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The changing in the vertical boundaries of a giant coronal hole

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We analyzed the vertical boundaries of a long-lived giant coronal hole (GCH) and their variation with height and time. The investigations are based on ground-based and space observations. Images of the Sun in the infrared line He I λ 10830 Å obtained on the Universal Spectrophotometer of the TST–2 CrAO RAS telescope and observations of SDO space telescopes in the line Fe XII λ 193 Å and magnetograms obtained by HMI in line Fe I λ 6173 Å. Analysis of the boundaries of CH on the different heights of the Sun atmosphere showed the following: the boundaries of the GCH, determined from the observations, are very close both in the E–W direction in the N–S direction. The boundaries of the GCH, determined from the magnetic field lines for the photosphere, are in good agreement at the moments of the beginning and end of the existence of the GCH with the observed boundaries, and differ in the maximum development of the GCH. The maximum expansion of the coronal hole is from the photosphere to the chromosphere. Approximately at height of 1.0045 $R_\odot$ and beyond there is a radial expansion.

The results obtained are important in the development of methods for predicting the solar wind.

Keywords: Sun, coronal holes

1 Introduction

Coronal holes (CHs) are large regions on the Sun that are mainly magnetically open. They are identified as the source of the fast solar wind (∼800 km/s) (Krieger et al., 1973) and are visible in coronal lines (formed at temperatures above 6×10^5 K) as regions with a reduced emission relative to the quiet Sun (Wilhelm, 2000; Stucki et al., 2002). Our interest in them deals with boundary detection on three levels of the solar atmosphere. Detecting CH boundaries is important for estimating their size and tracking their evolution through time and heights, as well as for comparing the physical properties within and outside of the feature.

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Today it is fairly clear that these zones are dominated by open magnetic field lines that 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 quiet Sun. Studies of how the plasma and the magnetic fields of the solar atmosphere – from the photosphere to the corona – extend outward to form the heliosphere have long been one of the central tasks of heliophysics. The open magnetic fields of the Sun and the CH structure change along with the total solar activity cycle (Harvey, Recely, 2002; Wang, 2009). The distribution of rotation and statistical characteristics of a CH is large-scale in nature and seems to be related to the global solar magnetic field, which allows them to be considered indicators of the large-scale magnetic field in the solar corona (Obridko, 1989; Bumba et al., 1995; Bilenko, Tavastsherna, 2016). But these issues remain topical.

The determination of the structure of the CH is essential for understanding the nature of the CH and conditions for the occurrence of high-speed solar wind flows. One of the main characteristics of the CH structure is the change in its area, vertical boundaries with height. Knowledge of these quantities makes it possible to judge the nature of the divergence of the magnetic field lines in CH.

Within the framework of the CORONAS-F project, the boundaries of the CH have been identified using the CH brightness observations and measured and calculated magnetic field values by our colleagues (Bugaenko et al., 2004). Several types of the CH boundaries based on the brightness data as well as their time variations have been considered. The rate of change of the CH area due to the shift of the boundaries has been estimated. The magnetic fields in a particular coronal hole have been computed by plotting the open and closed field lines, calculating the separatrices, and determining the DI parameter. A conclusion is made that the CH boundaries derived from the brightness observations coincide closely with the boundaries between the open field lines and the feet of the low arch systems, which surround the CH and the adjacent region with a reduced contrast of the chromospheric network and the brightness of undisturbed chromosphere. The comparison of evolution of the coronal holes and active regions in their environment suggests the stability of CH and a weak relation of the AR magnetic fields inside a coronal hole to the external magnetic fields.

One of the consequences of changing the boundaries is a changing of the area of the CH. The rate of this change usually indicates the physical processes that lead to such changes. If the rate of change of the area is comparable to $\sim 10^4$ km^2/s, then the change in the area of the CH is usually associated with the transport of solar magnetic fields due to diffusion ("Leighton" or supergranulation diffusion) (Nolt et al., 1978). This speed corresponds to the average speed of growth and decay of supergranulation cells having a characteristic diameter of $\sim 3.10^4$ km and an average lifetime of ~20–50 hours. Kahler and Moses (1990) showed that the rate of change in the area of a CH can be several times higher than the speed of supergranulation diffusion, and suggested that the physical mechanism of such changes in the size of the CH is the interaction of large-scale magnetic fields with fields of bright x-ray points, accompanied by magnetic reconnection. As a result of this process, some open magnetic field lines in the CH region disappear (the CH area decreases), or additional open field lines appear (the hole area grows).

This paper is the continuation of a series of works between 2017–2018 (Andreeva et

al., 2018a,b; Akhtemov et al., 2018a,b; Tsap et al., 2017; Andreeva and Malashchuk, 2018a,b; Baranovsky et al., 2018), which are dedicated to the study of evolution and influence of the long-lived GCH on the near-earth space. The authors obtained the results of the analysis of changes in such evolutionary characteristics of the GCH such as area, intensity, rotational speed, magnetic field intensity, and magnetic flux. Andreeva et al. (2018b) show that the evolution of the GCH had clearly expressed 3 stages: birth, formation and disappearance. In the initial stage of development, the area of CH increased due to changes in external boundaries, and due to the appearance of floccules, pores and active regions. During the existence of the GCH, two active centers passed through it, which affected the change in parameters. CH significantly reduced the magnetic flux over a large part of the Sun in a time interval of almost one and a half years. Even when the CH began to decay noticeably, the intensity of the magnetic field and the magnetic flux continued to fall. Variations in the average intensity of a large-scale magnetic field of a CH in comparison with changes in the CH area prior to rotation 2173 occurred almost in antiphase. With an increase in the CH area, the field strength decreased and, conversely, a decrease in the area, in most cases, led to an increase in the magnetic field. This can be explained either by the presence of active formations (groups of spots) near the CH boundaries or by the emergence from the depth of the photosphere of new magnetic tubes with a large field strength and the corresponding polarity. The value of the average strength of the magnetic field during the existence of CH since its origin decreased by 19 times. Two intervals of increase in the average intensity against the background of a general decline occurred immediately after the growth of the area and it can be associated with the output of two large active formations to the CH.

The purpose of this paper is to study the vertical boundaries of the GCH and their variation with height and time.

The signs of the GCH under study with a sharply delineated southwestern boundary and a diffuse northward and western boundary that passed into the intermediate region were first discovered in June 2015 at a latitude of about 25°. Two days later, when the CH was near the zero meridian, its boundaries were first determined. GCH occupied a significant part of the north hemisphere in the course of its evolution. It existed for more than 2 tens of Carrington rotations (CR). In its maximum GCH extended up to 30 degrees in the southern hemisphere. Different stages of the GCH evolution are presented in Fig. 1.

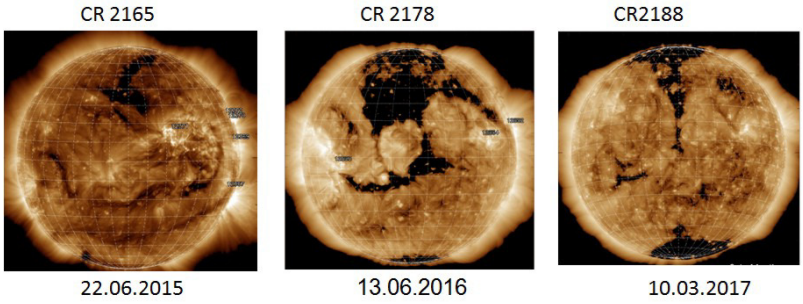


Figure 1 The GCH on the image of the Sun disk in the nucleation phase (CR 2165), at its maximum development (CR 2178) and at the disappearance stage (CR 2188).

2 Data and methods of research

We used data from GCH observations of ground–based and space instruments at three levels of the Sun's atmosphere. Observations in the He I 10830 Å (He I) line were obtained by us on the TST–2 Tower Solar Telescope (CRAO RAS) with a Universal Spectrophotometer (Stepanian et al., 2000) with a spatial resolution of 9.8″/pixel. Figure 2a,b shows an image of the Sun in the He I line derived at the telescope TST–2: (a) – an unprocessed image, (b) – with account of limb darkening. We also used the satellite data taken at SDO (AIA channel 19.3 nm and HMI channel 617.3 nm, Fig. 2c,d), as well as on the modeling of the magnetic field in the potential approximation (PFSS). CHs in the images of the He I are visible as light formations, and in Fe XII 193 Å (Fe XII) as dark.

For our studies, we selected by one image of the GCH for each of the 13 Carrington rotations, when the GCH was near the central meridian. We considered 3 stages of CH evolution (Fig. 1), for which there were data at three levels of the solar atmosphere (CR 2165–2168, 2177–2184 and 2187–2188).

During our research we used the following software:

The program of observations and processing of observational data on the telescope TST–2 CrAO RAS – for preliminary image processing in the He I 10830 Å line and account of limb darkening.

SolarDataApplication (SDA) – the special program developed by us earlier

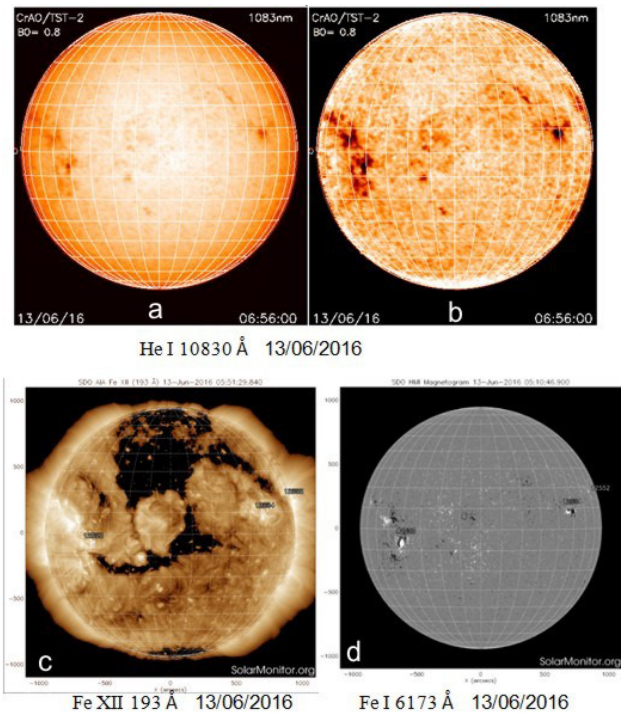


Figure 2 The image of the Sun in the lines He I (a,b), Fe XII (c), Fe I (d) for 13.06.2016.

(Andreeva et al., 2018b) for carrying out the boundaries and determining the heliographic coordinates of the GCH at given latitudes and longitudes of the images of the Sun in lines He I 10830 Å and Fe XII 193 Å.

SolarSoft PFSS – the package of programs that makes it possible to build the lines of force of the solar magnetic field for heights of 1.0 $R_\odot$– 2.5 $R_\odot$ ($R_\odot$, the radius of the Sun) by the method of potential approximation from the corresponding photospheric magnetograms. We built the force lines for the photosphere – 1.0 $R_\odot$.

The method of overlaying images – to obtain the coordinates of the boundaries of the GCH, drawn along the lines of force of the magnetic fields (FM).

A preprocessing procedure was applied to all the data. Darkening of limb was taken into account and the brightness of the image was normalized for images in the He I line. Images in the line Fe XII were reduced to the scale of the images in the He I line. To obtain the GCH contours on the Sun's disk selected by the parameter, we used the program SDA.

3 Determination of the vertical boundaries of the GCH

Currently, there are no generally accepted findings of CH boundaries, and technologies for their identification. The main reason for this is that CH often lacks sharp boundaries. In our work we used the SDA program developed by us earlier, for the detecting of the boundaries of the GCH. The eastern (E) and western (W) boundaries of the GCH were determined at a latitude of $\varphi = 40°$. The northern (N) and southern (S) boundaries of the GCH were determined on the longitude corresponding to the meridian passing through the middle of the GCH at a latitude of $\varphi = 40°$. The heliographic coordinates of the GCH on the images in the He I and Fe XII lines were also calculated using the SDA program. The method of superimposing the images of the lines of force obtained with the help of PFSS was applied to the original magnetograms to obtain the GCH contours on the photosphere. The result of contouring of the GCH on images of the Sun disk for 17.05.2016 for three heights is shown in Fig. 3.

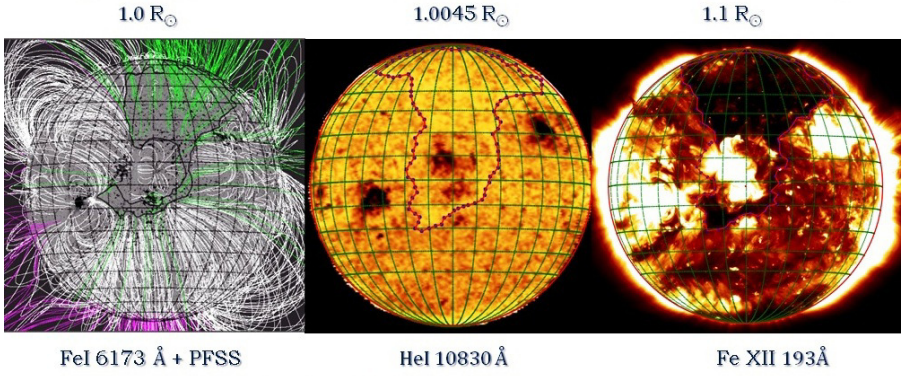


Figure 3 GCH contours, plotted on images of the solar disk for 17.05.2016 for the photosphere (1.0 $R_\odot$), chromosphere (1.0045 $R_\odot$) and corona (1.1 $R_\odot$)

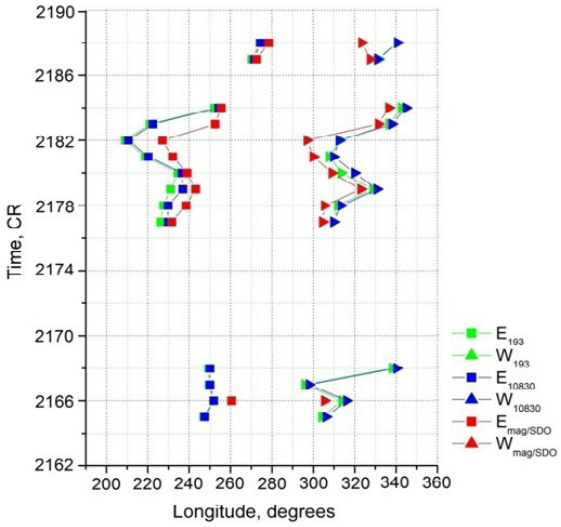


Figure 4 Variations in the eastern (squares) and western (triangles) borders of the GCH derived from observations in two spectral lines: Fe XII (green) and He I (blue), as well as from calculations in the potential approximation based on data about MF taken by SDO/HMI (red). The Y-axis represents the time in the Carrington rotations.

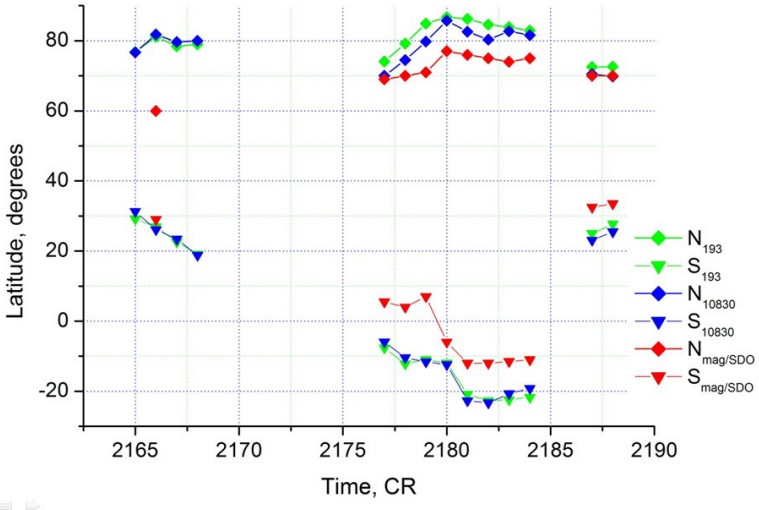


Figure 5 Variations in the northern (rhombus) and southern (inverted triangle) borders of the GCH derived from observations in two spectral lines: Fe XII (green) and He I (blue), as well as from calculations in the potential approximation based on data about MF taken by SDO/HMI (red). The X-axis represents the time in the Carrington rotations.

The material processing data allowed us to obtain the heliographic coordinates of the GCH boundaries from the observations in the He l and Fe XII lines and the

boundaries of the GCH, obtained by the force line calculation (PFSS). All of them were used for plotting the vertical GCH boundaries E–W (Fig. 4) and N–S (Fig. 5). They show the changes in E–W and N–S boundaries of the GCH with height and time, for 3 stages of its development (CR 2165–2168, 2177–2184 and 2187–2188).

Conclusions

Analyzing the graphs of the image of the Sun at different heights, one can conclude:

The E–W boundaries of the CH in the chromosphere and corona are very close. This is typical for all 3 stages of its evolution. At the stage of formation and at the end of its development, the expansion from the photosphere to the crown is small, ranging from 5 to 10 degrees. In the stage of maximum development, the expansion reaches 20 degrees. The development of active centers near and within the CH affects the variation of vertical boundaries at all levels of the Sun's atmosphere. The boundaries of the GCH, determined from the observations in the lines He l 10830 Å and Fe XII 193 Å, are very close both in the E–W direction and in the N–S direction. The boundaries of the GCH, determined from the magnetic field lines for the photosphere, are in good agreement at the moments of the beginning and end of the existence of the GCH with the observed boundaries, and differ in the maximum development of the GCH. The maximum expansion of the coronal hole is from the photosphere to the chromosphere, approximately at height of 1.0045 $R_{\odot}$ and beyond there is a radial expansion.

The results obtained are important in the development of methods for predicting the solar wind. They show that the use of coronal hole observations only in the He I 10830Å line is not enough for the forecast. It is necessary to attract data from observations of the corona and to model coronal magnetic fields from photospheric observations.

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References

Akhtemov, Z.S., Perebeynos, V.A., Shtertser, N.I., 2018a, Izv. Krym. Astrofiz. Obs. V. 114, No. 1, p. 123 (in Russian).

Akhtemov, Z.S., Tsap, Yu.T., Malashchuk, V.M., Shtertser, N.I., 2018b, Conference on the physics of the Sun "Magnetism, cycles of activity and solar and stellar flares", June 3–7, 2018. Proceedings. Nauchny, p. 32 (in Russian).

Andreeva, O.A., Malashchuk, V.M., Akhtemov, Z.S., Zhigalkin, R.K., 2018a, Izv. Krym. Astrofiz. Obs. V. 114. No. 1. p. 129 (in Russian).

Andreeva, O.A., Akhtemov, Z.S., Malashchuk, V.M., Zhigalkin, R.K., 2018b, Geomagnetism and Aeronomy. V. 58. No. 7. p. 916.

Andreeva, O.A., Malashchuk, V.M., 2018a,b, Conference on the physics of the Sun "Magnetism, cycles of activity and solar and stellar flares", June 3–7, 2018. Proceedings. Nauchny, p. 32, 48 (in Russian).

Baranovsky, E.A., Gopasyuk, O.S., Shtertser, N.I., 2018, Conference on the physics of the Sun "Magnetism, cycles of activity and solar and stellar flares", June 3–7, 2018. Proceedings. Nauchny, p. 33 (in Russian).

Bilenko, I.A., Tavastsherna, K.S., 2016, Solar Phys. V. 291, Issue 8, p. 2329.

Bugaenko, O.I., Rudenko, G.V., Fainshtein, V.G., Malashchuk, V.M., Stepanyan, N.N., Shtertser, N.I., et al., 2004, Bull. of the Crimean Astrophys. Obs. V. 100. p. 107.

Bumba, V., Klvana, M., Sykora, J., 1995, A&A. V. 298. p. 923.

Harvey, K.L., Recely, F., 2002, Solar Phys. V. 211. p. 31.

Kahler, S.W., Moses, D., 1990, Astrophys. J., V. 362, p. 728.

Krieger, A.S., Timothy, A.F., Roelof, E.C., 1973, Solar Phys., V. 29, p. 505.

Nolte, J.T., Gerasimenko, M., Krieger, A.S., Solodina, C.V., 1978, Solar Phys., V. 56, p. 153.

Obridko, V.N., Shelting, B.D., 1989, Solar Phys., V. 124. p. 73.

Stepanian, N.N., Dolgopolova, E.V., et al., 2000, Izv. Krym. Astrofiz. Obs., V. 96, p. 194 (in Russian)

Stucki, K., Solanki, S.K., Pike, C.D., et al., 2002, A&A, V. 381, p. 653.

Tsap, Yu.T., Malashchuk, V.M., Borisenko, A.V., Akhtemov, Z.S., Andreeva, O.A., 2017, XXI All-Russian Annual Conference on the Physics of the Sun "Solar and solar-terrestrial physics", October 9–13, 2017. Proceedings. Saint Petersburg, p. 365 (in Russian).

Wang, Y., 2009, Space Sci. Rev. V. 144. p. 383.

Wilhelm, K. 2000, A&A, V. 360, p. 351.