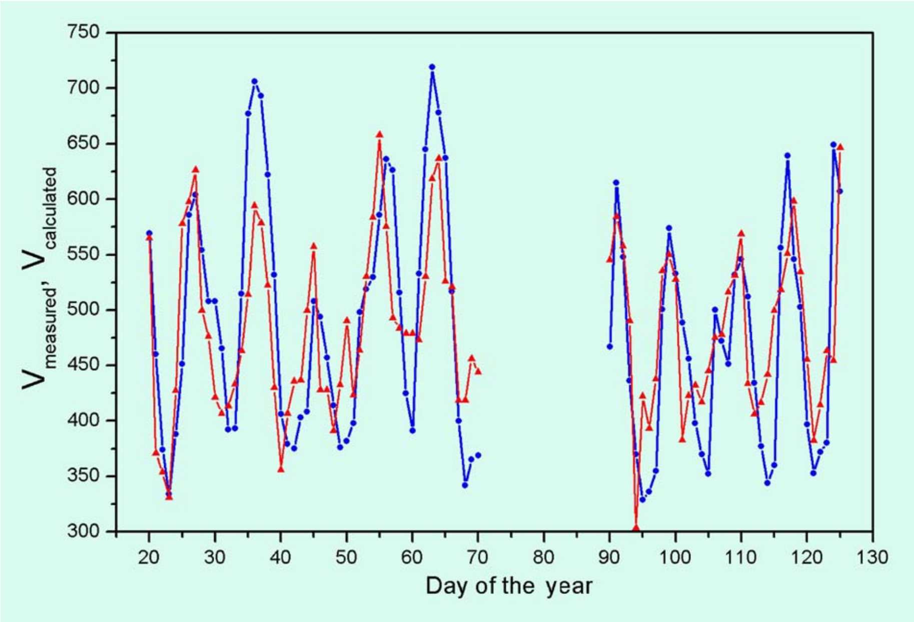

Figure 7 Solar wind velocity measured (blue) and calculated (red) during the time interval from 20 January to May 2005.

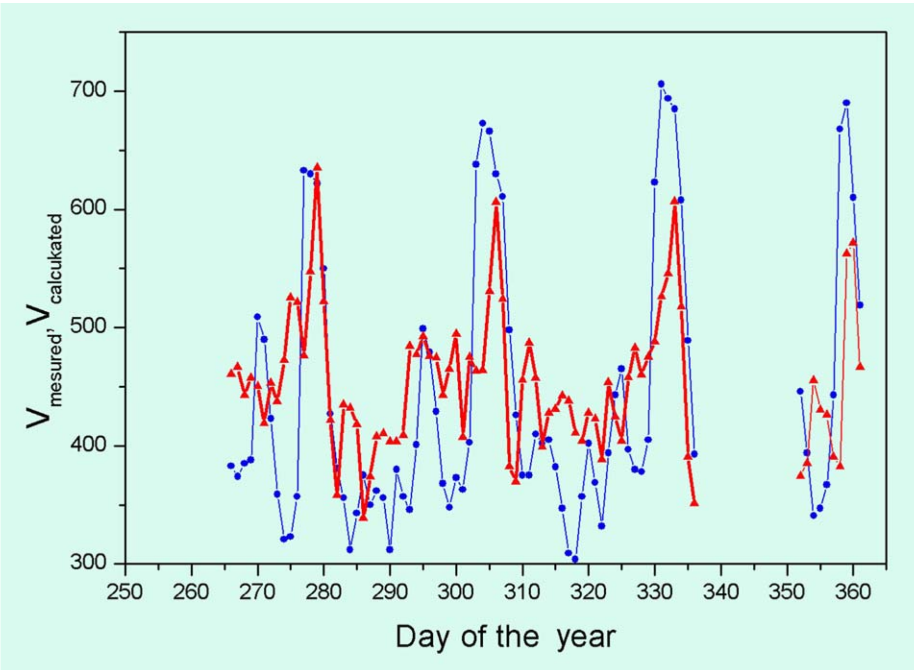

Figure 8 Measured and calculated SW velocities for DOY 266 – 361.

Note that we have assumed the standard transport time equal to 4 days, while, as seen from the figures and tables above, the real shift ranges from 3 to 5 days.

Finally, we have considered the period from 21 November to 26 December 2003, also free of CME events. This interval was also analyzed in Luo *et al.* (2008). The correlation between the mean brightness and velocity at a 4-day shift coincides in both works and amounts to 0.89.

Thus, the forecast of the quiet solar wind velocity on the base of brightness deficit in coronal holes is fully justified for the periods when the disturbing effect of coronal mass ejections is absent. An important thing to emphasize is that, regardless of the correlation coefficient, all events of the increase of velocity above 500 km s^{-1} recorded during the periods under discussion are well described by our calculated curves. The mean difference between the calculated and measured values is less than 50 km s^{-1}. The presence of CME, however, changes the situation dramatically.

5.2. Violation of CH – SW Relationships in the Presence of Halo Frontside CME

Daily indices have been calculated for the second half of 2005, when a number of halo frontside CME were observed. Naturally, the CME events were found out to distort the statistics based on coronal holes. Figure 9 illustrates the calculated and measured velocities for DOY 125 – 250 with one data gap. The abscissa shows the observation time in the Sun; the SW velocity data are given with a shift of 4 days.

As seen from the figure, the increase of SW velocity is not accompanied by the increase of d_m index in six cases. In five cases, the increase is definitely associated with

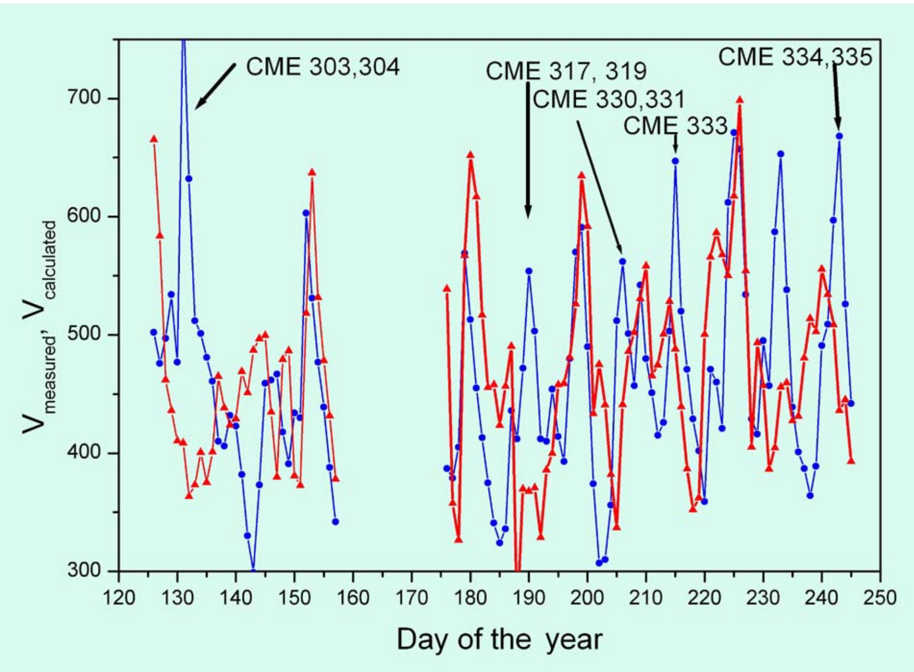

Figure 9 Measured and calculated velocities for DOY 125 – 250.

CME events. The list of these CME with comments is given below. Data are taken from http://lasco-www.nrl.navy.mil/halocme.html.

303 Full halo CME on 2005/05/11, frontside on DOY 131, associated with an M-class X-ray flare on NOAA AR 10758.
304 Full halo CME on 2005/05/13, frontside on DOY 133, associated with a LDE M-class X-ray event on NOAA AR 10759.
317 Two frontside events on 2005/07/07: M4.9 X-ray flare on DOY 188, associated with an M4.9 X-ray flare on NOAA AR 10786.
319 Full halo event on 2005/07/09, frontside on DOY 190, associated with an M2.8 X-ray flare on NOAA AR 10786.
330 Asymmetric full halo event on 2005/07/27 (DOY 208), determined as a strong limb event (barely on the backside).
331 Asymmetric full halo event on 2005/07/30, frontside on DOY 211, associated with an X1.3 X-ray flare on NOAA AR 10792.
333 Frontside event on 2005/08/05 (DOY 217), associated with a long duration C-class flare on AR 10792.
334 Complex event on 2005/08/31 (DOY 242).
335 Faint full halo event on 2005/08/31, frontside on DOY (242), associated with a C-class X-ray event.

The increase on DOY 233 (*i.e.*, on 22 August 2005) remains unexplained. The catalogue http://lasco-www.nrl.navy.mil/halocme.html does not contain information of CME on that day. But according to the catalogue by Gopalswamy *et al.* (2009) http://cdaw.gsfc.nasa.gov/CME_list, CME events were recorded on 22 and 23 August, though their source was close to the western limb, and it was not clear whether they were frontside CMEs.

Thus, all reported increases of SW velocity not predicted by our calculations were determined entirely by CME. Note also that our calculations do not describe well enough the cases of extremely low SW velocities, the cause of which still remains obscure. These streams are most likely to come from the regions of closed magnetic field, and their transport time at extremely low velocities would be more than 4 days.

6. Summary and Conclusions

In this work, we have compared the indices of contrast of coronal holes with some characteristics of the associated solar wind streams. The indices analyzed were the relative number of the pixels with the brightness below some standard level and the mean contrast in these pixels. The fully-calibrated solar images were used. Our main task was to verify the hypothesis of the relationship between the CH contrast and the velocity of the solar wind streams.

The hypothesis of direct correlation between the velocity of the quiet solar wind and CH contrast was verified for all days in 2005 when observations in 284 Å were available (total of 270 days), 35 days in 2003, and 138 separate observations of coronal holes from 2002 to 2006, *i.e.*, near 450 measurements. The length of the time interval under consideration was about 1500 days in the declining phase of cycle 23. All coronal holes recorded in this period in the absence of coronal mass ejections were analyzed. The deficit of brightness in CH was about 0.20 – 0.50 compared to the nearest CH environment and 0.70 – 0.90 compared to the mean disk brightness on that day.

On the whole, it can be stated that the hypothesis is fully corroborated. Since we only used the directly observed parameters and did not make any additional theoretical assumptions, this empirical relationship may provide another observational constraint on solar wind/coronal heating models.

With the transport time of 4 days, the correlation of our indices with the solar wind velocity is usually as high as 070 – 0.90. All increases of velocity above 500 $\mathrm{km\,s^{-1}}$, recorded during the periods under discussion, are well described by our calculations. The mean difference between the calculated and measured values is less than 50 $\mathrm{km\,s^{-1}}$.

This allows the use of this method for direct prediction of the SW speed. Note that the correction for CCD saturation and degradation fulfilled in this study has undoubtedly increased the reliability of our results. However, all correlations were conserved both qualitatively and (most notably) quantitatively compared to our earlier results described in Section 1 (Obridko *et al.*, 2009). This is, probably, due to the fact that both indices used in our analysis are the averaged quantities, and their correlation with the solar wind parameters depends weakly on the CCD saturation and degradation. It is very important to bear in mind that the prognostic rule based on the regression equation must be re-calculated annually. Besides, the everyday forecast must, naturally, take into account the possible superposition of coronal mass ejections, which additionally increase the recorded velocity. The use of raw data without re-calibration somewhat reduces the amount of work on issuing the forecast.

The other solar wind parameters are rather difficult to calculate from the CH contrast. We can only note a significant correlation with temperature and negative correlation with density. This fact is interesting in terms of the mutual relation of different solar wind parameters, but can hardly be used in an everyday forecast.

It should be noted that the presence of surrounding coronal material (loops) may partially or completely obscure small holes even at the central meridian. Therefore, our method is hardly applicable to very small CH.

Acknowledgements We are grateful to the SOHO team for the data available on the Internet site (http://sohowww.nascom.nasa.gov/cgi-bin/summary_query_form), as well as to the authors of the sites Coronal hole history (since late October 2002) – http://www.solen.info/solar/coronal_holes.html and http://nsssdc.gsfc.nasa.gov/omniweb/. We also thank Joseph B. Gurman and Frederic Auchere for valuable advice on handling the Solarsoft program eit_prep, and A.V. Belov and I.M. Chertok for useful discussions. The work was supported by the Russian Foundation for Basic Research, project no. 08-02-00070.

References

Arge, C.N., Pizzo, V.J.: 2000, *J. Geophys. Res.* **105**, 10465.
Arge, C.N., Odstrcil, D., Pizzo, V.J., Mayer, L.R.: 2003, In: Velli, M., Bruno, R., Malara, F. (eds.) *Solar Wind Ten, AIP Conf. Proc.* **679**, 190.
Arge, C.N., Luhmann, J.G., Odstrcil, D., Scrijver, C.J., Li, Y.: 2004, *J. Atmos. Solar-Terr. Phys.* **66**, 1295.
Badalyan, O.G., Obridko, V.N.: 2004, *Astron. Rep.* **48**, 678.
Badalyan, O.G., Obridko, V.N.: 2007, *Solar Phys.* **238**, 271.
Belov, A.V., Obridko, V.N., Shelting, B.D.: 2006, *Geomagn. Aeron.* **46**, 430.
Bromage, B.J.I., Browning, P.K., Clegg, J.R.: 2001, *Space Sci. Rev.* **97**, 13.
Chertok, I.M., Mogilevsky, E.I., Obridko, V.N., Shilova, N.S., Hudson, H.S.: 2001, *Astrophys. J.* **567**, 1225.
Cranmer, S.R.: 2002a, In: Martens, P.C.H., Cauffman, D. (eds.) *Multi-Wavelength Observations of Coronal Structure and Dynamics – Yohkoh 10-th Anniversary Meeting*, *COSPAR Colloq. Ser.* **13**, 3.
Cranmer, S.R.: 2002b, *Space Sci. Rev.* **101**, 229.
Cushman, G.W., Rense, W.A.: 1976, *Astrophys. J.* **207**, L61.
Gopalswamy, N., Yashiro, S., Michalek, G., Vourlidas, A., Freeland, S., Howard, R.A.: 2009, *Earth, Moon, Planets* **104**, 295.
Gosling, J.T., Pizzo, V.J.: 1999, *Space Sci. Rev.* **89**, 21.

Kahler, S.W., Hudson, H.S.: 2002, *Astrophys. J.* **574**, 467.
Luo, B., Zhong, Q., Liu, S., Gong, J.: 2008, *Solar Phys.* **250**, 159.
McComas, D.J., Elliott, H.A.: 2002, *Geophys. Res. Lett.* **29**, 1314.
Nolte, J.T., Krieger, A.S., Timothy, A.F., Gold, R.E., Roelof, E.C., Vaiana, G., Lazarus, A.J., Sullivan, J.D., McIntosh, P.S.: 1976, *Solar Phys.* **46**, 303.
Obridko, V.N.: 1998, In: Feng, X.S., Wei, F.S., Dryer, M. (eds.) *Advances in Solar Connection with Transient Interplanetary Phenomena, Proc. Third SOLTIP Symp.*, International Academic Publishers, Beijing, 41.
Obridko, V.N., Shelting, B.D.: 1999, *Solar Phys.* **187**, 185.
Obridko, V.N., Shelting, B.D., Kharshiladze, A.F.: 2004, *Astron. Vestn.* **38**, 261.
Obridko, V.N., Shelting, B.D., Kharshiladze, A.F.: 2006, *Geomagn. Aeron.* **46**, 294.
Obridko, V.N., Fomichev, V.V., Kharshiladze, A.F., Zhitnik, I., Slemzin, V., Wu, S.W., Ding, J., Hathaway, D.: 2000, *Astron. Astrophys. Trans.* **18**, 819.
Obridko, V.N., Shelting, B.D., Livshits, I.M., Asgarov, A.B.: 2009, *Astron. Rep.* **86**(10), 1–9.
Orrall, F.Q., Rottman, G.J., Klimchuk, J.A.: 1983, *Astrophys. J.* **266**, L65.
Robbins, S., Henney, C.J., Harvey, J.W.: 2006, *Solar Phys.* **233**, 265.
Rottman, G.J., Orrall, F.Q., Klimchuk, J.A.: 1982, *Astrophys. J.* **260**, 326.
Scholl, I.F., Habbal, S.R.: 2008, *Solar Phys.* **248**, 425.
Shen, C.L., Wang, Y.M., Ye, P.Z., Wang, S.: 2006, *Astrophys. J.* **639**, 510.
Veselovsky, I.S., Persiantsev, I.G., Ruasanov, A.Y., Shugai, Y.S.: 2006, *Solar Syst. Res.* **40**, 427.
Vrsnak, B., Temmer, M., Veronig, A.M.: 2007a, *Solar Phys.* **240**, 315.
Vrsnak, B., Temmer, M., Veronig, A.M.: 2007b, *Solar Phys.* **240**, 331.
Wang, Y.-M., Sheeley, N.R. Jr.: 1990, *Astrophys. J.* **355**, 726.
Wang, Y.-M., Sheeley, N.R. Jr.: 1992, *Astrophys. J.* **392**, 310.
Withbroe, G.L., Noyes, R.W.: 1977, *Annu. Rev. Astron. Astrophys.* **15**, 363.
Zhang, J., Woch, J., Solanki, S.K., von Steiger, R.: 2002, *Geophys. Res. Lett.* **29**, 1236.
Zhang, J., Woch, J., Solanki, S.K., von Steiger, R., Forsyth, R.: 2003, *J. Geophys. Res.* **108**, 1144.
Zhao, X.P., Hoeksema, J.T., Scherrer, P.H.: 1999, *J. Geophys. Res.* **104**, 9735.