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Coronal Holes in the 21-st to 23-rd Cycles of Solar Activity

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Abstract We present identifications of coronal holes (CH) from observations in the He I 10830 Å line at Kitt Peak observatory (years 1975 to 2003) and in the EUV 195 Å line with SOHO/EIT (1996 to 2012). In order to discriminate the CH we have developed semi-automatic techniques for delineation of CH borders on synoptic charts and for subsequent mapping of these borders on magnetic field charts. Using these techniques, we superimposed CH borders on magnetic field charts over the time interval 1975 to 2012. A major contribution to the total area was made by high-latitude CH, but in the decline phase of the 23-rd solar cycle, the contribution from low-latitude CH increased substantially. In the 23-rd cycle, CH displayed appreciably lower degree of unipolarity of the magnetic field. Both variations in the flux of galactic cosmic rays and those in the angle of inclination of the heliospheric current sheet conformed the cyclic variations of the area of CH. High-latitude CH affect the parameters of solar wind in the ecliptic plane.

Keywords: Coronal holes; Solar cycle; Solar wind

1. Introduction

Observations made with coronagraphs and during solar eclipses (Waldmeier, 1975), the data obtained with space missions, in the He I 10830 Å line, and radio observations indicate that coronal holes (CH) represent an important index of the solar activity. Coronal holes are long-lived extended formations with decreased temperature and abnormally low density (Granmer, 2009), localized in the regions of unipolar large-scale magnetic fields with open lines of force, which do not inhibit the radial expansion of coronal plasma (Harvey and Sheeley, 1979; Insley, Moore and Harrison, 1995; Obridko and Shelting, 1989). CH are sources of high-speed solar wind (with the average velocity around 700 km/s and a decreased plasma density $n \sim 4cm^{-3}$), which noticeably affects the Earth

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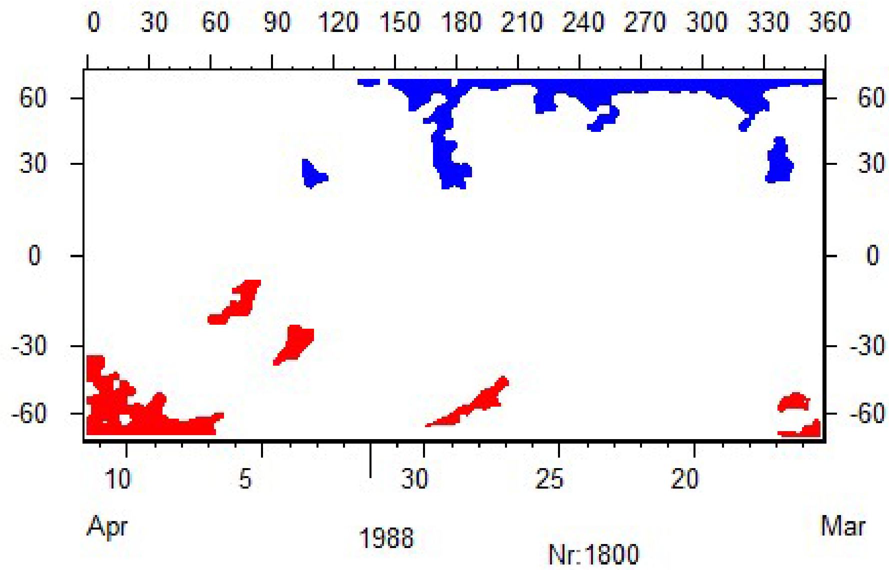

Figure 1. A synoptic chart for the synoptic rotation N1800. Coronal holes of the positive and negative polarity of the magnetic field are indicated with red and blue colors, respectively.

magnetosphere (Wilcox, 1968; Nolte et al., 1976; Sheeley, Harvey and Feldman, 1976; Sheeley and Harvey, 1981; Wang and Sheeley, 1990). Coronal holes are responsible for the formation of recurrent flows, which appear regularly with the period of approximately 27 days and exist for several months. EUV radiation in a CH region display decreased intensity, which may be related to both the lowered temperature ($0.8\,10^6 K^o$) and the density decreased to 0.25 of that in a quiet corona (Granmer, 2009). Hence it follows that identification and delineation of CH from observations of the Sun and determination of their parameters, such as their location, areas, latitudinal and longitudinal size, magnetic field and some others present an important problem.

2. Initial data and their processing

CH are detected with the use of the data obtained both with ground-based telescopes in the He I 10830 Å line and with satellite-borne EUV observations. Here, we present our identifications of CH from the 1975-2003 observations at Kitt Peak and from SOHO/EIT Fe XII 195 Å line observations 1996-2012; we also used the He I 10830 Å data obtained with SOLIS telescope from 2004 to 2012, when no SOHO/EIT observations were made. The Kitt Peak and SOHO/EIT observations are available in FITS-form at ftp://nsokp.nso.edu/kpvt/synoptic; http://www2.ess.ucla.edu/, the SOLIS data at http://solis.nso.edu/jingli/LSM/vsm-maps.php.

Identification of coronal holes faces some difficulties. CH display a lower electron density and temperature than typical quiet solar regions; for this reason,

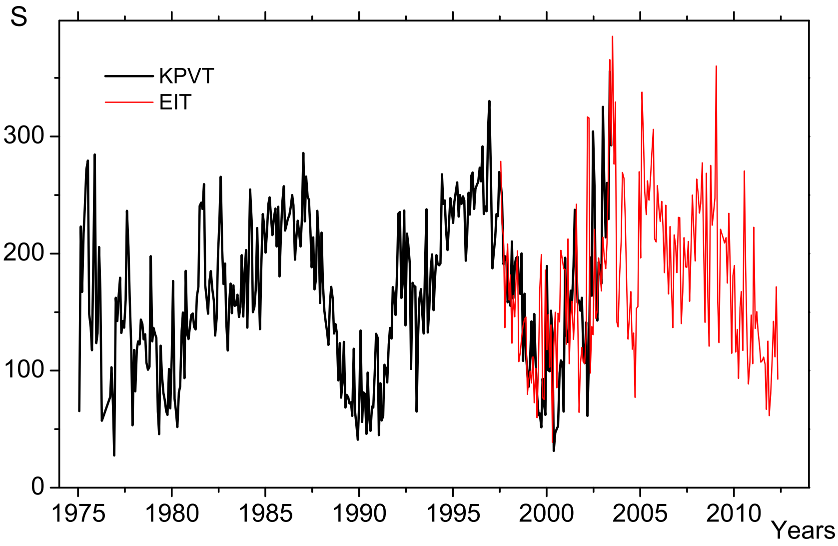

Figure 2. CH areas derived from Kitt Peak KPVT data (1975 to 2003) and SOHO/EIT data (1996 to 2012), in the units of 10^{-3} of the solar hemisphere, averaged for a Carrington rotation.

they look bright in the He I 10830 Å line and dark at EUV and X-ray wavelengths (Zirker , 1977). Nonetheless, this criterion does not make it possible to distinguish coronal holes unambiguously from other similar regions on the Sun. For example, light areas in the He I 10830 Å line might indicate not only CH, but also filament channels, which at EUV wavelengths also look dark. In addition, coronal holes may not display sharp boundary patterns and may be partly obscured by active regions. At different wavelengths, coronal holes look slightly different in their shape and area (Kahler, Davis and Harvey, 1983).

Initially, CH were identified visually by experienced observers (Harvey and Recely, 2002; McIntosh, 2003); recently, however, several automatic methods have been suggested. Some of them are based on the fixed threshold intensity at a given wavelength (Abramenko, Yurchyshyn and Watanabe, 2009). This technique, however, has proven insufficient (de Toma, 2011). In other methods, more complicated approaches are used (de Toma and Arge, 2005; Henney and Harvey, 2005). For example, from observations in He I 10830 Å line (Henney and Harvey, 2005), initially selected pixels with the intensity no lower than 1/10 of the average intensity over the image, truncated all regions below this level, and subsequently applied smoothing and filtering procedures. A technique developed for CH identification from EUV data (de Toma, 2011) also uses a variable threshold level, which varies from one chart to another; the threshold is determined as a width of the Gaussian distribution of pixel intensity, with a factor depending on the wavelength.

We tested different methods of CH identification and finally concluded that a totally automatic determination of the threshold level is insufficient. We developed a semi-automatic technique for delineation of CH borders on synoptic charts and for superimposing these borders on magnetic field charts.

Our method consists of several steps. Initially, we used a smoothing procedure for adjacent pixels, with the smoothing width of approximately 3 heliographic degrees. At the first stage, we selected a suggested threshold intensity level I_{th}, which was determined from the pixel intensity histogram $H(L)$. Further on, we took the logarithm of the cumulative histogram $P = \log(\sum H(L))$ and selected the threshold level I_{th}, which corresponded to the maximum difference $P_{i+1} - P_i$ of the logarithmic cumulative histogram. On the second step, a supervisor manually corrected the selection of the threshold intensity I_{th}. Then we filtered out filaments seen as low-intensity zones at EUV wavelengths, and filament cavities seen as bright structures in the He I 10830 Å line. To this end, we superimposed the position of the neutral line of large-scale magnetic field derived from the Hα synoptic maps obtained at Kislovodsk Mountain station. At the final stage, we filtered out regions with the area smaller than 10^{-3} in the units of the solar hemisphere area. The discriminated regions were combined into a single structure with a common border.

The data were digitized independently by two observers, in order to increase the accuracy in ambiguous situations; in general, both results appeared to be identical. In total, we identified 3943 CH from KPVT 1975 to 2003 observations and 1884 CH on SOHO/EIT-195 Å synoptic charts. In the absence of SOHO/EIT observations, the data were supplemented by CH derived from SOLIS observations. Figure 1 presents an example of a CH synoptic chart for the synoptic rotation N1800.

3. The results

The number, sizes, and latitudinal positions of coronal holes vary depending on the phase of the solar cycle. The coronal holes with the largest area occur at high latitudes within 5 to 6 years around the minimum of the solar cycle; closer to the cycle maximum, they disappear. At the phase of decline of the solar activity, gradual growth of CH with new polarity is observed. Figure 2 presents the areas of CH derived from KPVT He I 10830 Å observations and from SOHO/EIT 195 Å observations (the latter were supplemented with the data obtained with SOLIS telescope in the years 1997 to 2012). The two data series overlap in the interval 1997 to 2003, in which they display sufficient consistency (Fig. 2). The areas of CH observed in these two lines are related as follows: $S_{He10830} \approx 0.9 S_{Eit195}$.

On the basis of the observational series, we formed the consolidated CH series for the time interval 1975 to 2012 (synoptic rotations 1625 to 2123), which combined both optical observations in the He I 10830 Å line and EUV observations in the Fe XII 195 Å line. Figure 3 presents the CH areas at low ($\theta < \pm 30^o$) and high ($\theta > 60^o$) latitudes. The low-latitude CH in the 21-st and 23-rd solar activity cycles display the maximum area at the declining activity phase, with the largest area within the intervals 2003 to 2004 and 2005 to 2006.5. The increase in the

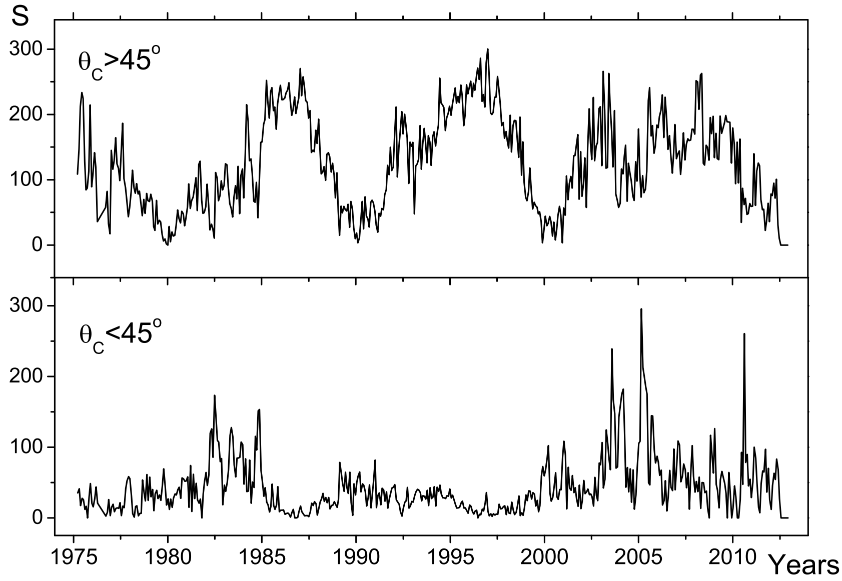

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Figure 3. CH areas averaged for a synoptic rotation, for a consolidated KPVT He I 10830 Å and SOHO/EIT 195 Å observational data. Top: the area of circumpolar CH with geometric center above the latitudes $\theta_c > 45^o$; bottom: the area of low-latitude CH with geometric center $\theta_c < 45^o$

area of the low-latitude CH in these years was also mentioned in the study (Abramenko *et al.*, 2010).

The characteristic areas for high- and low-latitude CH are different (Fig.4). While the maximum of the area distribution of the low-latitude CH is reached at $S \sim 3 \cdot 10^3$ in millionths of the solar hemisphere area units (MSH), for high-latitude CH this value is $S \approx 10^2$ MSH.

Coronal holes, as a rule, are located in the regions of the unipolar large-scale magnetic field. Therefore, in the minimum of the solar activity they are seen in circumpolar regions, at the latitudes higher than 60^o (Fig. 5). In the times of the alteration of the magnetic field sign, high-latitude CH disappear and then occur again 2 to 3 years later. At middle and low latitudes, coronal holes appear at the decline phase of the cycle, however, no separate latitude zone in which they concentrate (similar to that at high latitudes) exists.

The parameters of the magnetic field that underlies CH are essential. To determine them, we superimposed the CH borders on synoptic charts of magnetic fields obtained from the data of KPVT magnetograph (the years 1975 to 2003), SOHO/MDI (2003 to 2010), and SOLIS (after 2010). The synoptic charts of the magnetic fields for the year 2003 were reduced to the 360x180-pixel format of Kitt Peak magnetograms. The average magnetic field strength in CH was $B_{av} \approx 6.5$G. At the maximum and the decline phase of a cycle, centers of CH

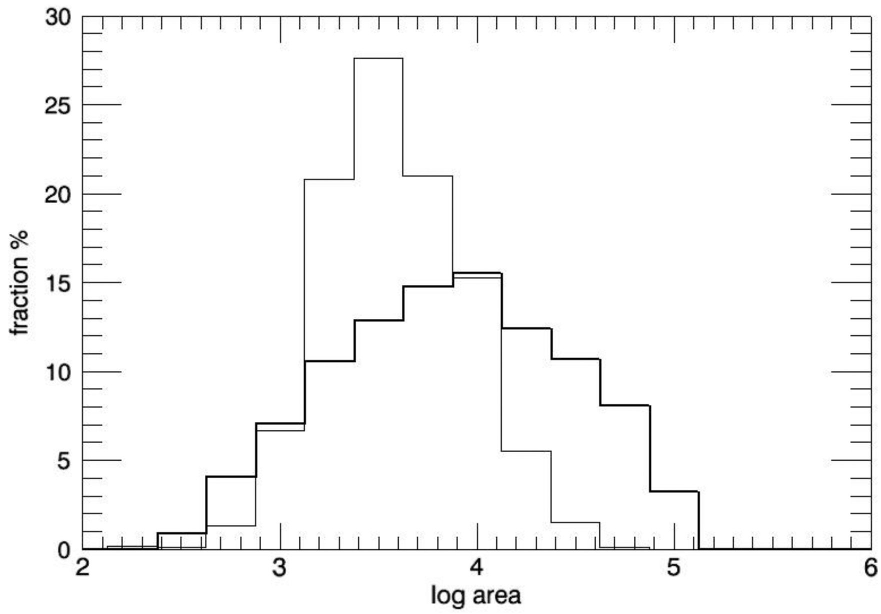

Figure 4. The histogram of CH area distribution in MSH for high-latitude CH with geometric center above $\theta_c > 50^o$ (thick line) and for low-latitude CH with $\theta_c < 40^o$ (thin line).

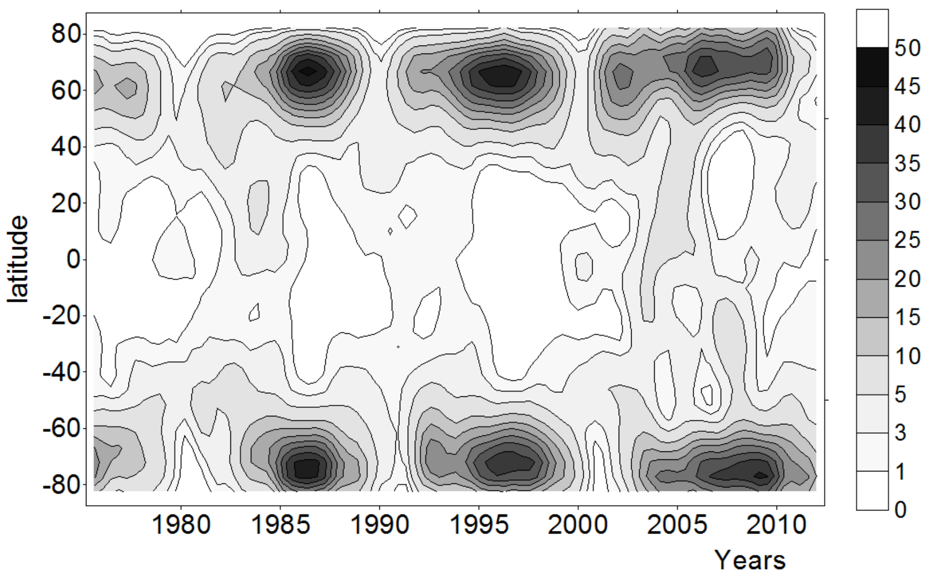

Figure 5. The time-latitude distribution of CH areas in the units of 10^{-3} of the solar hemisphere area calculated from synoptic charts in the 5-degree latitude interval.

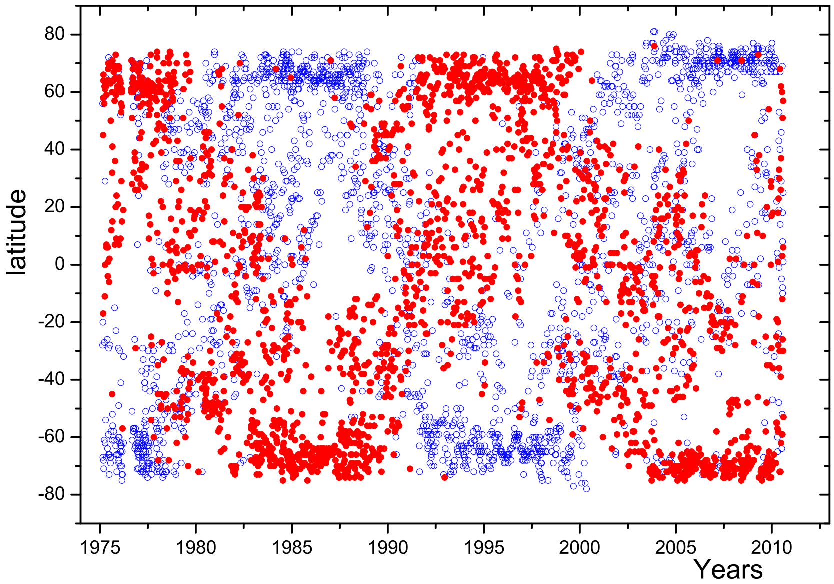

Figure 6. Time-latitude positions of CH centers. CH of negative polarity are marked with blue, those of positive with red color.

of the same polarity displace from one pole to the other. For example, in 1988-1993, CH with negative polarity drifted from the north pole to the south, while those with positive polarity moved in the opposite direction (Fig. 6). This effect might be interpreted as the rotation of the dipole large-scale field during a solar cycle (Livshits and Obridko, 2012), however, the longitudinal distributions of CH centers do not display any separated tracers for CH with different polarity (Fig. 7).

The average strength and the flux of the magnetic field in CH vary from one cycle to another. Figure 8 presents the variations of the magnetic flux in CH, in the units of 10^{20} Mx. In spite of the relatively high areas of CH in the 23-rd cycle, the magnetic flux in CH in this cycle was substantially lower than that in the previous cycles

This discrepancy may be due to a variation of the structure of the large-scale magnetic field in CH. The magnetic flux depends not only on the magnetic field strength, but also on the degree of unipolarity of the field. Figure 9 presents the variation of the degree of unipolarity in CH, calculated as $U = (F_p + F_n)/(F_p - F_n)$, where F_p and F_n are the absolute values of the flux of the magnetic field with the positive and negative polarity, respectively. At the growth phase of the 21-st cycle and at the decline phase of the 23-rd cycle, the decrease in the degree of unipolarity in CH, and consequently the small magnetic flux, is observed (Fig. 8).

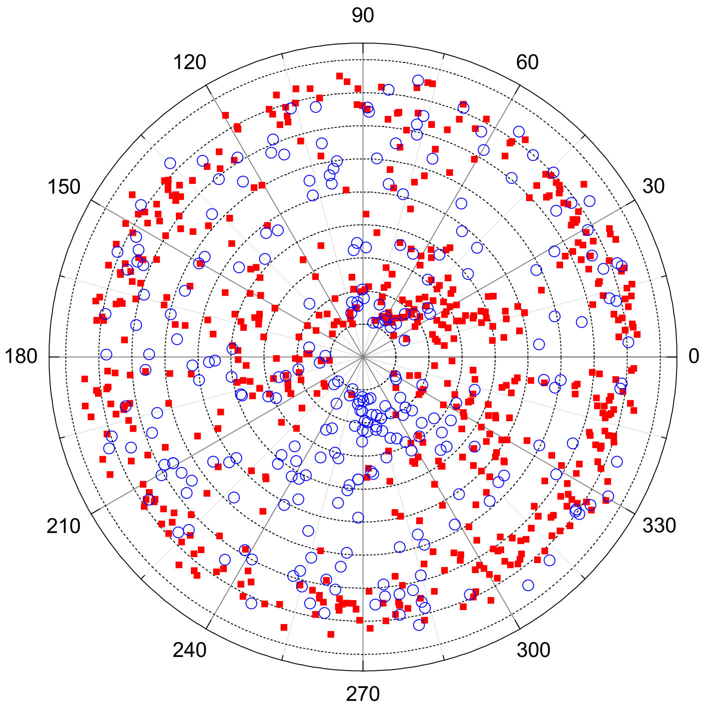

Figure 7. Positions of CH centers in 1988-1993, seen from the north pole of the Sun. The CH of positive polarity of the magnetic field are marked with red, those of negative with blue.

4. Discussion and conclusion

Coronal holes are solar regions with the open magnetic field. The study of their characteristics and evolution is important to understand not only the nature of the solar magnetic field and the mechanisms of acceleration and heating of the solar wind, but also the impact of CH on the magnetosphere of the Earth, since CH are the basic source of the interplanetary magnetic field and the solar wind. On the basis of synoptic observations made in Kitt Peak Observatory and of EUV observations with SOHO/EIT-195 Å, we have composed the catalogue of CH within the time interval 1975 to 2012, which includes three complete cycles of solar activity (21-st to 23-rd). The He I 10830 Å line data for CH in synoptic rotations No.1625 to 2003 and EIT 195 Å observations for rotations 1909 to 2123 are available at the site of Kislovodsk Mountain Astronomical Station (http://solarstation.ru/).

The obtained series makes it possible to compare the CH evolution with the parameters of the solar activity and the solar wind. Figure 10 presents the comparison between our consolidated CH series, the inclination angle of the heliospheric current sheet, calculated at the height $R = 2.5R_o$ from the data of WSO magnetograph (http://wso.stanford.edu/tielts.html), and the flux of the

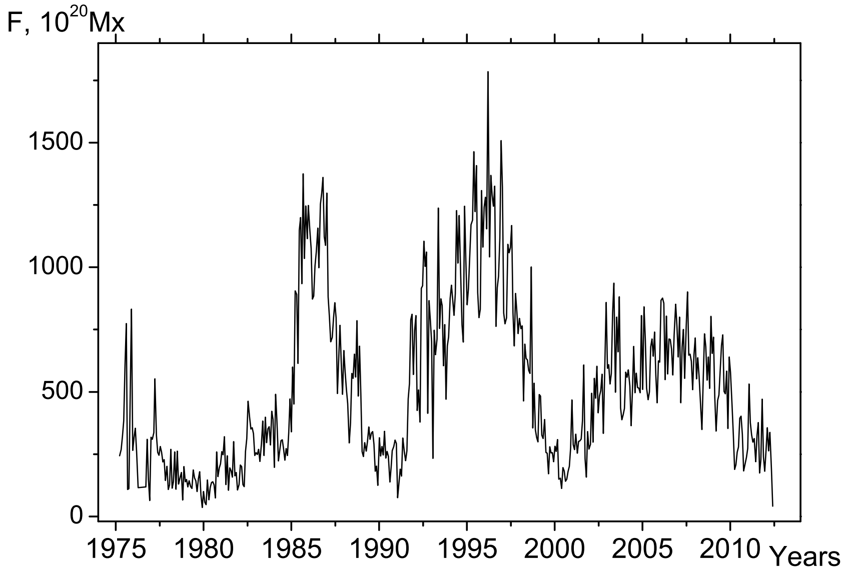

Figure 8. Magnetic flux of coronal holes.

galactic cosmic rays derived from the data of Kiel neutron monitor. The increase in the area of polar CH in the minimum of the cycle leads to the decrease in the inclination angle of the heliospheric current sheet and to the compression of the sheet towards the solar equator. In the 21-st and 22-nd cycles, these two indices of the solar activity display good consistency. In the 23-rd cycle, the consistency somewhat deteriorates, which may be due to a variation in the average flux of the magnetic fields in CH (Fig. 7).

CH are known to be a source of the high-speed solar wind (Nolte et al., 1976; Sheeley, Harvey and Feldman, 1976). As a rule, this is explained by the contribution of circum-equatorial CH, which may affect parameters of the plasma in the plane of ecliptics. Indeed, in the time interval 2003-2004, low-latitude CH were responsible for the increase in the velocity of the solar wind (Abramenko, Yurchyshyn and Watanabe, 2009; Manoharan, 2012). However, our analysis shows that polar CH may also influence the parameters of the solar wind in the vicinity of the ecliptics. Figure 11 presents the areas of circumpolar CH at latitudes exceeding 60^o compared with the variations of the magnetic Mach number of the solar wind , according to the OMNI2 data (http://nssdc.gfc.nasa.gov/omniweb). The comparison indicates sufficient consistency between these parameters. It is possible that the magnetic field of polar CH causes the compression of the solar wind flux towards the solar equator and thus the variation of the parameters of the solar wind at all latitudes (Tlatov, 2010).

In the 23-rd cycle of the solar activity, the total CH area is large (Fig. 2), with a substantial fraction of the low-latitude CH (Fig. 3). However, in spite of the

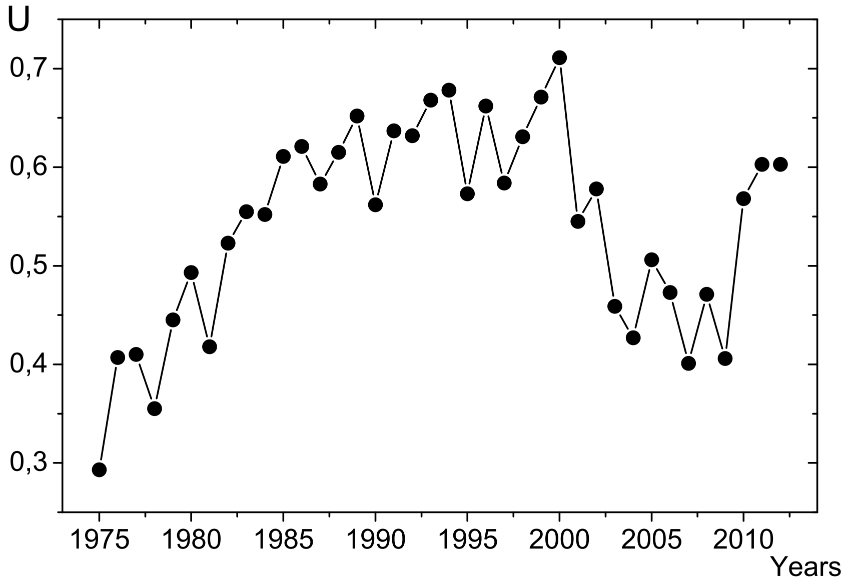

Figure 9. The annual average degree of unipolarity of the magnetic field in CH.

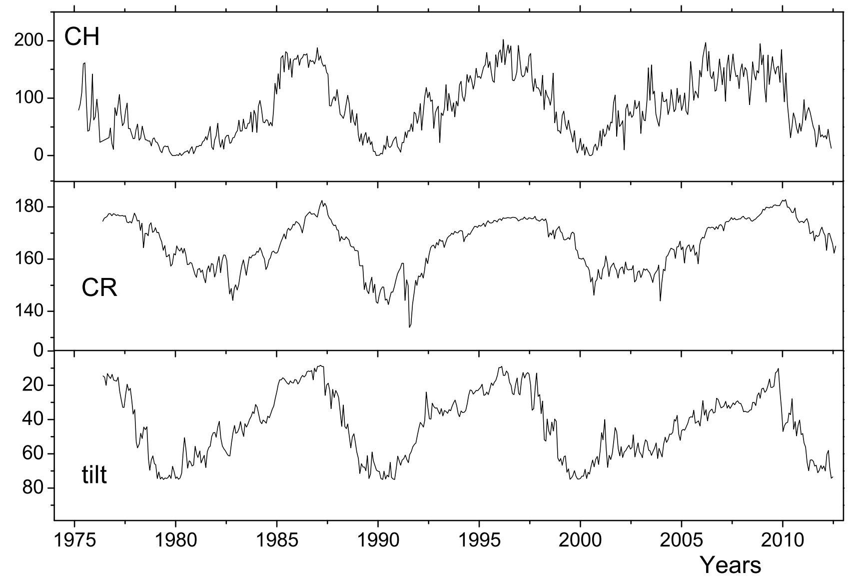

Figure 10. The comparison between the CH area at latitudes above $\theta > 60^o$ (above), the flux of the galactic cosmic rays (middle), and the inclination angle of the heliospheric current sheet calculated from the WSO data (below).

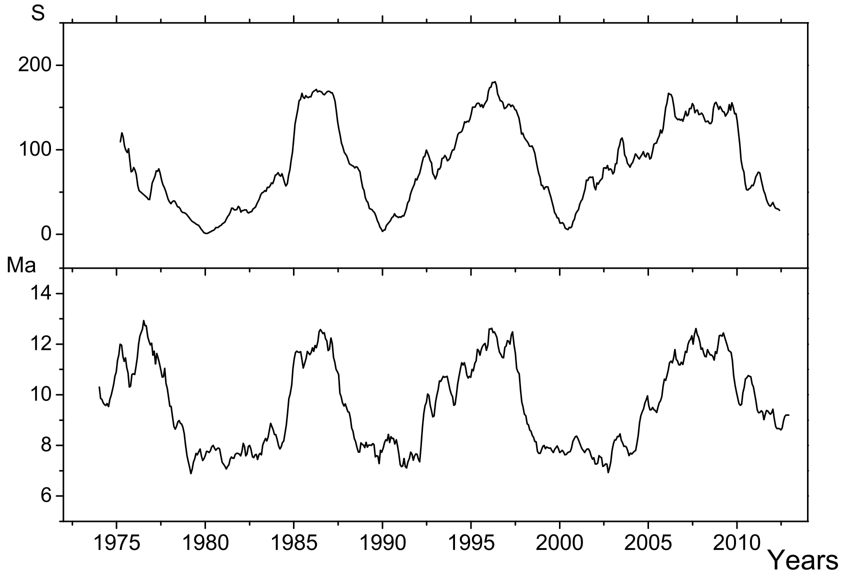

Figure 11. A comparison between the areas of polar CH at latitudes above $\theta > 60^o$ and the variations of the magnetic Mach number of the solar wind. The data were smoothed with the sliding window of 6 rotations.

large CH area, the total magnetic flux derived from the photospheric magnetic field for the minimum of the 22-nd and 23-rd cycles was substantially lower than that in the previous cycles. This is probably due to a decrease in the strength of the polar magnetic field. In the years 2003 to 2004, along with the relatively large area of the low-latitude CH, the increase in the velocity of the solar wind was observed. At the same time, the magnetic field in CH the 23-rd cycle displayed the mixed type of polarity (Fig. 8, 9), which may have been the reason why the increase in the wind velocity did not result in any noticeable growth of the geomagnetic activity (Manoharan, 2012).

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